Roadmap Theme 2 – Electric Drives and Charging

Introduction

The rapidity of electrification across all sectors, particularly the transportation sector, is leading to substantial technological changes while profoundly impacting global social and economic equilibria. Despite accelerations and decelerations, electrification does not seem to be ending anytime soon. However, depending on the chosen technical pathway, electrification is not always synonymous with sustainability. The implications of sustainable electrification are of foremost importance in the electromobility sector.
It is given that transportation electrification has spurred a technical development resulting in more energy efficient, reliable and cost-effective components and systems for the supply and conversion of electric energy. The issue is now to turn the electrification into a sustainable one, considering availability of materials, supply chain risks, production processes, energy-efficient operation, reusability and recyclability of components in electric vehicles.

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, the on- and off-board charging equipment, and auxiliary systems on board the vehicles, with focus on the electric and electronic parts that compose such systems.

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 (SEC) 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 on board the vehicles.

The main objective of the theme is to conduct research on the aforementioned technologies at the component or subsystem (drivetrain/vehicle) level to minimize the societal cost of electrifying the transport system. The societal cost includes both the environmental impacts of production and use, such as material use, byproducts, and electromagnetic compatibility (EMC), as well as the financial costs of ownership, which include clean manufacturing, installation, energy consumption, downtime reduction, maintenance, and recycling. The circular economy enables both.

Research conducted within the Theme may require understanding interactions with the mechanical system, 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 medium-voltage level, which are translated into Theme 2 requirements for the design of on-board charging equipment. Both the vehicle side and the power system side should also address EMI emissions generated by vehicle operation and charging. Theme 2 concerns these aspects for on-board equipment.

The time horizon of the research activities in Theme 2 is designed to influence industrial product plans, typically 10 years from the start of production (SOP). This long-term perspective encourages thinking "out of the box," free from existing solutions, regulations, or limitations, while keeping the research at a pre-competitive stage, thus allowing competing companies to collaborate. However, it is possible to conduct research focused on shorter perspectives if the topic is of interest to most theme partners.

Current Trends and Needs

Electrification of passenger cars and light transport vehicles (vans) has already reached a certain degree of maturity, and it is entering a second phase in which the research and development focus lies more on optimizing and refining the products, reducing cost, increasing reliability, etc. However, for other vehicle types such as long-haul trucks and coaches, and other transport modes such air or sea, new technical solutions may still be needed and are thus centering the research.

A review of current research on electrical machines and power electronics reveals several interesting trends described in this section.

A significant change in the **electrical machine** sector is that heavy rare-earth metals used to manufacture permanent magnets are becoming a source of global conflict. The dominance of China in the extraction of critical materials and the manufacturing of magnets is seriously impacting the economic forecasts of vehicle manufacturing outside China, as well as creating global imbalances due to politically driven supply chains. This issue must be addressed with the highest priority: either by removing the dependence on permanent magnets in electrical machines through redesigning competitive magnet-free machines, or by using alternative permanent magnet materials less affected by the aforementioned supply chain problems.

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 automotive manufacturers in Sweden source these components mostly from foreign suppliers. However, this situation will likely change in the near future, at least for some of the Centre's partners.

Wide-bandgap semiconductor technologies, especially SiC, are driving higher voltages and modulation frequencies in power electronics. 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. While enticing from an electrical point of view, there is a potential criticality in the power electronics supply chain. 40 – 50% SiC wafer manufacturing capacity is located in Asia. The next generation of power electronics using GaN components is even more affected, as almost all refined Gallium (90-98%) is sourced from China.

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 enables different integration options. However, as power levels, voltages, and switching frequencies increase, EMC phenomena become more critical, and it is necessary to investigate them to minimize their effects. With the growing scale of EV-related infrastructure, such as large EV charging parks or electric roads, coherent superposition may yield radiated EMI that exceeds site-level limits, even while individual chargers meet EMC standards. These must be mitigated on the facility level of the charging park or electric road system.

