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Energimyndighetens titel på projektet – engelska Electric Powertrain OptimiSation for Vehicles and Fleets – EPOS	
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Preface

The project is funded by the Swedish Energy Agency, Borg Warner Sweden AB and Haldex AB. It has been governed by a reference group with representatives from the industrial partners and Lund University.

Contents

Sammanfattning

Projektet tagit fram ett verktyg för detaljerad optimering av elektriska drivlinor, med fokus på kraftelektroniska omvandlare, elektriska maskiner och mekaniska transmissioner. Det har drivits från Augusti 2020 till April 2024, av två doktorander vid Lunds Universitet samt medarbetare vid Borg Warner Sverige AB samt Haldex A. Modellering av prestanda och fysiska egenskaper (moment, varvtal, ström, spänning, vikt, volym, kostnad, verkningsgrad mm) som funktion av geometri- och material-egenskaper har gjorts för både kraftelektroniska omvandlare, tre olika typer av elektriska maskiner samt flera olika varianter av mekaniska transmissioner. Dessa modeller har kombineras för optimering av drivlinor för både personbilar och lastbilar, för både enskilda fordon och fordonsflottor. Verktyget finns i en version

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som används av akademin och av de industriella deltagarna, samt en version som används av studenter vid Lunds Universitet.

Summary

The project has developed a tool for detailed optimization of electrical powertrains, focusing on power electronic converters, electrical machines and mechanical transmissions. It has been run from August 2020 to April 2024, by two PhD students at Lund University and collaborators at Borg Warner Sweden AB and Haldex A. Modelling of performance and physical properties (torque, speed, current, voltage, weight, volume, cost, efficiency etc.) as a function of geometry and material properties has been done for both power electronic converters, three different types of electrical machines and several different variants of mechanical transmissions. These models have been combined for the optimization of powertrains for both cars and trucks, for both individual vehicles and fleets. The tool is available in a version used by the academy and by the industrial participants, and a version used by students at Lund University.

Introduction

As automotive electrification advances, optimizing electric powertrains has become a central topic for original equipment manufacturers (OEMs) and tier-1 suppliers. The development of efficient and cost-effective electrified propulsion solutions is essential to lowering the cost barrier of electrified vehicles and increasing their adoption by the general public. Conventional approaches to powertrain development segregated the design and optimization of the main components in the system, i.e., Electrical Machine (EM) [1-4], Power Electronics Converter (PEC) [5-7], and Mechanical Transmission (MT). This often results in sub-optimal systems (i.e., more expensive or less efficient than possible) as the tradeoffs between the components are not properly captured and balanced. In order to overcome this drawback, some attempts to co-optimize the aforementioned components have been presented [8-10]; however, they lack sufficient detail regarding the modeling of the components to be practical in commercial use. An exception to this trend is the work presented in [11] and further expanded in [12,13], where a complete description of the models used is presented, and the outcome of the optimization process contains all the required component details for subsequent detailed simulations, design refinement, and prototyping. This project builds upon that work and expands in critical areas such as the inclusion of additional EM topologies to better reflect the market realities, the addition of validated Silicon Carbide (SiC) MOSFETs models, the expansion of the transmission model to include variants better suited for commercial vehicles (including multi-speed and central drive units), and the further development of the optimization methodology to address platform development (including development costs and benefits from system commonality) and multi-motor powertrains.

This project has provided a significant industrial and societal contribution by reducing development times from months to days and improving the overall outcome of the system design in terms of efficiency and cost, which in turn improves the competitiveness of the Swedish automotive industry and could help reduce the overall energy consumption in the transport sector. Furthermore, the results from this project have been included as part of the Electric Vehicle course at Lund University to train the next generation of automotive engineers.

This project has been executed in cooperation between Lund University, BorgWarner Sweden AB and Haldex AB, with the support of the Swedish Energy Agency. The overall project budget was 10.4M SEK, out of which the Swedish Energy Agency contributed 5.2M SEK (50%), BorgWarner contributed 1M SEK in direct financing to Lund University, and 3.4 M SEK in in-kind, Haldex contributed with 850k SEK in in-kind and Lund University used 6.2M SEK. The project was officially kicked off after the recruitment of the PhD students in August 2020 and completed in April 2024 after a granted extension from the Swedish Energy Agency due to both PhD students having parental leave during the project execution.

