Scalable Electric Drive Unit for Multifunctional Vehicles

The opportunities offered by electric mobility apply not only to passenger cars, but also to multi-functional vehicles used in urban areas, as they contribute a large proportion to noise and air pollution. To explore this market, a German consortium is developing a scalable electric drive unit for multifunctional vehicles. The development consortium consists of the medium-sized companies Max Holder, Groschopp, REFU Drive and Nantis, the University of Stuttgart and the Universities of Applied Sciences in Düsseldorf and Aalen. They are embedded in the e-mobility network managed by the innovation consultancy EurA AG.

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REQUIREMENTS FOR THE ELECTRIC DRIVE UNIT

The research association is developing an electric drive unit that can be used in multifunctional vehicles and similar vehicle types. In addition to extensive scalability of various performance and application areas, a high degree of flexibility of the drive unit was a key requirement of the project. The concept is configured in such a way that, as a rule, the driving is done purely electrically. However, in order to enable extreme loads or to supply the battery, the range extender principle can also be applied and thus a diesel generator can be switched on. However, the entire concept is also open for future developments and is structured in such a way that the diesel can be replaced by a fuel cell if the market develops accordingly. The body and chassis of the C70TC from Max Holder serve as the basis for the prototype of an electrically powered multifunctional vehicle.

ENGINE CONCEPT

The installation space available for the electrification of the powertrain in the demonstrator vehicle is very limited. It is therefore necessary to use an electric motor technology with the highest possible torque density and an additional transmission. A synchronous reluctance machine (SynRM) was chosen as the traction motor technology here, as it has a higher efficiency than an asynchronous machine (ASM). This is due to the absence of rotor losses and, compared to a permanent magnet excited synchronous machine (PMSM), does not use expensive and sensitive rare-earth magnets.

A SynRM consists of two magnetically active elements: the stator, with the current-carrying winding, and the rotor, rotating synchronously with the stator magnetic field. A four-pole IEC sheet metal (IEC132/4) with an outer diameter of 200 mm is used for the stator. This has the advantage that no new, expensive winding, pull-in and insulating tools are required for the production and insertion of the winding into the stator core.

The SynRM requires a magnetically anisotropic rotor geometry to function. This geometry is created by inserting punched holes, so-called flux barriers, in the rotor lamination. This results in two magnetically differently acting axes per

