Roadmap

Theme Electrical machines, Drives, and Charging

Introduction

Electrification of both on-road and off-road transportation develops now faster than ever before, and all predictions indicate that this rate development will continue in the foreseeable future1. It drives a need for more efficient, reliable, cost effective and sustainable components and systems for the supply and conversion of electric energy. These new systems and components make electric and hybrid-electric vehicles not only comparable to, but superior in all the previous categories to their combustion engine counterparts.

Theme 2 - Electrical machines, Drives, and Charging covers the technologies related to electric energy transfer and conversion that arise from the electrification of transport. This includes the propulsion system, charging equipment and auxiliary systems on board the vehicles.

The research activities conducted in the theme span over a broad area, including theoretical and numerical modelling and simulation of individual components (through analytical equations, Finite Element Analysis, Computational Fluid Dynamics, etc.), integration of the component models into a complete drive unit dynamic model (through Matlab / Simulink or similar software platforms), development and laboratory testing of prototypes for validation purposes, and real-life conditions testing when relevant.

Scope and boundaries

Theme 2 - Electrical machines, Drives, and Charging of the Swedish Electromobility Centre is a competence base for technologies related to electric energy transfer and conversion between the electric utility grid and the propulsion elements of electric transport vessels – wheels in road vehicles or propellers in boats and airplanes. This includes the propulsion system, charging equipment and auxiliary systems on board the vehicles.

The main objective of the Theme is to minimize the cost of ownership and environmental impact of the aforementioned equipment on a component or sub-system (drivetrain / vehicle) level, in a transport system perspective. The cost of ownership comprises manufacturing, installation, energy consumption, downtime reduction, maintenance and recycling.

Research conducted within the Theme may require understanding the interaction with the mechanical, the power supply (e.g. batteries / fuel cells) and the power system boundaries. On the mechanical side, this includes the mechanical transmission to the wheels / propeller or to the combustion engine if present, and on the power supply side the interactions with the battery and other components on the DC link of the electric traction system. On the power system side, it includes the dynamic effects in the distribution grid up to the Medium Voltage level, which influence the design of charging equipment.

The time perspective should be such that the research conducted in the theme is able to influence industrial product plans, which normally means a time horizon in the range of 10 years to start of production (SOP). This long-term perspective is a way to encourage thinking “out of the box”, not limited by existing solutions, regulations or limitations, while keeping the research at a pre-competitive stage, thus allowing competing companies to cooperate. However, research focusing on shorter perspectives could be conducted if the topic is interesting for most theme partners.

[1]IEA (2020), Global EV Outlook 2020, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2020

Current Trends and Needs

A review of the current research conducted in the area of electrical machines and power electronics reveals a number of interesting trends, which are described in this section.

Countries with large vehicle production facilities (e.g. China, India, but also Germany and the US) are focusing on improving **manufacturing technology** for the expected high production volumes of electromobility related components. Swedish automotive manufacturers currently source these components mostly from foreign suppliers, and even if a new electrical machine production facility has been recently installed in Sweden, there are still very few production facilities of either electrical machines or power electronics in the country. This situation is likely to change in the near future however, and research on manufacturing processes and design for manufacturing is already gaining relevance.

On the power electronics field, the use of **wide-gap band semiconductor technologies**, especially SiC, pushes for higher voltage levels and higher modulation frequencies. This has obviously a number of implications in the design of the power converter itself, the choice of passive components, the control algorithm, the insulation system in the electrical machine, and the EMC performance of the drive.

Electromagnetic compatibility (EMC) itself is growing in importance as a research topic. Compared to combustion engines, the location of electric drivetrain components within the vehicle is more flexible. This increase in packaging flexibility allows for different integration possibilities. However, with increasing power levels, higher voltages and faster switching frequencies, EMC phenomena become more important and there is a need to investigate them in order to minimize their effects.