Implementation

The project is divided into work packages according to the drivetrain subsystem division and the common modelling and system simulation needed:

WP 1 **Literature review**. This WP involves all groups and was executed once in the beginning of the project and then continuously during the project.

WP 2 **Optimization methodology**. This WP has mainly involved Lund University that has applied a Particle Warm Optimization (PSO) to the complete drivetrain. The method creates a “sworm” of solutions with different parameter sets in a reasonable space for which it calculates the optimization function (cost, energy efficiency, …) and repeatedly change the parameter sets to drive the solutions towards the one with the best optimization function. The parameter sets represent the electric machine, the power electronic and the transmission design.

WP 3 **EM modelling**. This WP is mainly performed by one PhD student (Meng Lu) at Lund University. Three relevant electrical machine types are modelled. Detailed geometrical parameters, material property parameters, thermal parameters, cost parameter are used to define the physical machine properties (torque, speed, power, losses, …), the manufacturing and operational cost (in the vehicle). Since performance modelling requires high computing power, a database of thousands of machines is precalculated and then scaled in the optimization loop, a solution that greatly speeds up the system optimization process.

WP 4 **Transmission modelling**. This WP is mainly performed by engineers at Borg Warner Sweden AB. Several transmissions, deemed suitable for cars and trucks, are modelled with respect to gear meshes, material properties, size, efficiency and cost.

WP 5 **PEC (Power Electronic Converter) modelling**. This WP is mainly performed by one PhD student (Hannes Bydén) at Lund University. Detailed geometrical parameters, material property parameters, thermal parameters, cost parameter are used to define the physical power electronic converter properties (voltage, current, power, losses, …), the manufacturing and operational cost (in the vehicle). Particular focus has been on the thermal propertied of the chip-insulation-heatsink structure, to reliably predict the heat dissipation, both for individual components and for systems of components.

WP 6 **Cost modelling**. This WP involves all groups. A challenge has been to provide neutral but relevant material and manufacturing cost figures, since the industrial partners cannot reveal their actual figures for these properties. Thus the cost figures used are somewhat generalized in the version that is used by the university in simulation studies and in the student version, but still considered relevant and representative.

WP 7 **Simulation studies**. This WP is mainly performed by both PhD student at Lund University together. The sub system models (EM, Transmission, PEC) are combined in a system model in a vehicle. Thereby a comprehensive system optimization of the complete drivetrain has been made. The project has taken this opportunity to a higher level and used it to study drivetrain optimization for vehicle fleets, both for car and truck fleets. Each fleet is subdivided into groups after weight or class. Drivetrains in different versions from individually optimized drivetrain per group to a "one size fits all" drivetrain is studied, accounting for the number of vehicles, annual driving distance and drive cycle of each group to evaluate sharing drivetrain components across weight or class borders.

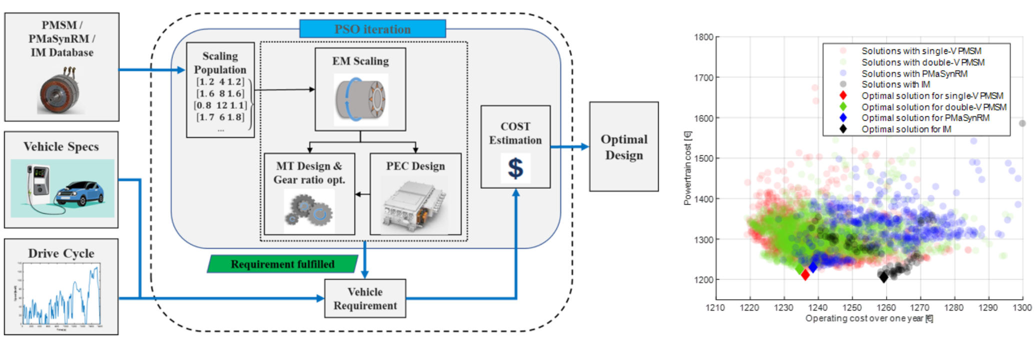
WP 8 **Reporting**. Apart from the annual report to the Swedish Energy Agency, a number of scientific publications and soon also a PhD thesis and a midway review (halfway to PhD) are produced.

