MAXIMA: Modular Axial Flux Motor for Automotive

Stéphane Clenet *[1], Maeva Philippot [2], M'hamed Belhadi [3] , Daniel Montesinos [4], Xavier Jannot [5], Johannes Maurath [6], Dirk Zepp [7], Ahmed Abouelyazied [8], Claudiu Cotovanu [9], Claudia Martins [10], Ángela Muñiz Varela [11]

[1] École nationale supérieure d'Arts et Métiers 8, Boulevard Louis XIV 59046 Lille (E-mail: stephane.clenet@ensam.eu)
[2] EVERGi Research Group, Mobi Research Center, Vrije Universiteit Brussel
[3] Stellantis
[4]Centre d'Innovació Tecnològica en Convertidors Estàtics i Accionaments (CITCEA-UPC), Departament d'Enginyeria Elèctrica, Universitat Politècnica de Catalunya. ETS d'Enginyeria Industrial de Barcelona, Av. Diagonal, 647, Pavelló G. 08028 Barcelona, Spain
[5] Nidec PSA Emotors
[6] Mplus Technologies GmbH & Co. KG
7 Höganäs
[8] ArcelorMittal Global R&D Gent, OCAS NV, Belgium
[9] 4Multiphysics
[10] Technical University of Cluj-Napoca, Romania
[11] Universidad Empresa Universidad Gallega, Campus universitario lagoas-marcosende 36310, Vigo, Spain

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ABSTRACT: The MAXIMA project, funded by the Horizon Europe programme, aims to design and develop a low-cost modular permanent magnet (PM) axial flux electrical machine (EM) for the automotive market with improved performances while limiting the use of critical raw materials (CRM) and the environmental impact. The project started in February 2023 and will last 4 years. To achieve this objective, the project will develop an advanced multiphysics design procedure that combines new concepts for thermal management and a Digital Twin (DT) to optimise control strategies and operate the EM to its full potential. To reduce costs, the project will optimise the EM's manufacturing process flow using a modular concept design for mass production. The project will also address the EM's end-of-life by considering recycling options for the PM, which is made from critical raw materials. To reduce the project's environmental impact, the life cycle of each solution will be analysed using Life Cycle Assessment (LCA). The project will conclude with the manufacturing of prototypes for testing, assessment, and validation of the new concepts addressed in MAXIMA, including the modular EM design, optimal control based on DT, and the manufacturing/recycling process flow. Limitations of the MAXIMA project may include that the methodology being developed must address multiple conflicting constraints, including efficiency, cost reduction, high performance in power/torque density, and recyclability, particularly for critical raw materials. Finding a design that satisfies all of these requirements may be challenging. Additionally, the project may face obstacles in achieving the desired balance between cost reduction, performance improvement, and environmental impact reduction. The MAXIMA project offers a new approach to designing and developing low-cost, high-performance EMs for the automotive market that takes into consideration the entire value chain from raw material suppliers to car manufacturers. The project also focuses on the development of a methodology for designing and manufacturing EMs, which will accelerate the time to market and reduce costs. Furthermore, the use of DT for optimal control of the EM represents an innovative approach to improving performance. In conclusion, the MAXIMA project represents a significant step forward in the development of low-cost, high-performance EMs for the automotive market. The project brings together a diverse group of stakeholders to address the main technological and scientific challenges in designing and manufacturing these machines while reducing their environmental impact. The project will lead to tools and know-how which will reduce the time to market for future EMs while providing a validated methodology and new technologies like Digital Twin for operating EMs to their full potential.

KEY WORDS: electrical machine, manufacturing processes, life cycle assessment, magnetic materials, digital twin

1. Introduction

Massive electrification in automotive will necessarily require the manufacturing of low-cost components to ensure that vehicles remain accessible to the greatest number of people. In sustainable development, these components must additionally lead to a limited environmental impact throughout their life cycle, particularly by promoting energy efficiency and recycling. Besides, the use of Critical Raw Materials (CRM) should be limited to reduce the high risk associated with their supply. The rotating Electrical Machine (EM), a key component of the powertrain, is not exempt from these constraints. In 2020, most EMs on the market were Permanent Magnet (PM) synchronous EMs. These EMs were designed to satisfy manufacturing cost and performance constraints without necessarily considering the environmental impact throughout their life cycle or the use of CRM.

This situation is not acceptable anymore: From the early stage of their design, future EMs should integrate an assessment of the environmental impacts over all their life cycle (from raw material extraction to dismantling/recycling, through manufacturing and operation of the EM) while limiting the use of CRM.

