Manufacturing of electric powertrains
Motivation and objectives

Background

The motivation to minimize the negative effects on the environment together with the aim to improve operating costs of commercial transportation, is leading to an increase in demand for alternative truck solutions. Electrifying the powertrain of heavy vehicles has therefore evolved as new topic within the automotive sector showing the potential to influence the powertrain sector strongly.

The challenge

In electric powertrains, new parts like battery packs, fuel cells, electric motor and power electronics are introduced and replacing the conventional combustion engine. Gearbox and axles can still be present, depending on the preferences. In general, the choice of components depends strongly on the chosen concept as well as powertrain design and differs for e.g. all-electric and hybrid solutions. Hereby, the powertrain design is quite flexible and various solutions exist. Generally, the new electric components are linked to new manufacturing techniques processing new materials and requiring different competencies.

Figure 1 Schematic view of conventional and electric powertrain components potentially integrated in an all-electric truck

Conventional powertrain components that can be integrated in an all electric powertrain
Conventional powertrain components not present in an all-electric powertrain
Electric powertrain components
Since battery cell/pack production as well as large-scale electric motor and fuel cell manufacturing are not yet commonly established in Europe, a relatively easy access to the automotive industry for new players is imperative.

“Early positioning, supply chain adaptations and competence development are therefore crucial for original equipment manufacturers (OEM) and suppliers to keep their relevant market share.”

Jannik Henser, managing director

Our approach

Our goal is to support getting involved in electric powertrain production to keep the current degree of added value created from powertrain manufacturing. Therefore, we offer detailed technology studies on the production of electric powertrain components to help understanding the production process better. Identifying challenges within the required production steps, as well as presenting current State of the Art manufacturing technologies, provides players in the automotive sector with a complete picture to drive forward their development. The design and manufacturing choices of the electric motor, battery pack, fuel cells and power electronics are interdependent on many factors like cost, production volume and design flexibility. Therefore, right from selecting the configuration by analyzing the requirement to understanding every step in the manufacturing of each component, PMH Application Lab together with its research partners offers extensive expertise in both the design process and production chain.

Figure 2 From concept to manufacturing- A simplified process neglecting interdependencies
Electric motor
When it comes to the powertrain design, all-electric trucks offer a high degree of freedom. Unlike combustion engines, the motor placement within the powertrain and the number of integrated motors can vary from a single, main electric traction motor to drivetrains containing several electric motors located inside or near several wheel hubs. Diverse and application dependent motor requirements result in a variety of electric motor types and designs. Today, the most commonly used traction motors are induction machines and synchronous machines with permanent magnet (PM) rotors. Promising designs in terms of efficiency like inductively excited brushless synchronous motors and switched reluctance motors are also rapidly evolving.

The stator and rotor winding are directly influencing the motor's performance and play an important role during the motor design phase. Today, distributed random wound windings are widely used. Bar windings (especially hairpin-type windings) are representing a recent trend due to the higher fill factors that can be achieved and a better suitability for use in highly automated production processes. The choice of the ideal motor configuration depends on characteristic performance factors like torque and power density, speed range, efficiency, reliability, robustness and costs that suit best the specific demand and varies for each application.

Skills and competences during the electric motor production heavily differ from those in conventional motor production. Mechanical processes (e.g. machining / forming) are transforming towards mechanical–electric process (e.g., winding and joining) which challenges currently available competences in the powertrain manufacturing sector.

In terms of PM rotors, neodymium-iron-boron-type magnets (Nd-Fe-B) are most commonly used. However, these types of rare-earth based materials are rather expensive and, together with concerns regarding the negative environmental impact during the material production, the replacement of rare-earth materials is a current hot topic.

Figure 3 Exemplary production chain for an asynchronous electric motor
Battery pack
To keep the battery size and weight as low as possible enabling both a long range and high payloads for commercially used electric trucks, a high energy density of the batteries is crucial. Therefore, lithium-ion (Li-ion) based battery technologies are considered for fully electric trucks since their high energy density and fast charging rate supersedes nickel-metal hydride (NiMH) based batteries.