Another interesting trend in automotive application research is safety and reliability. In the long term, improving reliability implies finding new solutions for both components and systems that are inherently safer and more reliable. **Fault-tolerant designs** with some degree of redundancy will ensure that the vehicle can still operate in case of a fault, even if the performance is degraded. Moreover, with an increasing number of electric drives in vehicles, there is a need for **condition monitoring and lifetime estimation** techniques for the relevant components already from the design stage. This is necessary not only for safety reasons, but also for economic reasons, to make electric vehicles competitive with the traditional combustion solutions – also called “right sizing”.

The supply of energy is critical for electromobility to take off. **Charging solutions** can be implemented in several ways (inductive/conductive, manual/automatic, fast/slow, on-board/off-board, static/dynamic). Despite both a long history of development and substantial standardization, the technology area is still subject to a lot of development. For example, the power levels are pushed up, automation is still almost non-existing for light vehicles and dynamic charging is under extreme development with high expectations. The R&D efforts should be oriented to those aspects of the charging process that are common to all vehicle types or will likely be common within the proposed time perspective. A system perspective should be kept, where battery cost plus charging infrastructure costs from both a vehicle customer and a societal level are maintained. Additionally, for applications in which the moderate energy density of current batteries may pose a problem, hydrogen is emerging as the primary energy storage on-board. Therefore, the design and control of power converters intended to interface fuel cells and electrolyzers are gaining importance.

Finally, a trend for **integration of different components** in the same volume, or even different functions in the same component is observed. For this reason, the drivetrain becomes somehow more complicated, and to optimize its design multi-physical conjugated models are needed for a simultaneous approach of the electromagnetic, thermal, mechanical, and even acoustic challenges.

Strategic research areas

Considering the availability of research personnel and funding possibilities, Sweden is a rather small player in a global perspective. It is thus important to focus on selected segments of the electromobility field. The following are selected:

- Design of cost efficient environmentally friendly electric drive trains
- Charging systems

Research efforts along these lines should be developed as joint cooperative projects between SEC partners. This should be supported by a functional way of setting reference groups with strong representation from industry, as a tool to convey the industry needs into SEC and the universities.

The aspects identified as most relevant to focus R&D efforts on, split into the different areas, are (not necessarily in order of priority):

Electric Traction Machines.

- Cost of ownership and environmental impact: design for manufacturability, design for reliability, design for recycling.
- Performance, comfort and driving experience: efficiency, torque / power density, noise vibrations and harshness (NVH). Potential research topics are high speed machines, new materials, permanent magnet free topologies, etc.
- Thermal management: advanced cooling concepts, integrated cooling
- Development of additional features, e.g. integrated charging
- Advanced control strategies to improve any of the above

Power Electronic Converters.

- Cost of ownership and environmental impact: design for manufacturability, design for reliability, design for recycling.
- Commonalities and synergies with the rest of the drivetrain, e.g. integration with electric machines to reduce the number of components.
- Alternative semiconductor materials like SiC/GaN
- Improvement of the peak power limitation of power electronic devices.
- Thermal management: advanced cooling concepts, integrated cooling.
- Advanced control strategies to improve any of the above.

Charging Systems.

- On-board chargers (topologies and control in relation to not only efficiency but also e.g. battery lifetime)
- Automation of the charging process on a broader perspective: inductive charging vs. automated conductive approaches. Developments in this area may be conducted with consideration of autonomous electric vehicles.
- Integration of charging equipment and the power grid: bi-directional charging (vehicle to grid V2G, vehicle to home V2H), smart charging management (with e.g. solar cells).
- Although it may not be one of the core research activities of the Theme, there is a need for standardization of charging solutions, and the Swedish Electromobility Centre – in particular Theme Electrical Machines and Drives – should contribute and support the development of such standards.