Another trend in electromobility research is **safety and reliability**. Fault-tolerant designs with some degree of redundancy will ensure the vehicle can still operate even in the event of a fault, albeit with reduced performance. This is particularly important for electric aircraft. In the long term, improving reliability implies finding new solutions for components and systems that are inherently safer and more reliable. Experience shows that the potential increase in component costs is typically not an issue, given the overall reduction in operational costs when components are reliable. Moreover, with the increasing number of electric drives in vehicles, there is a need for condition-monitoring and lifetime-estimation techniques for the relevant components from the design stage onward. This aspect is necessary for safety and economic reasons related to ordinary maintenance, ultimately making electric vehicles competitive even for heavy vehicles whose reliability requirements are more stringent than those for passenger cars.

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 sector remains underdeveloped. One steady trend over the last years has been the increase of charging power levels – mostly for fast charging. From the initial Tesla 120 kW superchargers to today's 400 kW CCS for passenger cars and over 1 MW for heavy vehicles. However, as power levels rise, charging automation remains almost nonexistent for most vehicles. Alternative solutions such as electric road systems (ERS) or battery swapping systems are being evaluated as a way to mitigate the problems associated with high-power fast charging. In China, battery swapping has become a common feature of battery electric trucks.
When evaluating different charging solutions a system perspective is essential, considering battery and charging infrastructure costs from both a vehicle owner/customer perspective and a societal level. Additionally, for applications where the moderate energy density of current batteries or the availability of a sufficiently robust power grid may pose a problem, hydrogen could serve as the primary onboard energy storage medium. Therefore, the design and control of power converters intended to interface fuel cells and electrolyzers is gaining importance.

Finally, there is a trend toward integrating multiple components with enhanced functionality into the same volume. For this reason, the drivetrain becomes somewhat more complicated, and the design optimization requires conjoint simulation across various multi-physical conjugate models for a simultaneous, coherent approach to electromagnetic, thermal, mechanical, and even acoustic challenges. Virtually all previous research relies on models representing the physical (mechanical, thermal, electrical…) properties of individual components. These models simulate a component's behavior under different operating conditions. They are used, e.g., to optimize its design, identify modes of failure and predict their occurrence, or understand how various components in a system might work together. Pushed beyond the model's boundaries to represent the extreme conditions expected during component integration, where interactions between components become nontrivial, the models may yield inaccurate results. Thus, the trend toward integration drives the development of more accurate and reliable modelling tools and methods for electric drives, supporting both current and future designs.

Strategic research areas

Sweden enters the coming decade with a strong tradition in electrification research and industrial innovation, but with very limited domestic manufacturing capacity for automotive electric drive systems. In contrast, as stated in Current trends and needs, China currently dominates the supply of critical materials—particularly permanent-magnet rare earths—as well as the global production infrastructure and related manufacturing expertise. It is also progressing quickly in design and innovation, areas in which it was long viewed as trailing other regions.

In this context, Swedish research and innovation efforts must be directed toward areas where they can generate the greatest strategic impact. Competing internationally through incremental improvements is unlikely to close the existing technology gap. Instead, long-term research focusing on potential disruptive innovations is needed to position Swedish industry for future competitiveness, strengthen national capabilities and contribute to resilient, sustainable transport electrification. Sweden has several unique advantages to build upon: a deeply rooted environmental commitment, advanced competence in lifecycle analysis and resource efficiency, and a dynamic research ecosystem that fosters collaboration, creativity and system-level thinking. By leveraging these strengths and focusing on transformative innovations in electric machines and power electronics, Sweden can contribute to a sustainable, competitive and robust transport sector over the next decades.
With this in mind, the following research areas have been selected strategically important for SEC in the upcoming phase.