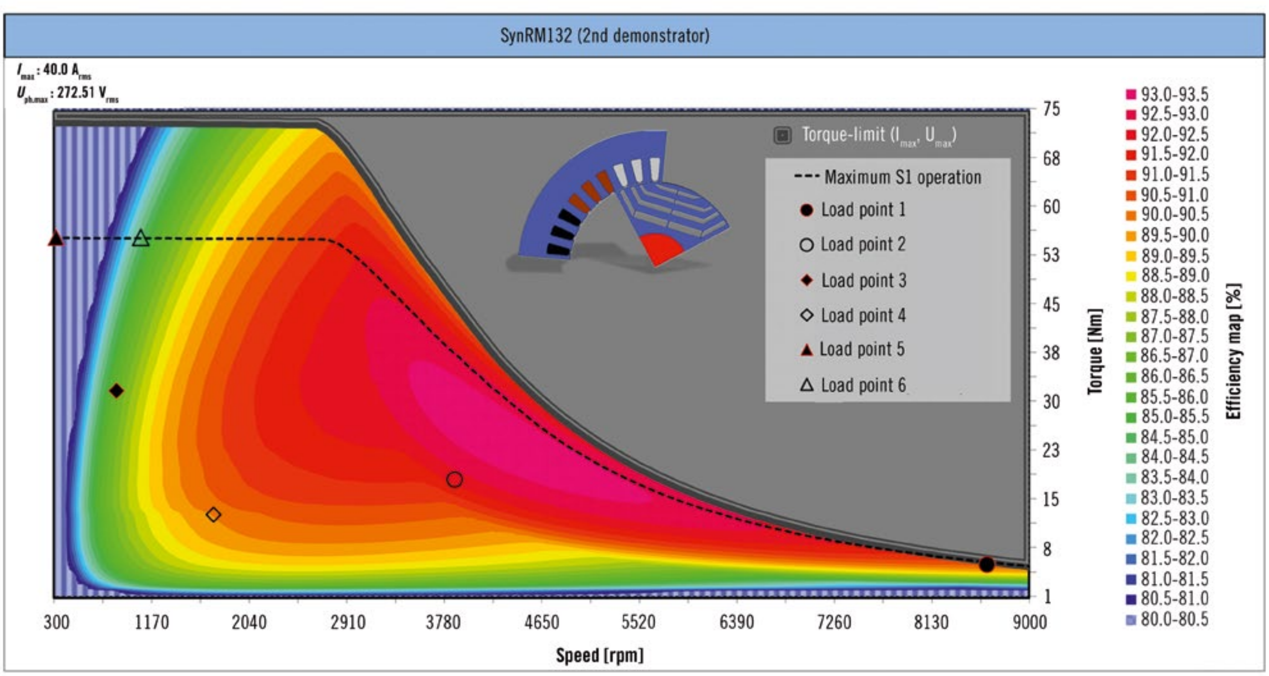

FIGURE 1 Efficiency map of the synchronous reluctance machine (© Dipl.-Ing. Andre Au | Hochschule Düsseldorf)

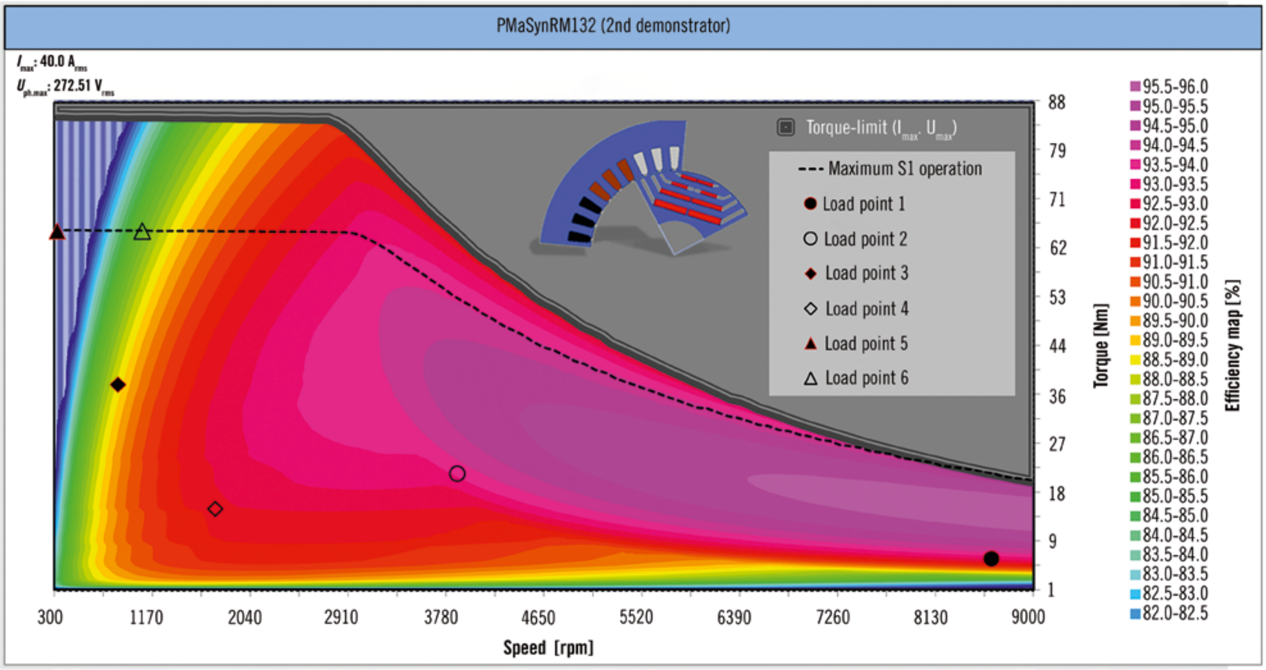

FIGURE 2 Efficiency map of the permanent magnet-supported synchronous reluctance machine (© Dipl.-Ing. Andre Au | Hochschule Düsseldorf)

magnetic pole (d-/q-axis). The q-axis with the contained flux barriers has a higher magnetic resistance (reluctance) than the d-axis, which contains a lot of iron. The operating principle of the reluctance machine is now based on the fact that the axis of the rotor with the smaller magnetic resistance (d-axis) is aligned with the magnetic field of the stator, which is generated by the electric currents in the stator winding. The greater the magnetic anisotropy of the rotor geometry, the higher the resulting torque. A measure for the rotor anisotropy is the ratio of the inductances of the two different magnetic axes (L_d/L_q ratio). The larger this ratio is, the greater the reluctance torque that can be generated by the machine.

