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XXXII Cycle

Design, Analysis and Testing Procedures for Synchronous Reluctance and Permanent Magnet Machines

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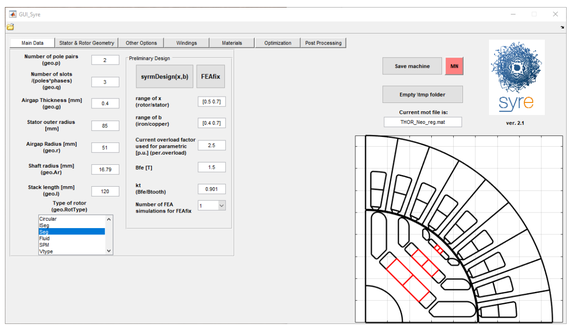
Research context and motivation

Synchronous Reluctance (SyR) Machines are a viable alternative to other kind of electrical machines. Thanks to the distinctive rotor geometry, SyR machines have low manufacturing cost and high efficiency. Moreover, their design is complex and not well established. For some applications, Permanent Magnets (PMs) can be inserted in the rotor, increasing the performances, but further aggravating the design process. The need of a reliable design tool is evident. This should incorporate FEA validation tools, compatible also with the experimental test procedures, in order to have a common environment. This research is closely related to **SyR-e** (**Sy**nchronous **R**eluctance-**e**volution), a design tool for SyR and PM machines. The link is twofold: SyR-e helps the research for all the basic operations, while the research activity add several novel contributions and state the tool reliability, making SyR-e a good reference for further studies and industrial projects



Addressed research questions/problems

The main topics covered in the research activity can be divided into three sections:

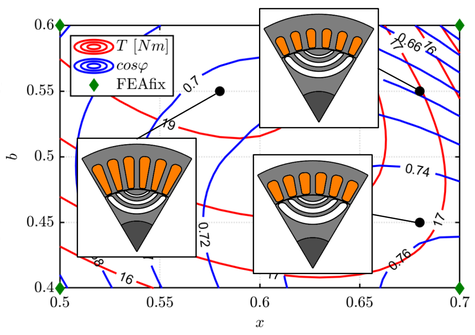
1. **SyR and PM-SyR machines design**: define a fast and aware design procedure .
2. **Asymmetric SyR and PM-SyR rotors:** study on asymmetric rotors to reduce the torque ripple of SyR and PM-SyR machines.
3. **Interior Permanent Magnet (IPM) machine design**: extension of the SyR machine design approach to V-type IPM machines.

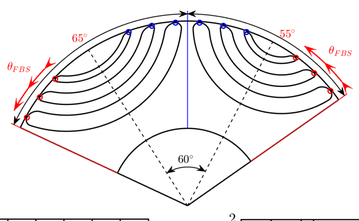
Novel contributions

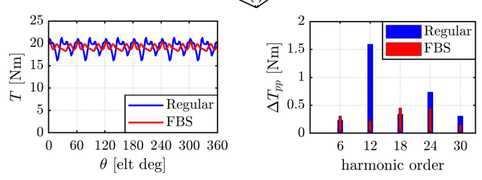
1. SyR and PM-SyR machines design

Design equation for a fast and conscious design of SyR and PM-SyR machines. Main contributions are:

- Estimation of the iron saturation effect
- FEAfix procedure: few FEA simulations correct the analysical model estimation.
- Fast PM design for field weakening operations







2. Asymmetric SyR and PM-SyR rotors

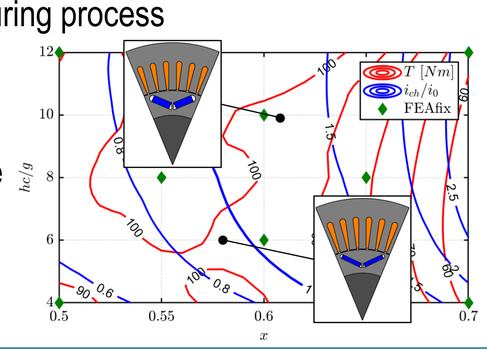
Torque ripple reduction using the Flux Barrier Shift (FBS) concept for SyR and PM-SyR motors:

- Fast: optimization is possible, but not compulsory
- Effective: target harmonics are reduced,
- Feasible: no side effects of performance and manufacturing process

3. IPM machine design

Extension of the design plane approach to V-type IPM machines. Features are:

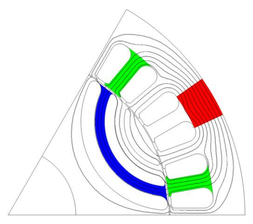
- Design equations, based on analytical models
- FEAfix procedure: needed for high accuracy