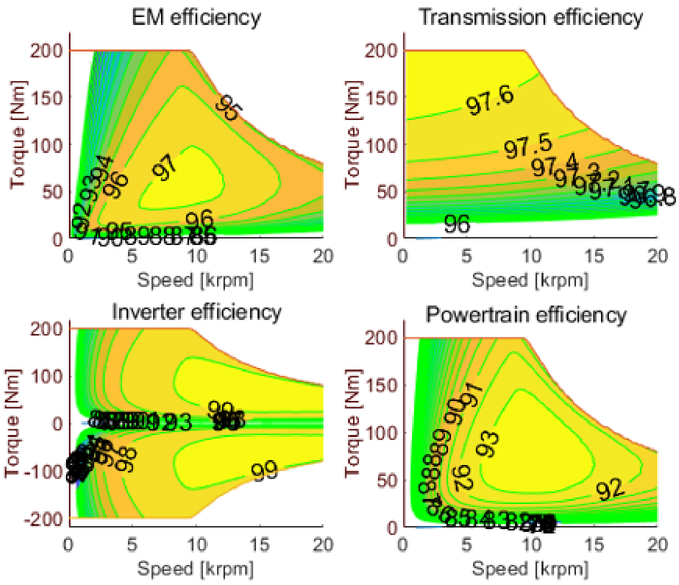
Results

The project promised and completed the following deliverables:

1 **A complete propulsion system optimization**.

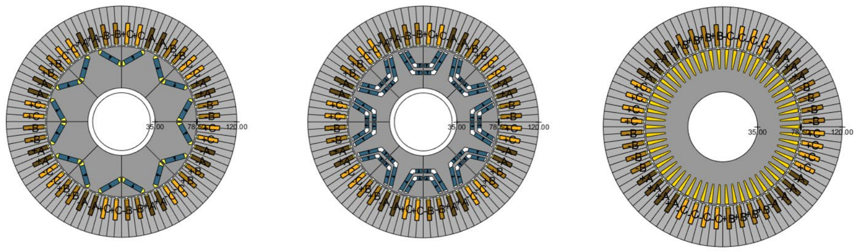
An extensive drivetrain system optimization tool was developed. It is based on detailed subsystem/component models that interact to estimate the manufacturing cost and the operation cost of the vehicle targeted. The developed component models account for production volume dependence and has in the project been used to study the drivetrain cost dependence on sharing drivetrain components between vehicles of different sizes in a fleet.





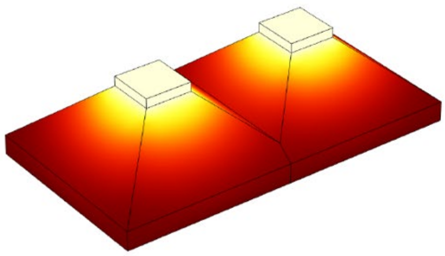
2 **To develop component models that include the latest trends in electromobility**.

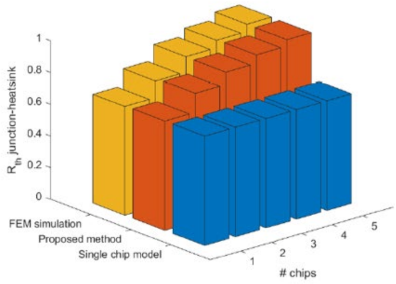
Validated scalable performance, cost and thermal models have been developed for Permanent Magnet Synchronous Machines (PMSM), Permanent Magnet Assisted Synchronous Reluctance Machines (PMaSynRM) and Induction Machines.



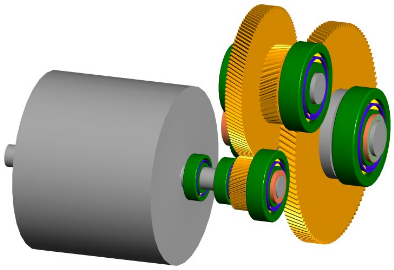
(a) PMSM (b) PMaSynRM (c) IM

Detailed electrical and thermal models for power electronic components applied to traction inverters have been developed. These models allow to capture the thermal cross coupling between chips inside the same power module in a computationally efficient way that makes them suitable for system optimization. Validation of the proposed model against internal test data and high fidelity 3D simulation models have been performed to ensure that the accuracy level is sufficient for system optimization.





