# Roadmap Theme 2 – Electric Drives and Charging

## Introduction

Transportation's electrification is developing faster than ever before, and all predictions indicate that this rate development will continue in the foreseeable future[1]. 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 categories mentioned above to their combustion engine counterparts.

Theme 2, "Electric Drives & Charging" covers the electric energy transfer and conversion technologies and challenges that arise from the electrification of transport. This includes the propulsion system, on and off-board 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 modeling and simulation of individual components (through analytical equations, Finite Element Analysis, Computational Fluid Dynamics, and more), 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

The Swedish Electromobility Centre Theme 2, "Electric Drives & Charging" 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. It includes the propulsion system, the charging equipment, and the auxiliary systems onboard the vehicles.

The main objective of the Theme is to minimize the cost of ownership and the cost of the equipment's environmental impact on a component or sub-system (drivetrain/vehicle) level from a transport system perspective. This should be done while respecting societal requirement of the use of material, the emission of biproducts and emission of radio frequency disturbances (EMC). The cost of ownership comprises clean manufacturing, installation, energy consumption, downtime reduction, maintenance, and recycling, with an eye on the circular economy.

Research conducted within the Theme may require understanding the interaction with the mechanical, the power supply, and the power system boundaries. The mechanical side includes the mechanical transmission to the wheels/propeller or the combustion engine (if present). The power supply side refers to the interaction with the battery / fuel cell and other components on the DC link of the electric traction system. The power system side includes the dynamic effects in the distribution grid up to the

[1] IEA (2020), Global EV Outlook 2021, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2021

medium voltage level, which influences the design of charging equipment. Both the vehicle side and the power system side include tackling the EMI-emissions generated by operation and charging of vehicles.

The time perspective should be such that the research conducted in the Theme can influence industrial product plans, which usually means a time horizon in the range of 10 years to start of the 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, it is possible to conduct research focusing on shorter perspectives if the topic is interesting for most theme partners.

## Current Trends and Needs

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

Countries with extensive vehicle production facilities (e.g., China, India, Germany, and the US) focus on improving **manufacturing technology** for the expected high production volumes of electromobility-related components. Currently there are very few electrical machines or power electronics production facilities in the country, and Swedish automotive manufacturers source these components mostly from foreign suppliers. However, this situation is likely to change in the near future, and research on manufacturing processes and design for manufacturing is already gaining relevance.

**Wide-bandgap semiconductor technologies**, especially SiC, push for higher voltage levels and higher modulation frequencies in the power electronics field. This trend has some 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 Electromagnetic Compatibility (EMC) performance of the drive.

**EMC** itself is growing in importance as a research topic. Compared to combustion engines, the vehicle's location of electric drivetrain components 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 critical, and there is a need to investigate them to minimize their effects. With growing EV-related infrastructures, like big fast charging parks or electric roads, radiated EMI may aggregate from a certified level per charging pole to too high levels that must be mitigated on the system level of the charging park or electric road design.

Another trend in electromobility research is **safety and reliability**. Fault-tolerant designs with some degree of redundancy will ensure that the vehicle can still operate in case of a fault, even with reduced performance. This is particularly important in the case of electric aircraft. In the long term, improving reliability implies finding new solutions for both components and systems inherently safer and more reliable. 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 aspect is necessary for safety and 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, onboard/off-board, static/dynamic). Despite a long history of development and substantial standardization, the technology area is still underdeveloped. For example, with rising power levels, automation is still almost non-existing for light vehicles, and dynamic charging is under extreme development with high expectations. The R&D efforts should consider those aspects of the charging process common to all vehicle types within the proposed time perspective. A system perspective is essential, considering battery cost plus charging infrastructure costs from both a vehicle customer and a societal level. Additionally, for applications in which the moderate energy density of current batteries or the availability of a sufficiently strong power grid may pose a problem, hydrogen is emerging as the primary energy storage onboard. Therefore, the design and control of power converters intended to interface fuel cells and electrolyzers are gaining importance.

Finally, there is a trend for **integrating different components with increased functionalities** in the same volume. For this reason, the drivetrain becomes somehow more complicated, and the design optimization requires simulation of multi-physical conjugated models for a simultaneous approach of the electromagnetic, thermal, mechanical, and even acoustic challenges.

Virtually all the previous research trends rely on models of different kind representing the physical (mechanical, thermal, electrical…) properties of the different components. These models are used e.g. to understand how a certain component behave under operation and optimize its design, to identify modes of failure and predict their occurrence or to understand how different components in a system work together. Often the models are pushed out of their boundaries to represent extreme conditions, which may lead to inaccurate results. For these reasons, there is a standing need for the development of **accurate and reliable modelling tools and methods** for electric drives supporting both present and future research.

## Strategic research areas

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

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

These research efforts should be joint cooperative projects between SEC partners, supported by reference groups with solid representation from the industry, as a tool to convey the industry needs to 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 Machines

- Cost of ownership and environmental impact: a design for manufacturability, design for reliability, design for recycling. The major research projects in this strategic orientation are shown in Table 1.