Due to the required high maximum speed (9000 rpm) and the resulting great centrifugal forces acting on the rotor, it is necessary to optimize the mechanical rotor geometry in addition to the electromagnetic geometry. To mechanically reinforce the rotor, webs are inserted into the flow barriers. However, in the electromagnetic design, the mechanically necessary webs represent disturbing magnetic short circuits. To eliminate this influence, small inexpensive ferrite magnets are inserted into the flux barriers. The magnetic flux of these permanent magnets creates a magnetic saturation of the interfering bars, so that they are no longer electromagnetically negatively effective. This is then called a permanent magnet-supported synchronous reluctance machine (PMaSynRM), which has an improved performance. The final rotor geometry is therefore designed in such a way that the machine can be realized both as a pure SynRM (without ferrite magnets) and as a PMaSynRM (with ferrite magnets).

The PMaSynRM is characterized by the fact that the motor current required for the same torque is approximately 12 % lower compared to the pure SynRM. Moreover, even significantly higher torques can be achieved at higher speeds in the field-weakening range with the same motor voltage (maximum inverter output voltage), **FIGURE 1** and **FIGURE 2**. This results from the additional – albeit very small – permanent magnetic flux linkage in the PMaSynRM, which leads to an improvement in field-weakening operation. The PMaSynRM is thus able to approach all required operating points with a sufficiently high degree of safety. The motor concept is a joint project between the University of Applied Sciences Düsseldorf and Groschopp.

DRIVE

The multi-functional vehicle is designed as an articulated steering system, the two axles are designed as non-steered rigid axles, each carrying separate drive units. Limited installation space conditions are defined by the articulated steering system's kinematics, the ground clearance for driving in rough terrain and the space required by the auxiliary units. These are intended to provide the user group with the usual functionalities even with the electric drive variant. An electric motor with flange-mounted transmission is mounted on both sides of each axle, which in a compact arrangement allows the usual track width. The torsionally stiff axle protects the drive units from dirt and salt water through the downward closed profile and integrates the cabling and tubing for power, control and cooling water. **FIGURE 3** shows the complete unit of a drive axle (black) in the installed state with drive unit (green). The axle is designed as a welded construction and can be produced economically for small series of up to 700 pieces/year due to its modular design. It can be used variably in articulated steering as a front axle and rear axle.

THERMAL MANAGEMENT

A major challenge for electric drive platforms is, for example, air conditioning. In winter, a specified heat level must be maintained; in summer, on the other hand, the components must be cooled more intensively. The thermal system

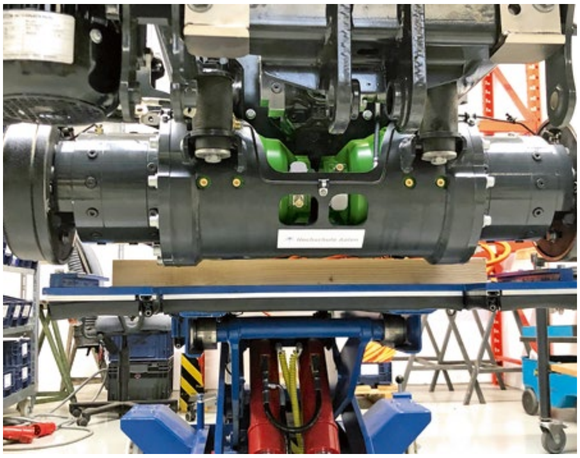

FIGURE 3 Complete unit of a drive axle (© Sebastian Reusch | Max Holder GmbH Reutlingen

developed must work reliably and take up only a very small installation space. The thermal management concept for the demonstrator vehicle characterizes an innovative approach for a modern electric drive platform. Different temperature levels of the individual powertrain components must be reliably provided with cooling power. **FIGURE 4** shows the different temperature ranges that prevail in the vehicle. For example, the power electronics of the drive motors operate at a temperature level of approximately 45 °C, the traction battery at approximately 35 °C and the heating for the interior, as well as the combustion engine for the auxiliary units, at a coolant temperature of approximately 90 to 120 °C.

The thermal management consists of two independent cooling circuits. The more powerful circuit of the two cools the drive components. These include the power electronics of the drive motors, the drive motors themselves, the power electronics of the generator, and the generator. The power electronics of the generator are also required for charging the battery from the power grid. The built-in coolant pump is controlled according to power demand, which allows energy-efficient cooling. In addition, the fan motors of the radiators are controlled in the same way. The smaller cooling circuit contains the battery cooling respectively its heating at very low outside temperatures. The battery is heated by an auxiliary heater, which is also used to heat the driver's cab.