Most electric vehicles still rely on radial flux EM. Among them, PM radial flux EM was chosen by most car manufacturers and suppliers as traction motors, either using the interior PM radial flux or the PM-assisted synchronous reluctance topology. The most performant EM are axial flux EM like, for example, the one developed by YASA company [1]. An in-depth analysis of the technology of axial flux EM shows that a great potential to increase the performance of the electric powertrain still exists [2]. Besides continuing to improve the performance in terms of torque/power density and efficiency, the main challenges that are to be faced by PM axial flux EM are linked to the scarcity of rare earth PMs and to mass production manufacturing costs which are still too high to address the automotive core market (50 kW-120 kW).

The aim of the MAXIMA project, funded by the EU and which started in February 2023 for 4 years, is to design and develop a low-cost modular PM Axial Flux EM for the automotive core market, with improved performances, integrating CRM-less strategies with low environmental impact. To improve the performance, an advanced multiphysics design procedure combining new concepts for thermal management will be developed. A Digital Twin (DT), a virtual replica of the EM, will be built to develop an optimal control strategy to operate the EM up to the limit. To reduce costs, the EM will be designed simultaneously with its manufacturing process flow which will be optimised for mass production by considering a modular concept design. The EM's end of life will also be considered, especially recycling the PM made from CRM. In order to reduce the environmental impact, the life cycle of each solution will be analysed using Life Cycle Assessment (LCA). At the end of MAXIMA, prototypes will be manufactured for testing, assessment, and validation of the new concepts addressed in MAXIMA related to the modular design of the EM, the optimal control based on DT and the manufacturing/recycling process flow.

2. Scope of the project

The scope of the MAXIMA project is described in the call HORIZON-CL5-2022-D5-01-09 [3] and particularly should address:

-Increasing primary efficiency, in particular by widening the high-efficiency area and compactness, for example, through topology or operational improvements, the inclusion of increased features in integrated solutions, and analysis of performance aspects over the machine-in-system life-cycle.

-Demonstrate the following specific targets (percentages concerning the automotive state of the art in 2020):

*Continuous power densities >23 kW/l and >7 kW/kg or continuous torque densities > 50 Nm/l and >20 Nm/kg, for the complete motor, including its cooling, allowing global performance optimisation specific for the category and type of vehicle;

*A 20% reduction in losses during typical vehicle operation;

*A reduction in the use of rare resources by 60%;

*Unit cost for the complete motor at mass production levels (100.000 units/year) < 6 €/kW;

*A recyclability rate >60%, or demonstrating the possibility of "functional" recycling of critical raw materials by repurposing magnets without extracting the single rare elements, thus keeping a higher share of the value.

-Increase high system voltages offering new opportunities for readdressing the current versus voltage trade-offs throughout the vehicle systems and aspects of the recharging infrastructure, duly considering potential impacts.

-Guarantee the heat rejection of high energy density motors through multiphysics models in order for an optimal design (use of rare resources, reduction in losses, high efficiency).

-Novel manufacturing process supporting increased integration, enabling, amongst other things, improved thermal control.

-The proposed motor concepts are expected to comply with automotive standards, given the normal dynamic and duty-cycle requirements, reliability, EMC, etc. The proposed concepts should consider the motor (integration of electronics, excluding their development at component level) and integration of any related transmission. The concept has to be validated through representative duty-cycle evaluation, as a minimum on the test bed or, optionally, with minimum-change integration, on an existing vehicle.

-The provision of a digital twin of the concept, in line with current best practice modelling and simulation standards, is required.

3. Context

According to the scope of the project, topics like the design of Axial Flux EM, DT, manufacturing process flow, recycling of PM and life cycle analysis are addressed in the project. In the following, some elements about the state of the art related to the Axial Flux EM.