- 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, and more. Projects that work in this strategic orientation are shown in Table 2.

- Thermal management: advanced cooling concepts, integrated cooling. Table 3 shows the projects under this specific strategic orientation.

- Development of other auxiliary machines, e.g., for off-road vehicle actuator.

- Advanced control strategies to improve any of the above. The projects on the control aspect are shown in Table 5.

Power Electronic Converters

- Cost of ownership and environmental impact: a design for manufacturability, design for reliability, design for recycling. Projects that work on power electronic converters regarding this specific strategic orientation are shown in Table 6.

- Identification of commonalities and synergies with the rest of the drivetrain: for example, integrating electric machines to reduce the number of components.

- Alternative semiconductor materials like SiC/GaN.

- Improvement of the peak power limitation of power electronic devices. Table 7 shows the projects that work on peak power limitation of the power electronic devices.

- Thermal management: advanced cooling concepts, integrated cooling. Projects that work on thermal management and integrated cooling system are shown in table 8.

- Advanced control strategies to improve any of the above.

Charging Systems

- Onboard chargers (topologies and control considering not only efficiency but also, e.g., battery lifetime). Projects that are focusing on onboard charging is shown in Table 9.

- Automating the charging process on a broader perspective: inductive charging vs. automated conductive approaches. Developments in this area may consider autonomous electric vehicles. Projects that are working in this perspective are shown Table 10.

- 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). Table 11 shows the projects that towards this dimension.

- 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 theme should contribute and support the development of such standards.

## Forecast (perspective in five years, ten years, fifteen years ahead)

### Five years ahead

- Road vehicles: The performance and cost of electrified passenger cars are steadily improved. Better batteries, more ingenious EV-specific platform designs, and mass production are behind this improvement. Comfort improves through careful noise, vibration, and harness (NVH) analysis of the electric drivetrain integrated into the vehicle. Charging infrastructure is under development but still insufficient to cover all transport needs unless a reasonably large battery is present on the vehicles (with the corresponding weight and price penalty). High-power automatic charging equipment is under development. 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 these vehicles' second-hand value are required to find viable business models.

- Flight transport: a few prototypes of larger full-electric aircraft are under test. 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 reaches a higher integration level.

- Marine applications: hybrid diesel/electric propulsion systems are readily available. The electrification of small vessels is ongoing, many prototypes available with a charging infrastructure that resembles that of electric cars. The largest issues in the electrification of long-distance travels and very large ships still remain, especially on the energy storage side. Alternative storage solutions like hydrogen become part of the R&D roadmaps.

### Ten years ahead

- Road vehicles: Electrified passenger cars are now mature. The business models behind EVs are established now, and there are methods to assess the condition of the vehicles and estimate, e.g., the second-hand value. Charging infrastructure is still developing, although it is no longer a significant concern for the user, except in some isolated regions. Recycling of valuable materials such as copper and magnets is also functioning well. The necessary charging infrastructure for heavy-duty commercial vehicles is under fast dissemination, with the major freight corridors already implemented in several countries. Thanks to the steady improvement in battery technology, charging powers are high enough to provide reasonable charging times. However, the lack of charging opportunities still implies the need for large batteries on these vehicles, with the corresponding cost and weight penalty. The biggest challenges are on the power grid side: integration of the electromobility-related loads in the power grid, intermittent CO2-free renewable generation, and increased electrification of industries.

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

- Marine applications: Small vessels are fully electric, efforts continue to improve their efficiency and reliability in harsh environmental conditions. Hybrid hydrogen/battery systems for larger vessels and long-distance travels establishes as the main energy storage solution for this segment.

15 years ahead

- Road vehicles: Electrification of passenger cars has become a commodity, and most vehicles sold in this segment are fully electric. The electrification of heavy-duty vehicles (trucks) is reaching maturity. Some technological advances from other applications areas find their way into electromobility (e.g., new materials, different energy storage solutions, and more). A well-defined ecosystem (vehicles, charging infrastructure, business models) allows long-distance transport. Some challenges remain in integrating extensive charging facilities into the power grid.

- Flight transport: Electrification of short-distance flights with small/medium-sized airplanes is possible. To increase the range and capacity of electric aircraft, much higher power density machines and drives are necessary. This target will unlikely happen with incremental improvements of the existing technology but with new, revolutionary concepts. Battery technology will experience a further boost similar to the one that occurred after introducing (H)EVs at the beginning of the $21^{st}$ century.

- Marine applications: Electrification of small vessels is mature. Protypes of electrified large vessels for long-distance travels are under testing.

## Relation between theme areas:

| Strategic research area | Systemstudier och metoder | Elektriska maskiner, drivsystem och laddning | Energilagring | Elektromobilitet i samhället | Samverkan mellan fordon och elnätet |
|---|---|---|---|---|---|
| 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 |
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