Li-ion battery packs contain several modules consisting of battery cells that are connected in series and parallel to achieve the required voltage and charge level. The battery management system (BMS) is an important and challenging aspect because the battery characteristics change with operating temperature, state of charge (SOC) and charging/discharging current. Therefore, estimation of battery model parameters is essential to assess the SOC and the state of health (SOH) of the battery. The BMS usually has a master slave topology design where each stack is monitored by the BMS slave measuring cell voltages and cell temperatures. The BMS master coordinates and communicates with the slaves to perform cell balancing, realize various protection functions and also estimates SOC and SOH. Efficient thermal management of the battery pack can make a significant difference in the overall performance and life of the battery.

The fundamental constituents of the cell as smallest element in the battery pack are the positive and negative electrodes (anode and cathode), the electrolyte and the separator isolating anode and cathode from each other. Those components are similar for (I) cylindrical, (II) prismatic and (III) pouch cells. However, every cell type is showing different performance characteristics referring to energy density, lifetime, ease of cooling, cost and the required production processes. The cell manufacturing hereby consists of three main production steps: (1) electrode production, (2) cell assembly and (3) cell formation, whereby step (2) varies depending on the cell type. The entire cell production process is governed by specific environmental and safety requirements as well as advanced measurement methods for quality assurance. The cell quality hereby directly influences the battery pack performance resulting in high demands on the production.

![Exemplary production chain for battery packs](image-url)
Power electronics
The motor control unit in electric vehicles consists of a power-electronic converter and its associated control. The converter controls the power flow from the direct current (DC) source to the electric machine enabling to charge the battery pack during regeneration. Control area network (CAN) protocol are commonly used as the interface between the motor controller and the engine control unit (ECU) of the vehicle. Field oriented control (FOC) is commonly adopted to realize the closed-loop current/torque control.

Insulated-gate bipolar transistors (IGBT) are commonly used due to their high voltage and high power capability. DC-voltage ratings in the range of 0.7 kV to 1 kV are not uncommon in heavy-duty hybrid electric and fully electric vehicles. Silicon carbide (SiC) and gallium nitride (GaN) based semiconductors are also being considered for automotive applications thanks to their reduced losses and improved power densities compared to silicon-based counterparts.

To reduce the associated losses in the electric machine, the converter adopts a high switching frequency. Multi-level converters have started to be considered in automotive applications requiring very high powers. Box-type packaging is the usual way of incorporating the motor control unit in the powertrain. The idea of integrated power electronics is quickly evolving, where the electric drive (combination of converter and electric machine) is part of the same housing as the drivetrain or the wheel hub.

“The converter topology and control strategy is dependent on the specific electric machine and commonly allows for a high efficiency, high reliability and high bandwidth.”

Svenja Gelpke, research engineer

Figure 5 Elements and simplified production process of motor controller
Fuel cells
One of the aspects of electrification of trucks is the requirement of robust power storage devices and systems. Fuel cells are one such system with promising potential for the field of heavy vehicle electrification. To satisfy rising future demands for electric commercial vehicles, the development of cost effective and high volume production techniques is crucial.

Fuel cells have the potential to increase the range of electric trucks and complement integrated battery systems or usage as individual application in a stand-alone system. In general, several types of fuel cells exist, whereby the proton exchange membrane (PEM) fuel cell presents the commonly used type for mobile and vehicle applications. In those, electricity is generated by a chemical reaction between the supplied hydrogen together with the oxygen contained in the ambient air. Next to electricity, this reaction creates water, which is released as steam. The electricity can either be used directly in the electric motor to power the vehicle or be stored in a buffer battery for a later use. Since fuel cells do not store energy but only act as energy converter, the vehicle needs to have integrated hydrogen storage tanks to supply the required hydrogen, preferably under high pressure to allow a high energy density.

The lower weight of fuel cells and storage tanks compared to battery systems is offering the potential for higher payloads, which is especially important for commercially used vehicles. To cover the same distance, the total weight of the fuel cell system providing the required electricity, is lower than respectively used batteries. This allows the transport of higher loads or, considering the same total vehicle weight, to cover longer distances.

However, today’s fuel cell and storage tank production is not on a mass production scale, which results in relatively high prices for the system. Efforts to reach a scale of high production volumes is therefore required to achieve cost-effectiveness and bring fuel cells to economic competitiveness. Realizing the impact of upscaling of fuel cells on the future of powertrain production is hereby essential.