3.1-Design of the Axial Flux EM

PM Axial Flux EM for Electric Vehicle propulsion systems has been the subject of intense research during the last decades, given its advantages compared to PM Radial Flux EM. Several topologies were proposed, designed and analysed [2], spanning a wide range of structures, including single- and double-sided, slotted and slotless stator, yoke and yokeless stator, cored and coreless, concentrated and distributed windings, etc. Yokeless and Segmented Armature PM axial flux EM (YASA) represents one promising topology for electric vehicle propulsion [1,4,5]. Regarding cooling (a key point for EM compactness), an indirect liquid jacket is the most common approach to cool the stator windings. Still, the contact area between the cooling system and the winding is small and restricted to the outer surface of the stator. An innovative indirect system [4] consists in implementing fins between the winding slots with embedded U-shaped cooling pipes, thus extracting heat from the internal part of the stator. Other alternatives are based on heat spreaders and heat pipes [6] [7]. Some direct liquid cooling systems were also developed, improving the heat transfer efficiency of the EM but bringing great challenges to the subsequent manufacturing and increasing the motor cost. Regarding the rotor, the air gap acts as an insulation layer that reduces heat transfer, increasing the temperature with a risk of PM demagnetisation. Different approaches have been developed in the literature, most of them by creating a forced convection effect with fresh air or generating an auto-induced airflow [8].

3.2 Digital twin

Nowadays, one of the main limitations of operating a PM EM up to its limit is an inaccurate determination of the rotor and stator temperatures. Indeed, the temperature should be limited to avoid PM demagnetisation and early ageing of the winding insulation, which leads to a degradation of the performance and a reduction of the machine's lifetime. DT are real-time digital replicas of physical assets based on models combined with recalibration based on measurements. Several advantages are attributed to the DT of an EM: i) monitor the interior temperature of a motor during operation, ii) evaluate the risk of PM demagnetisation, iii) diagnose fault timely and correctly by scheduling necessary repairs during downtime and before breakdown [9]. DT is a real opportunity to control the EM up to the limit optimally. Recently, a DT has been developed for an induction EM showing the validity of the methodology [10]. The application of DT has not been applied to PM machines, which are more sensitive and less robust to high temperatures than induction EM, due to the PM demagnetisation effect. Consequently, the DT must be able to determine temperature more accurately and locally, requesting a fine prediction of losses in the ferromagnetic materials (PM, ES, SMC).

3.3 Manufacturing process flow

The radial flux EM currently dominates the core market of electric vehicle powertrains. One of the main reasons is that it can be easily produced in mass even for complex rotor topologies (rotor with magnetic flux barriers, for example). In fact, manufacturing processes (stamping, assembling, winding…) are very well known, and machinery is readily available. It leads to a manufacturing cost compatible with the automotive market. On the other hand, axial flux EM are very efficient and compact machines, but they are still in niche markets. Many companies (Phi Power, Whylot, Yasa, Magnax, integral e-drive, Magelec Propulsion...) produce such kinds of machines but for applications such as motorsport, e-motorcycle, e-trucks… Manufacturing costs remain the main issue to tackle before addressing the mass market targeted by MAXIMA [2]. Assembling the parts of an axial flux EM remains much more constraining than a radial flux EM. Moreover, optimal manufacturing methodology and machinery are not necessarily available. Finally, some manufacturing processes that are not well mastered yet can lead to a degradation of the magnetic material characteristics, which is detrimental to the overall performance of the EM [11].

3.5 Recycling of PM

Rare earth PMs based upon neodymium-iron-boron are used in a wide range of EM. However, the supply of neodymium has become more and more of a problem in recent years. Moreover, there is a strong dependence on China as the main supplier of rare earths. Hence, it is very attractive to establish a recycling process of neodymium-iron-boron PM to increase the availability of raw materials for the new PM. The established production processes of rare earth PM are either press sintering or polymer-bonded PM. While the press-sintered PM shows excellent magnetic properties, their shaping is limited to simple geometries like cylinders or cuboids. In contrast, polymer-bonded PMs have a large degree of freedom in the selection of their shape, whereas the magnetic strength is low. Metal Injection Moulding (MIM) PM combines the two advantages of the press-sintered and polymer-bonded PM. As a result, MIM is a very promising technology for manufacturing strong neodymium-iron-boron PM with a high degree of design freedom [12] [13].

3.6 Life cycle analysis of an EM

LCA is a standardised methodology that supports the assessment of the environmental impacts of products, systems, and design options. It is considered the best existing framework to assess the potential environmental impacts of products. The LCA methodology has been widely used in vehicle applications [14,15,16,17]. However, very few studies consider assessing its ex-ante and prospective environmental impacts from a life cycle perspective. However, this assessment methodology is required for the environmental assessment of the EM during multiple stages of its development towards better design choices and better assessment of end-of-life impacts.

4. Project MAXIMA

MAXIMA aims to design an axial flux PM-less EM for automotive applications with high performance, low cost, and limited environmental impact. The general overview of the methodology is described in Figure 3. The inputs of MAXIMA will be the functional (driving cycle, efficiency map…) and organic (volume, voltage…) specifications for the EM defined by experts in the domain of automotive (OEM), EM (manufacturing company and academics) and LCA (academics).