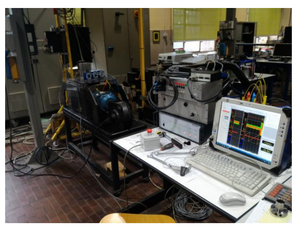


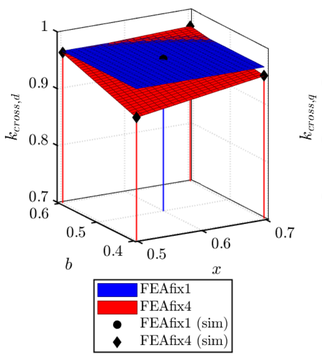
Adopted methodologies

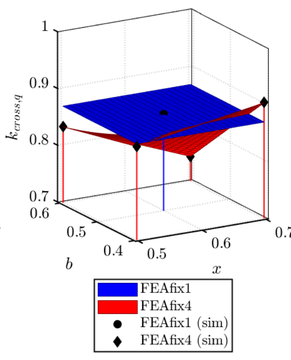
1. SyR and PM-SyR machines design

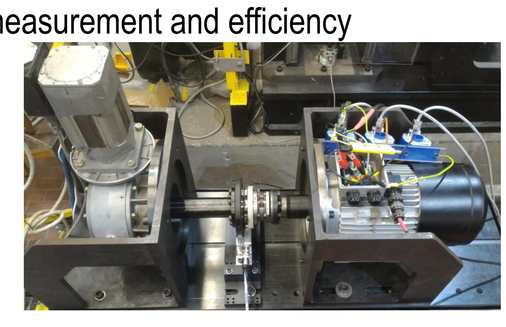
- Automatic SyR stator and rotor design starting from two parameters (x,b).
- Analytical equations and FEA simulations to have a precise performance estimation
- FEA procedures to automatically identify the magnetic models and post-processing tools, compatible with FEA and experimental results
- Custom test bed for lab tests: magnetic model identification, torque ripple measurement and efficiency

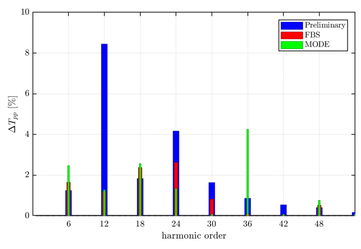


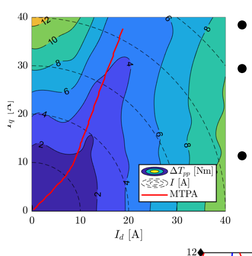










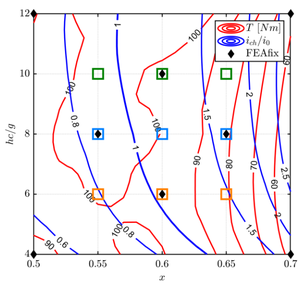


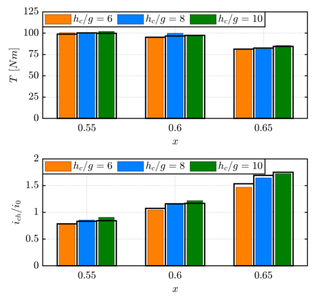
2. Asymmetric SyR and PM-SyR rotors

- Analytic and FEA tools developed in SyR-e
- Custom FEA post-processing tools
- FBS comparison against optimization algorithm and skewing
- Experiments: 4 prototype to validate FBS on SyR and PM-SyR machines

3. IPM machine design

- Analytical equations for the initial design
- FEAfix process extended to IPM
- FEA validation against an existing commercial machine





Future work

1. **SyR and PM-SyR machine design**: improvement of the PM-SyR machines design and validation against optimization algorithm.
2. **Asymmetric SyR and PM-SyR rotors**: extension of the FBS concept to IPM machines. Further analysis on asymmetric PM-SyR machines
3. **IPM machine design**: improvement of the design equations and extension to multi-barrier V-type IPM machines.