The thermal management already showed the planned effect in the first driving tests conducted on the crown roller test bench of the University of Aalen. Fine tuning for different driving situations has a positive effect on energy efficiency. For this purpose, a specially developed driving cycle for multifunctional vehicles, including recuperation, has been developed and implemented on the crown roller test bench. Individual load points, as well as the complete driving cycle, represent the entire operating range of the vehicle.

POWER ELECTRONICS AND MODEL-BASED SOFTWARE DEVELOPMENT

The HY-TTC 580 model from Hydac/TTControl is used as the central control unit. It has a large number of inputs and outputs to control and read out the various system components. Communication is generally via the CAN bus. The control unit has integrated monitoring functions and provides the developers with a programming interface (API) in the programming language C. In order to handle safety-critical and non-safety-critical functional parts better and to be able to test changes more effectively, SafeRTOS was used as the operating system. This enabled the mixed criticality approach to be implemented well.

The vehicle was conceptually divided into individual functions, which were then implemented model-based in the tools Mathworks Matlab, Simulink and Stateflow. Graphical programming techniques are used to a large extent, which depict functions and processes in a comprehensible way. Functions can be simulated with the tools used even before a real vehicle is built. Further test setups with the Electronic Control Unit (ECU) and the individual components involved in the respective functions ensure that the virtual models can also be transferred to the real world. For example, the control of the electric hydraulic pump could be simulated in advance and later successfully transferred to the vehicle. A toolchain translates the models from the model level into C code, which is then translated into executable machine code for the ECU in a second step.

FIGURE 5 shows the structure of the power electronic system (1 to 6) with its connection to the overall system (A to F). The various energy conversion functions were realized by compact double inverters from Refu. Due to the limited space available in the area of the vehicle axle, the entire power electronics were moved to a separate housing, the so-called HV box. This box contains the power electronics as well as the battery cells, including the Battery Management System (BMS). The compact unit is connected to an external cooling circuit and serves as a mechanical interface to the vehicle. The full functionality of the vehicle is still guaranteed by the pivoting arrangement.

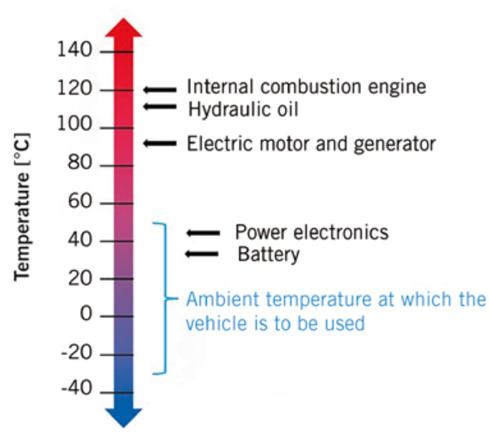

FIGURE 4 Temperature ranges of the vehicle (© Prof. Dr.-Ing. Markus Merkel | Hochschule Aalen)