To reach the objectives, MAXIMA is based on three pillars:

-*EM design*: compactness, the key to high performance, requires magnetic materials used up to their limit, a multiphysics approach accounting for the high coupling between the different phenomena (electromagnetic, thermal and mechanical). The design process will address all these aspects through a holistic approach.

-*Digital Twin:* high performance as well as life increase go through a perfect understanding of the magnetic and thermal states of the EM via a DT. The DT enables exploitation up to the limit without damaging the EM. A DT will be developed by combining a physical reduced model with artificial intelligence based on experimental data for maximum accuracy as well as compatibility with real-time control.

-*Manufacturing/recycling process flow:* The final cost of a product highly depends on the cost of the raw material and the manufacturing process flow, which will be optimised. The end of

life of the EM will also be considered, especially the recycling of the PM made with CRM.
The LCA will be addressed through a Transversal axis which will provide the tools and the expertise to analyse the environmental impact of the different solutions in terms of design, manufacturing and recycling proposed within MAXIMA.
At the end of the project, Prototypes will be manufactured for testing, assessment and validation of the new concepts addressed in MAXIMA related to the design of the EM as well as its manufacturing/recycling process flow.
Pillars will interact through, of course, data exchange during the project. This interaction will go much further between Pillars 1 and 3 with the co-design of the EM and the manufacturing/recycling process. This co-design is a key point for MAXIMA's success and is based on an iterative procedure enabling us to correct the EM design to reach an affordable manufacturing solution.

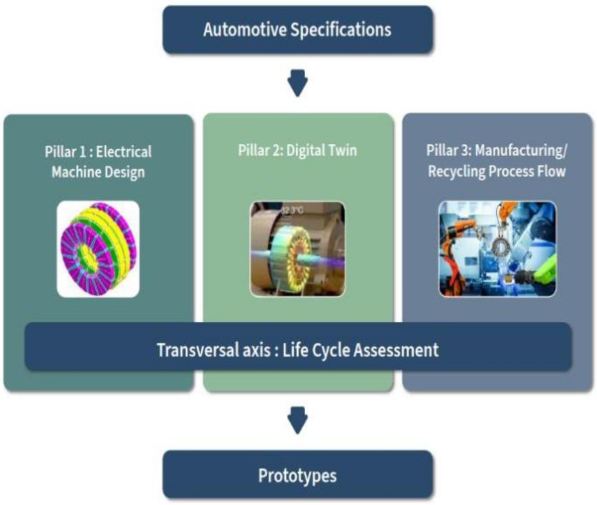

Figure 1: General overview of the MAXIMA methodology

5. Consortium

The MAXIMA consortium (Figure 2) is composed of 11 partners from 6 European Member States (France, Spain, Belgium, Romania, Sweden and Germany). The MAXIMA Team is not only geographically diverse by involving countries from Eastern Europe, Scandinavia and Southern Europe, but it is also a strong multidisciplinary group. This group covers the full research and industrial development value chain (Figure 3) and involves 4 academics, 1 SME, 5 companies, and 1 non-profit organization that brings along expertise in open science practices. All of them benefit from a strong background in R&I initiatives and projects execution. Thus, it makes a relevant team for the performance improvement of EM, for the development of circularity and low use of rare resources of its components. Moreover, MAXIMA will take advantage of the facilities provided by the partners for the manufacturing and the test of the prototypes, which will be carried out in an industrial environment enabling them to reach high TRL. All partners have been selected considering their competencies and complementarities to fulfil the skills and know-how needed for the achievement of the MAXIMA objectives as follows:

- Academic partners (ENSAM, UTCN, UPC and VUB) will be dedicated to the main scientific developments in magnetic materials, EM design, Thermal Management, Manufacturing/Recycling, Power Electronics and EM control, DT and LCA. Each of those partners provides special expertise, skills and infrastructure necessary to the execution of the project and complements each other. ENSAM is the coordinator of this project.

- SME and large companies (EMOTORS, HOG, OCAS, STELLANTIS, 4MP and MPT). These companies collectively share the necessary critical mass of expertise and experience across the MAXIMA value chain, each in his field: raw materials, EM manufacturing, car manufacturing and PM recycling.

- Non-profit foundation fostering technology transfer between the university, industry and society (FEUGA) that will support the consortium in Communication, Dissemination, Intellectual Property (IP) management and Exploitation of R&D results, with a special focus on Responsible Research and Innovation (RRI).