In the area of electrical machines:

- **Novel electrical machine topologies with minimized environmental impact and that rely on materials with a secure supply chain**
- **Methods to minimize operational and maintenance costs for these machines.** Since such machines may be more expensive to manufacture than conventional machines, operational and maintenance costs should be reduced as much as possible to keep a competitive total cost of ownership. Thus, advanced design methods, condition monitoring, early fault detection, and other techniques that enhance the reliability and robustness of these machines are also prioritized.

- **Specific control schemes.** Novel machine topologies designed for low environmental impact, with low-risk materials and high reliability may require new or at least adapted control strategies to operate optimally.

In the area of power electronics, as stated in Current trends and needs, SiC has become the de-facto standard for automotive applications, with GaN being promoted as the coming generation of semiconductors. However, China currently produces more than 90% of the world's refined gallium—the essential precursor for GaN semiconductors—creating a supply-chain vulnerability similar to that faced in electric machines. Therefore, we believe that Theme 2 should prioritise research that mitigates or bypasses these strategic material dependencies, including:

- **Use of materials with low supply-chain risk in automotive power converters**, such as the new generation of ultra-wide-bandgap semiconductor materials currently under investigation in Lund and Linköping, which could significantly reduce reliance on gallium or other constrained materials. Their adoption will impose new constraints and opportunities in component and converter design, packaging and thermal management, and will likely require new control strategies.
- **Advanced converter topologies for extended lifetime and reduced operating costs.** Multilevel converters, modular multilevel converters (MMC) and current source inverters (CSI) can lower ripple and harmonics, improve EMC, and extend the lifetime of machines and batteries, helping reduce overall drivetrain operating costs. However, specific implementations may depend on semiconductor materials with significant supply-chain vulnerabilities (e.g., GaN bidirectional switches) – such dependencies should be reduced.
- **Power-electronics solutions for high-power and high-voltage levels.** The introduction of Megawatt Charging Systems (MCS) for heavy vehicles demands converters capable of handling high voltage and power levels. Conventional automotive power-electronics approaches may not be capable of handling these high voltage and power levels. HVDC technology exists in other sectors (e.g., wind power, power transmission) and may serve as inspiration, but it likely needs to be adapted and optimized for charging applications. High-frequency power electronics solutions, such as those being currently developed for powering data centers may find an application within electromobility. Although initially coupled to charging solutions, this research is also applicable to high-voltage high-power drives for e.g. railway or marine applications.

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

Five years ahead

<u>- Road vehicles:</u> 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. In Sweden, charging infrastructure is still developing, although it is no longer a significant concern for the user, except in some isolated regions. However, in other places charging infrastructure may still be insufficient to cover all transport needs. High-power automatic charging equipment is under development. Full-electric heavy-duty vehicles constitute about 10-15% of the fleet,

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.

- Flight transport: a few prototypes of larger full-electric and hybrid 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 are available with a charging infrastructure that resembles that of electric cars. The largest issues in the electrification of long-distance travel 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: 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 as well. Significant efforts are done to recycle valuable materials such as copper and magnets. The necessary charging infrastructure for heavy-duty commercial vehicles is under fast dissemination, with the major freight corridors already implemented. Thanks to the steady improvement in battery technology, charging rates are high enough to provide reasonable charging times. The biggest challenges are on the power grid side: integration of the electromobility-related loads in the power grid, intermittent CO_2-free renewable generation, and increased electrification of industries.

- Flight transport: the first commercial models of medium-size electric 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/biofuel + battery systems for larger vessels and long-distance travels emerges as the main energy storage solution for this segment.

15 years ahead

- Road vehicles: 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) facilitates long-distance transport. Some challenges remain in integrating extensive charging facilities into the power grid.

<u>- Flight transport:</u> 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 21st century.

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

Cross-thematic research topics

SEC Theme	1	2	3	4	5
Thematic research area	Systemstudier och metoder	Elektriska maskiner, drivsystem och laddning	Energilagring	Elektromobilitet i samhället	Samverkan mellan fordon och elnätet
Research topic:					
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