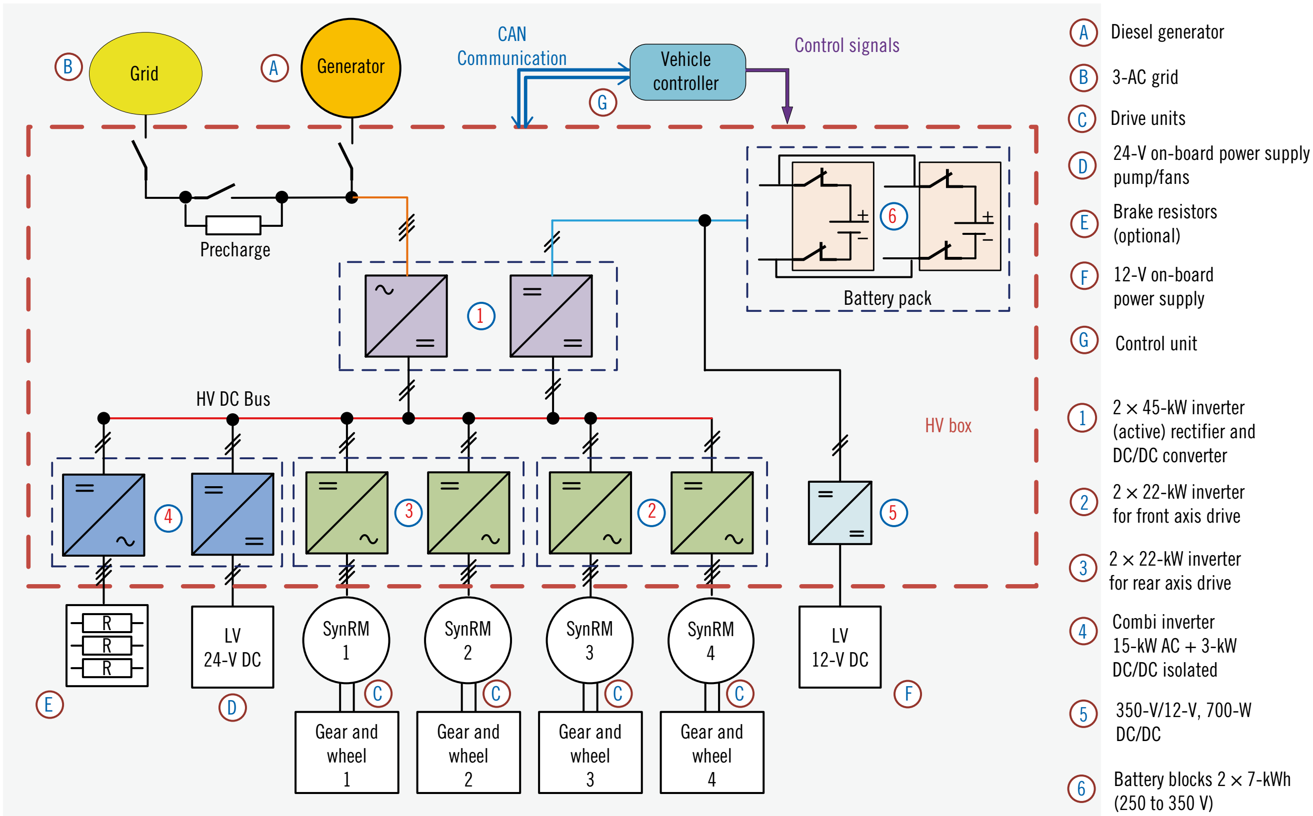

FIGURE 5 Structure of the power electronic system in the HV box (© Dr.-Ing. Norbert Schmidt | REFU Drive GmbH Pfullingen)

The basic component for the realization of the individual energy conversion functions in the vehicle, **FIGURE 5** (1 to 4), is a double inverter. It consists of two active B6 bridges, which are controlled by a control board and share an intermediate circuit. By suitable connection to the peripherals and the use of the corresponding function blocks in the firmware, various functionalities can be realized very easily. For the test vehicle, the device types shown below were derived from this:

- Generator inverter and DC/DC controller: When connected to the generator, the High Voltage (HV) bus voltage can be actively controlled. Alternatively, charging operation via the mains is possible. In addition, the second inverter operates as a bi-directional DC/DC controller.
- Motor inverter: Both motors of an axis are controlled independently of each other via the common control.
- Combined inverter: The first B6 bridge is intended for driving auxiliary units. Usually this is the steering pump. With the second inverter, an isolated DC/DC controller for the 24-V on-board power supply is realized.

FINAL TESTS

After mathematical proof of the achievement of the set goals and many successful detailed tests on various test benches, the prototype is now completely assembled and equipped with the central control system. The entire system is currently undergoing extensive system tests to prove its suitability for a wide range of applications and types of stress. This concept can also be used for other industries, for example in the construction industry, due to its flexibility.

SUMMARY

A development consortium consisting of medium-sized companies and university institutions developed an electric drive unit for multifunctional vehicles, which was integrated into the body and chassis of a Max Holder vehicle. The research focus of this project was the electric motor concept, and the realization of the thermal management and the power electronics. The electric drive consists of a PMaSynRM, which has an improved performance compared to the SynRM. It is connected to the gearbox in a common axis with the wheel. The hallmark of the thermal management system is the two independent cooling circuits to ensure that the various components of the vehicle are optimally supplied with power even when outside temperatures and driving cycles change. The central control unit has integrated monitoring functions that can also be simulated outside the vehicle. The power electronic system realizes the different energy conversion functions by means of compact double inverters. The entire power electronics, together with the battery cells and management system, are housed in a separate enclosure. The drive concept is also suitable for other industries due to its flexibility and scalability.

THANKS

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