Forecast (perspective in 5 years, 10 years, 15 years ahead)

5 years ahead

- Road vehicles: The performance and cost of electrified passenger cars are steadily improved. Better batteries, smarter EV specific platform designs, and mass production are behind this improvement. Comfort is also improved through careful noise, vibration and harness (NVH) analysis of the electric drivetrain integrated in the vehicle. Charging infrastructure is under development, but still not sufficient to cover all transport needs unless a fairly large battery is installed on the vehicles (with the corresponding weight and price penalty). Full electric heavy-duty vehicles are starting to emerge on the roads with models commercially available from all heavy-duty vehicle OEMs. The increased number of electric and electronic components, combined with the higher power levels and potentially longer cables (due to the size of the vehicles) make the cabling harnessing and layout more challenging, not least from an EMC perspective. Additionally, due to the nature of these vehicles, there is a need to ensure reliability and maximize uptime through fault-tolerant solutions and advanced condition monitoring and diagnostics. Based on similar principles, methods to assess the second-hand value of these vehicles are required in order to find viable business models.
Additionally, high power automatic charging equipment (static / dynamic) should be developed.

- Flight transport: a few prototypes of larger full electric aircrafts are being tested. The main challenges compared to road vehicles are related to power density, efficiency and reliability of both the battery and the electric drive. Operational support of jet engines by electrical machines reach a higher level of integration.

- Marine applications: (to be completed)

10 years ahead

- Road vehicles: Electrified passenger cars are now mature. Charging infrastructure is still developing, although it is no longer a major concern for the user, except in certain isolated areas. The business models behind EVs are clearer now, and there are methods to assess the condition of the vehicles and estimate e.g. the second-hand value. Recycling of valuable materials such as copper and magnets is also implemented. For heavy duty commercial vehicles, the necessary charging infrastructure is under fast dissemination, with the major freight corridors already implemented in several countries. Thanks to the steady improvement on battery technology, charging powers are high enough to provide reasonable charging times. However, the lack of charging opportunities still imply that large batteries must be installed on these vehicles, with the corresponding cost and weight penalty. The most important challenges now are on the power grid side: integration of the electromobility related loads in the power grid, together with intermittent CO_2-free renewable generation and increased electrification of major industries.

- Flight transport: the first commercial models of medium-size airplanes for short distance (domestic intercity) flights are appearing in the market – for very selected applications / routes. Compared to road vehicles, the requirements needed to electrify aircraft are much more demanding, especially in terms of power density, efficiency, and reliability. This is expected to drive the development of electric drives and batteries further.

- Marine applications: (to be completed)

15 years ahead

<u>- Road vehicles:</u> Electrification of passenger cars has become a commodity, and most vehicles sold in this segment are full electric. Some of the technological advances coming from other applications may be adapted (e.g. new materials, different energy storage solutions, etc). Electrification of heavy- duty vehicles (trucks) is reaching maturity. A well-defined ecosystem (vehicles, charging infrastructure, business models) allows for long distance transport to be made. Some challenges remain to be solved in the integration of large charging facilities into the power grid.

<u>- Flight transport:</u> Electrification of short distance flight with small / medium size airplanes has been successfully achieved. In order to increase the range and capacity of the electric airplanes, much higher power density machines and drives are required. This will unlikely happen just with incremental improvements of the existing technology, and new, revolutionary concepts may be required. Battery technology will experience a new boost similar to the one that followed the (H)EV introduction in the beginning of the 21st century.

<u>- Marine applications:</u> (to be completed)

Relation between theme areas:

Strategic research area	Systemstudier och metoder	Elektriska maskiner, drivsystem och laddning	Energilagring	Elektromobilitet i samhället	Samverkan mellan fordon och elnäte
EM design for recycling		x		x	
EM alternative materials		x		x	
Integration of functions	x	x	x	x	x
Thermal management	x	x	x		
PE design for recycling		x		x	
PE design optimization (for different batteries / fuel cell)	x	x	x		
Integration of charging equipment and the power grid (V2G, V2H)		x			x
Charging equipment standardization	x	x			x