![Exemplary and simplified structure of a PEM fuel cell](image)

Figure 6 Exemplary and simplified structure of a PEM fuel cell
## Focus and competences

### Battery pack

- Battery modelling and simulation
- Materials
  - Material selection
  - Structural energy storage
  - Composites
  - Lignin research
  - Nonwoven electrodes based on non-metal materials
  - Synthesis of cathode active materials
  - Development for electrolyte, cathode and anode materials
  - Surface treatment of active materials (coating and doping of active materials)
  - Development of separator (PVDF-based membranes)
  - Characterization of materials and coatings
- Production of electrodes
- Cell assembly
  - Winding
  - Joining technology and pretreatment for battery assembly
  - Casting, forming and stamping processes for battery housings
  - Structural Integration of batteries and battery housings
  - Welding, insertion & closing
  - Electrolyte filling
  - Degassing and sealing
- Formation of cell
- Simulation of manufacturing processes and assembly
- Battery thermal management
- Aging & Testing
  - Battery safety: Abuse testing, fire testing and crash testing
  - Simulation tools
  - Cycling and performance testing on cell level
  - Electromagnetic compatibility (EMC) testing
- Automation and robot path planning

### Power electronics and control

- Converter topologies
- Motor control techniques/ interfaces
- Simulation of power electronic converters
- Basic electrical/electronic components
- Electronics Packaging
  - Low inductance power module packaging
  - Double sided cooling
  - Sintered die attach materials
  - Silicon carbide (SiC) and Gallium nitride (GaN) device packaging
- Reliability of electronics
  - Assembly level reliability assessments
  - Physics-of-Failure (PoF) approach, models and simulations
  - Root cause failure analysis
  - Integrated condition monitoring sensors
  - Prognostics and health management
  - Combining PoF and data-driven (AI) methods for predictive maintenance
- Printed circuit boards
- Electromagnetic compatibility
- Cooling of power electronics
- Inverter assembly
- Experimental evaluation

### Strategic planning

- Production management
- Market analysis
- Technology purchasing/forecasting/planning
- New production line layouts
- Techno-economic analysis
- Industry standards and requirements
- Realization of ultrashort process chains
- Development of holistic energy and resource management systems
- Added value analysis
- Roadmapping and scenario analysis
- Profitability assessment of production and assembly concepts
Fuel cell systems

- Pressure vessel for hydrogen storage
  - Selection of pressure vessel type (Type 1/2/3/4)
  - Material selection (liner material and matrix system)
  - Selection of liner production (blow moulding, roto moulding, injection moulding)
  - Selection of composite process chain
  - Winding (thermoplastic, towpreg, dry-fibre)
  - Novel winding machinery
  - In-line process control systems
- Fuel Cell Stack (PEM)
  - Metal bipolar plates
  - Rubber forming
  - Matched metal die forming
  - High volume progressive die production (coil to stack)
  - Trimming
  - Welding
  - Material selection (1.4404, 1.4310, ...)
  - Evaluation of process chain (welding, coating, forming)
  - Mold making
- Compound/graphite bipolar plates
  - Milling
  - Forming
  - Membrane exchange assembly (MEA)
  - Evaluation roll-to-roll process steps
- Assembly
  - Development of automated assembly solutions
  - Design of endcaps
- Balance of plant
  - Selection of buy-in parts
  - Turbine manufacturing for fuel cell air supply

Electric motor

- Machine topologies
- Electromagnetic and thermal design
- Machine topologies
- Light weight construction for wheel hub motors
- Stack of sheets production
- Geometry assurance
  - 3D scanning and measurement of components
  - ∆Alpha measurements at elevated temperatures
- Rotor Manufacturing
- Stator Manufacturing
  - Slot insulation
  - Joining and assembly of laminates for stator cores
  - Stamping of laminates for stator applications
  - Winding technology/production/placement/processing
  - Wire bundling
  - Winding heating
  - Trickle impregnation for stator windings
  - Testing
- FEM- and CFD-based simulation of electric machinery
- Experimental evaluation
- Testing technologies
- Additive manufacturing technology

General Manufacturing

- Joining methods and assembly
- Pretreatment
- Virtual manufacturing
- Mechanical testing methods
- Development of smart materials
Follower membership is the smallest membership category in the R&D Cluster and gives access to the community. A Follower pays an annual membership fee for community management of EUR 2,500. A follower participates in the preparation process for collaborative R&D projects and may suggest new project ideas. Furthermore, a Follower receives mailings about all matters in the R&D Cluster, may participate in the annual conference and gets reduced seminar fees. The participation in collaborative R&D projects which enables a Follower to receive project results and gives access to the sessions about collaborative R&D projects in the annual colloquium is optional and requires additional financial expenses of EUR 27,500. The option to join and contribute to the collaborative R&D projects has to be chosen at least every third year.