6. Conclusion

In this communication, we have described the context and the objective of the project MAXIMA which is to design and develop a low-cost modular PM axial flux EM for the automotive core market with improved performances, integrating CRM-less strategies and with a low environmental impact. We give some information about the methodology based on three pillars the Axial Flux EM design, the development of a digital twin and the development of a low-cost manufacturing and recycling process flow. The environmental impact evaluation and its limitation will be considered through the analysis of the complete life cycle of the EM. Prototypes will be provided at the end of the project in order to evaluate and illustrate the new concepts developed within the project.

Figure 2: Coverage map of the consortium

Figure 3: MAXIMA full value chain for EM manufacturing and recycling

References

[1] https://www.yasa.com/
[2] 1 L. Shao, e.a. Design and construction of axial-flux permanent magnet motors for electric propulsion applications – a review, IEEE Access, 2021
[3] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl5-2022-d5-01-09
[4] J. Chang e.a., "A yokeless and segmented armature axial flux machine with novel cooling system for in-wheel traction applications," IEEE Trans. Ind. Electron., vol. 68(5), May 2021, pp. 4131–4140
[5] Compact Motors For Next-Gen Powertrains [Online]. Available:
[6] D. Winterborne, e.a., "An Air-Cooled YASA Motor for in-Wheel Electric Vehicle Applications", IEEE Trans. on Ind. Applications, vol. 56 (6), 2020
[7] W. Le, M. Lin, K. Lin, K. Liu, L. Jia, A. Yang, S. Wang, "A novel stator cooling structure for yokeless and segmented armature axial flux machine with heat pipe", Energies 2021, 14, 5717.
[8] H. Chuan, R. Burke, Z. Wu, "A comparative study on different cooling topologies for axial flux permanent magnet machine", 2019 IEEE Vehicle Power and Propulsion Conference (VPPC), Hanoi, Vietnam.
[9] G. Falekas, and A. Karlis, "Digital twin in electrical machine control and predictive maintenance: state-of-the-art and future prospects", Energies, 2021, vol. 14, 18, pp. 1-26
[10] F. Toso, R. Torchio, A. Favato, P. G. Carlet, S. Bolognani and P. Alotto, "Digital Twins as Electric Motor Soft-Sensors in the Automotive Industry," 2021 IEEE International Workshop on Metrology for Automotive (MetroAutomotive), 2021, pp. 13-18
[11] P. Andrada, B. Blanqué,E. Martínez, J.I. Perat, J.A. Sánchez, M. Torrent, "Influence of Manufacturing and Assembly Defects and the Quality of Materials on the Performance of an Axial-Flux Switched Reluctance Machine", *Energies* 2019, *12*, 4807
[12] C. Burkhardt,P. Imgrund,O. Weber, T. Schlauf, K. Pischang, J. Gonzalez-Gutierrez, C. Kukla, M.J. Degri, I.R. Harris, L. Pickering,A. Walton, "Metal Injection Moulding of NdFeB based on Recycled Powders", 24th Int. Workshop on Rare Earth Permanent Magnets and their Applications (2016) Darmstadt, Germany, 2016, pp 63-68.
[13] P. Imgrund, O. Weber,T. Schlauf, K. Pischang, L. Pickering, A. Walton,J. Gonzalez-Gutierrez,C. Kukla,C. Burkhardt, "Metal Injection Moulding of NdFeB Based on Recycled Powders", Powder Metallurgy World Congress and Exhibition, Hamburg, Deutschland, 2016, pp 1-7.
[14] A. Nordelöf, M. Alatalo, M;L. Söderman, "A scalable life cycle inventory of an automotive power electronic inverter unit—part I: design and composition". Int. J. Life Cycle Assess. 24, 2018, pp 78–92.
[15] A. Nordelöf, E. Grunditz,A.M. Tillman, T. Thiringer, M. Alatalo,"A scalable life cycle inventory of an electrical automotive traction machine—Part I: design and composition", . Int. J. Life Cycle Assess. 23, 2017, pp. 55–69.
[16] A. Nordelöf, A.M. Tillman, "A scalable life cycle inventory of an electrical automotive traction machine—Part II: manufacturing processes", Int. J. Life Cycle Assess. 23, 2017, pp 295–313.
[17] B. Marmiroli, M. Messagie, G. Dotelli, J. Van Mierlo, « Electricity generation in LCA of electric vehicles: A review", Appl. Sci. 8, 2018

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