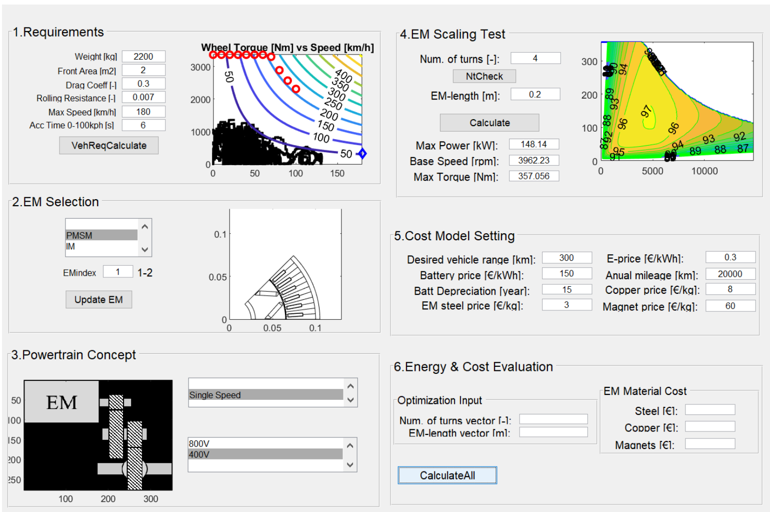
A transmission model capable of estimating the size, efficiency and material composition of two and 3 stage layshaft transmission in both off-axis and transversal layouts have been developed and validated against test data from existing designs and higher fidelity (and computationally intensive) simulation models.



3 **Two post-graduate degrees:** A PhD thesis and a Midterm review (corresponding to a Licentate thesis) will be presented a few months after the project is finished. Both the PhD and the Midterm Review are scheduled for Oct/Nov.

4 **Case studies and academic publications:** Several very relevant case studies on both vehicles and fleets, with different drivetrain configurations and components are published.

5 **A system optimisation software package** in a version adapted for students. This is accomplished and already used once (fall 2023) in a course about electric and hybrid electric drivetrains at LTH.



Discussion

This project has developed comprehensive system optimization methods for electric powertrains that significantly reduce the pre-development time while improving the final result in terms of overall system cost and efficiency. These tools and methods have already been adopted by the industrial partners to accelerate their development efforts, resulting in improved competitiveness of the Swedish automotive industry.

Furthermore, the project results have benefitted the academic community as key developments have been presented in conferences and journals and a student version of the optimization tool has been developed to support the Electric Vehicle course at Lund University, and therefore improve the education of the next generation of automotive engineers.

Future projects related to the holistic optimization of electric powertrains should include emerging technologies, like the recent increase in electrically excited motors, and new optimization targets, such as equivalent carbon emissions derived from Life Cycle Assessment, in order to capture the environmental impact of the proposed design and use this information to find more environmentally friendly system solutions.

Publications

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2. M. Lu, G. Domingues-Olavarría, H. Bydén, M. Aleksandar and M. Alaküla, "Optimization of Powertrain Platform for Electric Passenger Vehicles," 2023 IEEE Transportation Electrification Conference & Expo (ITEC), Detroit, MI, USA, 2023, pp. 1-6.
3. M. Lu, G. Domingues-Olavarría and M. Alaküla, "Comparison of PMSM versus PMa-SynRM and IM from an Optimized Electric Vehicle Powertrain Perspective," 2023 26th International Conference on Electrical Machines and Systems (ICEMS), Zhuhai, China, 2023, pp. 4075-4080.
4. M. Lu, G. Domingues-Olavarría, F. J. Márquez-Fernández, H. Bydén and M. Alaküla, "Optimization of Induction Machine Design for Electric Vehicle Powertrain," 2023 IEEE International Electric Machines & Drives Conference (IEMDC), San Francisco, CA, USA, 2023, pp. 1-6.
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[12] P. Fyhr, Electromobility: Materials and Manufacturing Economics, Lund University , 2018.

[13] G. Domingues-Olavarría, Modeling, Optimization and Analysis of Electromobility Systems, Lund University, 2018.

Attachments

The administrative attachment and publication 1-9 are attached. Publication 10-12 are still in process and are thus not attached.

The PhD thesis by Meng Lu to be presented in October 18th 2024 is marked as "Sensitive information" and must NOT be made public.