Partner

A Partner pays an annual fee for community management of EUR 2,500 and expenses for collaborative R&D in the amount of EUR 27,500. Furthermore, a Partner commits to annual expenses of at least EUR 50,000 for individual R&D projects. In addition to the above mentioned Follower benefits, a Partner has a seat in the Steering Group in which the representative may distribute 8 points for the first selection of collaborative R&D projects. In other decisions all Partners have a collective vote in the Steering Group.

Key-Account

The third category is the Key-Account category. A Key-Account pays a fee for community management of EUR 2,500 per year and expenses for collaborative R&D in the amount of EUR 47,500. Furthermore, a Partner commits to annual expenses of at least EUR 150,000 for individual R&D projects. In addition to the above mentioned Follower & Partner benefits, a Key-Account may distribute 20 points for the first selection of collaborative R&D projects and has an own vote in all other decisions. Furthermore, Key-Accounts receive a key-account manager as contact person for all R&D Cluster matters and receives an annual finance report.

Premium partner

A Premium partner pays the same annual expenses for community management and collaborative R&D as a Key-Account but commits itself to higher annual expenses for individual R&D in the amount of EUR 300,000. In addition to the above mentioned Key-Account benefits, a Premium Partner may distribute 35 points in the first selection of collaborative R&D projects and gets two votes in the Steering Group.

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* This option has to be selected at least every third year
** Sessions about results of collaborative R&D require a financial contribution to the collaborative R&D projects
*** One shared vote for all partners in strategic decisions
Manufacturing of electric powertrains

Research partners

Powertrain Manufacturing for Heavy Vehicles Application Lab

The Powertrain Manufacturing for Heavy Vehicles Application Lab (PMH Application Lab) is a research center at KTH which is operated in collaboration with the German research organization Fraunhofer and the Swedish network of research and technology organizations RISE with its associate Swerim. The PMH Application Lab works in research and development for the improvement of technologies in the field of powertrain manufacturing for heavy vehicles on high technology readiness levels to strengthen the competence of the Swedish heavy vehicle industry in this area. This comprises project execution, project coordination and dissemination with the goal to validate technologies and to accelerate the transfer of these technologies into industrial application.

KTH Royal Institute of Technology

KTH is Sweden’s largest technical research and learning institution and home to students, researchers and faculty from around the world. From KTH the Department of Production Engineering and the Powertrain Manufacturing for Heavy Vehicles Application Lab are active partners in the PMH R&D Cluster.

Fraunhofer IPT

Fraunhofer IPT is an institute of Fraunhofer-Gesellschaft and is located in Aachen, Germany. In the areas of process technology, production machines, production metrology and quality as well as technology management, IPT offers partners and customers tailor made solutions for a connected, adaptive production.

Fraunhofer IWU

Fraunhofer IWU is an institute of Fraunhofer-Gesellschaft and is located in Chemnitz, Germany. The main focus of Fraunhofer IWU’s work is on application-oriented research and development in the field of production technology for the automotive and mechanical engineering sectors focusing the entire process chain.

RISE

RISE is the Swedish Research Institute and innovation partner. In international collaboration with industry, academia and the public sector, RISE ensures the competitiveness of the business community and contribute to a sustainable society. The employees of RISE support and promote all manner of innovative processes. RISE is an independent, state-owned research institute that offers unique expertise, testbeds and demonstration facilities, instrumental in future-proofing technologies, products and services.

Swerim

Swerim, an associate to the RISE group, is located in Stockholm, Sweden. Swerim conducts applied research within mining engineering, process metallurgy, materials and applications, mainly for the mining, steel and metal industries.

Chalmers University of Technology

Chalmers is a highly progressive university situated in Gothenburg which is known for education, research and innovation with focuses on technology, natural science, architecture, maritime and other management areas. From Chalmers the Department of Industrial and Materials Science is active in the PHM R&D Cluster.
Contact

Powertrain Manufacturing for Heavy Vehicles Application Lab - a collaboration between KTH, Fraunhofer and RISE

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