Submitted and published works

1. S. Ferrari, G. Pellegrino and E. Bonisoli, "Magnetic and structural co-design of synchronous reluctance electric machines in an open-source framework", in International Journal of Mechanics and Control, vol. 17, no. 1, pp. 59-66, July 2016
2. C. Lu, S. Ferrari and G. Pellegrino, "Two Design Procedures for PM Synchronous Machines for Electric Powertrains," in IEEE Transactions on Transportation Electrification, vol. 3, no. 1, pp. 98-107, March 2017.
3. R. Leuzzi, P. Cagnetta, S. Ferrari, P. Pescetto, G. Pellegrino and F. Cupertino, "Analysis of overload and sensorless control capability of PM-assisted synchronous reluctance machines," 2017 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD), Nottingham, 2017.
4. M. Gamba, G. Pellegrino, E. Armando and S. Ferrari, "Synchronous Reluctance Motor with Concentrated Windings for IE4 Efficiency," 2017 IEEE Energy Conversion Congress and Expo (ECCE), Cincinnati (OH), October 2017
5. C. Lu, S. Ferrari, G. Pellegrino, C. Bianchini and M. Davoli, "Parametric Design Method for SPM Machines Including Rounded PM Shape", 2017 IEEE Energy Conversion Congress and Expo (ECCE), Cincinnati (OH), October 2017
6. R. Leuzzi, P. Cagnetta, S. Ferrari, G. Pellegrino and F. Cupertino, "Performance Assessment of Ferrite- and Neodymium- Assisted Synchronous Reluctance Machines," 2017 IEEE Energy Conversion Congress and Expo (ECCE), Cincinnati (OH), October 2017
7. S. Ferrari, G. Pellegrino, M. Davoli and C. Bianchini, "Reduction of Torque Ripple in Synchronous Reluctance Machine through Flux Barrier Shift," 2018 XXIII International Conference on Electrical Machines (ICEM), Alexandroupoli, Greece, September 3-6, 2018
8. S. Ferrari and G. Pellegrino, "FEA-Augmented Design Equations for Synchronous Reluctance Machines", 2018 IEEE Energy Conversion Congress and Expo (ECCE), Portland (OR), September 23-27, 2018
9. P. Pescetto, S. Ferrari, G. Pellegrino, E. Carpaneto and A. Boglietti, "Short-Time Transient Thermal Model Identification of Multiple Three-Phase Machines", 2018 IEEE Energy Conversion Congress and Expo (ECCE), Portland (OR), September 23-27, 2018
10. S. Ferrari, G. Pellegrino, M. J. M. Zubair and I. Husain, "Computationally Efficient Design Procedure for Single-Layer IPM Machines," 2019 IEEE International Electric Machines & Drives Conference (IEMDC), San Diego, CA, USA, 2019.
11. R. Leuzzi, P. Cagnetta, S. Ferrari, P. Pescetto, G. Pellegrino and F. Cupertino, "Transient Overload Characteristics of PM-Assisted Synchronous Reluctance Machines, Including Sensorless Control Feasibility," in IEEE Transactions on Industry Applications, vol. 55, no. 3, pp. 2637-2648, May-June 2019.
12. S. Ferrari, E. Armando and G. Pellegrino, "Torque Ripple Minimization of PM-assisted Synchronous Reluctance Machines via Asymmetric Rotor Poles, " 2019 IEEE Energy Conversion Congress and Expo (ECCE), Baltimore (MD), September 29 – October 3, 2019.
13. S. Kahourzade, A. Mahmoudi, W. L. Soong, S. Ferrari and G. Pellegrino, "Correction of the FE Calculated Efficiency Map Using Simple Experimental Measurements," IEEE Vehicle Power and Propulsion Conference 2019, Hanoi (Vietnam), October 14-17, 2019.
14. S. Ferrari and G. Pellegrino, "FEAfix: FEA Refinement of Design Equations for Synchronous Reluctance Machines," submitted to IEEE Transaction on Industry Applications
15. P. Pescetto, S. Ferrari, G. Pellegrino, E. Carpaneto and A. Boglietti, "Thermal Modeling and Parameters Identification of Multi-Three Phase Machines Based on Short-Time Transient," submitted to IEEE Transaction on Industry Applications
16. S. Kahourzade, A. Mahmoudi, W. L. Soong, S. Ferrari and G. Pellegrino, "Correction of Finite-Element Calculated Efficiency Map using Experimental Measurements, " 2019 Energy Conversion Congress and Expo (ECCE), Baltimore (MD), September 29 – October 3, 2019.

List of attended classes

- 01RJLRV – Advanced control in electrical energy conversion: a practical approach to real-time implementation (17/02/2017, 20 hours)
- 01QRORO – Application of cell method in multiphysics analysis (23/02/2017, 25 hours)
- 02LWHRV – Communication (07/06/2017, 5 hours)
- 01SHMRV – Enterpreneurial finance (20/06/2018, 5 hours)
- 01LCPIU – Experimental modeling: costruzione di modelli da dati sperimentali (15/04/2018, 33 hours)
- 01SGRRV – Magnetic materials for electrical energy (22/11/2017, 20 hours)
- 01RGBRV – Optimization methods for engineering problems (12/06/2018, 30 hours)
- 01SFURV – Programmazione scientifica avanzata in Matlab (19/04/2018, 20 hours)
- 08IXTRV – Project management (07/06/2017, 5 hours)
- 01RISRV – Public speaking (07/06/2017, 5 hours)
- 01RONKG – Python in the lab (22/09/2017, 20 hours)
- 01QEZRV – Sviluppo e gestione di sistemi di acquisizione dati (29/06/2017, 25 hours)
- 02RHORV – The new Internet Society: entering the black-box of digital innovations (04/09/2017, 6 hours)
- 01QORRV – Writing scientific paper in English (20/02/2018, 15 hours)

- 17th European PhD School: Power Electronics, Electrical Machines, Energy Control and Power Systems (23/05/2016, 30 hours)
- JMAG Basic and Advanced Training (03/10/2016, 16 hours)
- IEEE Energy Conversion Congress and Expo 2017 – Tutorials (30/09/2018, 8 hours)
- HBM Electric Power and Motor Fundamental (02/10/2019, 7 hours)

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