New Battery Driven Vehicle Generation of Electric Tractors

Battery electric vehicles are becoming increasingly important in commercial vehicle technology. Wheel loaders and tractors are usually electrified by replacing the conventional combustion engine with an electric drive train while the vehicle structure is maintained. In contrast, the e-tractor by AVL is a completely new development with innovative, integrated and intelligent solutions.

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FULLY ELECTRIC VEHICLE SYSTEM

Today, existing electrically driven tractors are based primarily on the replacement of the conventional drive train by adequate electrical components. The basic vehicle structure remains as is. To offer an alternative economical solution to the customer, it is necessary to transition away from today's vehicle structure.

Constructionally the chassis is divided into three main modules. The electric power module is located in the middle of the chassis to optimize the center of gravity of the vehicle. This arrangement, as well as the elimination of diesel engine and gearbox, accommodates a sufficiently large battery capacity and allows a purely electrical use for up to 6 h in real conditions. Due to the higher power density, a fully electric commercial vehicle is initially equipped with a hydraulic system that enables internal vehicle functions such as steering, braking or the coupling and operation of existing equipment. In the long term, these functions might also be realized by electric drives. Nevertheless, existing mechanically or hydraulically driven machines will need to continue to be used for a transitional period to give implement manufacturers enough development time for new electric driven implements. In addition to the hydraulics, a pneumatic power module can optionally be used to operate an air-braked trailer suitable for the performance class of the tractor. Alternatively, an additional high voltage battery is installed in this space to increase the total capacity and the service life of the vehicle.

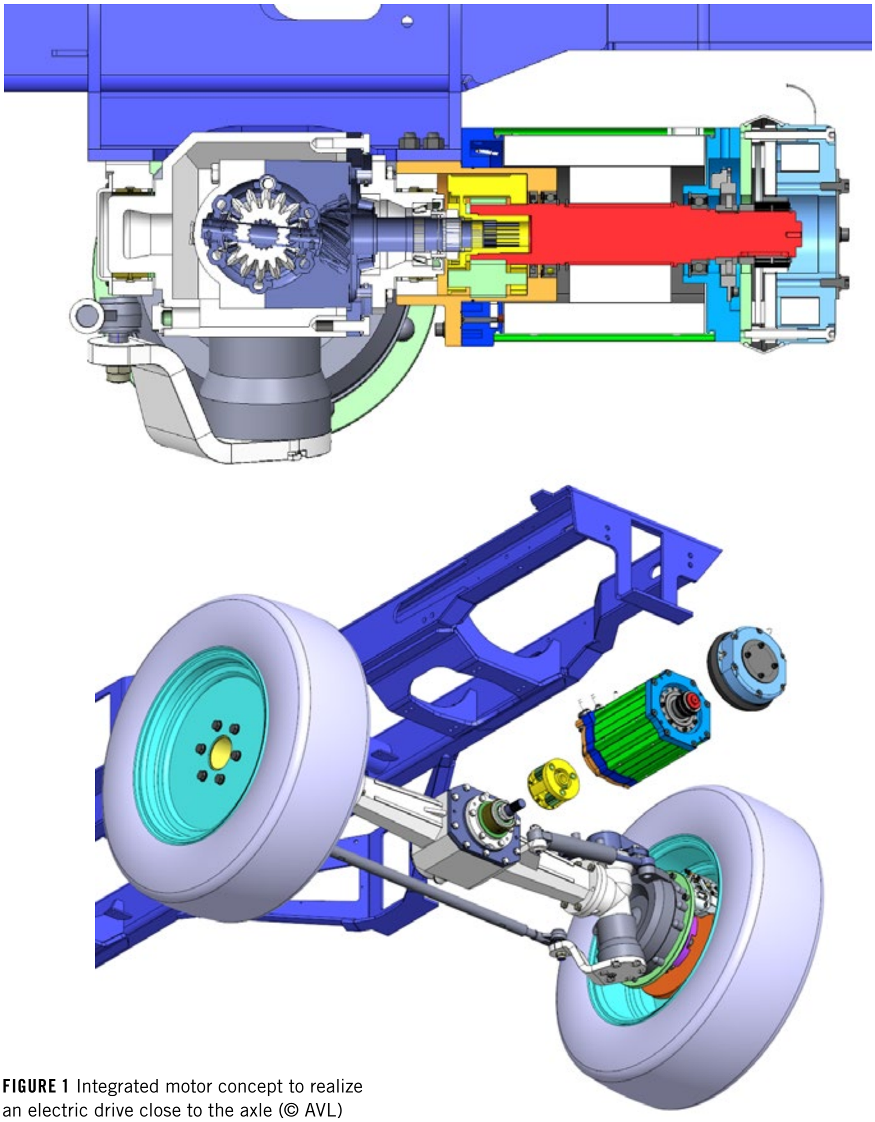

FIGURE 1 Integrated motor concept to realize an electric drive close to the axle (© AVL)

The three power modules mentioned are mounted in the main frame, which also support the respective implements and system modules. Due to the combination of the power consumers, it is possible to use this chassis as a basis to build not only a tractor but also other mobile work machines of a comparable power class. While the expensive power components such as the battery and drive units, which are used across applications, are included in the common power chassis, different systems can be combined to provide the ideal vehicle configuration for each application.

INTEGRATION OF ELECTRIC DRIVES

Looking at common prototype vehicle builds, drive units are usually realized with off-the-shelf solutions. For example, a fully self-contained and evaluated electric motor can be flanged to the rest of the powertrain. If necessary, for speed adjustment, a differential or a reduction gear can be installed between the electric motor and the transmission. By using existing functioning components, the development focus may initially be on the overall vehicle architecture. Only in the further development of a close-to-production vehicle, an additional effort for a targeted packaging is needed.

By contrast, the vehicle concept of the e-tractor is designed to integrate all functions into the given installation space of the performance chassis from the beginning. This is achieved by using fully integrated solutions, such as the traction motor, in which the active components, the stator and the rotor, are housed together with an additional planetary gear set. In addition, the housing of the electric motor includes the bearing support of the pendulum axle, supports the drive torque and realizes the mechanical connection of the complete drive unit to the vehicle frame, **FIGURE 1**. The rotor shaft of the electric motor is the sun shaft of the reduction transmission, which means an additional shaft/hub connection is not necessary. The housing of the electric motor includes the function of the internally toothed ring gear so that the output, via the planet carrier, directly drives the differential input shaft. Due to the compact design of the electric motor a standard axis can be used, especially since the connection of the electric motor can be ideally adapted to the existing axis.

In this case, a variety of details and tolerances must be considered. Electric motors are based on the principle of Lorentz force and require a magnetic flux. In order to achieve the lowest possible magnetic resistance, the air gap between rotor and stator is correspondingly small and has to be kept constant even at high rotor speeds of more than 10,000 rpm. Particular attention must be paid to the tolerance chain between the stator housing and rotor bearing. In addition, the permanent magnet synchronous motors require a rotary encoder each to keep the magnetic fields of the rotor and the stator approximately synchronous with exception of the load-dependent differential angle using the power electronics. The integration of the rotary encoder requires very low tolerance due to the required accuracy and has to be protected against external interference, both mechanical and inductive.

The cooling of the electric motor is particularly important for the power density of the drive unit. For this purpose, each electric motor has a structurally given maximum torque which can only be used for a short time and is dependent on for example, the dimensions and the materials of the active motor components. The nominal torque with which the motor can be permanently loaded is lower, depending on the engine cooling. Thus, in an air-cooled motor usually only a nominal torque of about 20 % of the maximum torque can be achieved. To achieve a higher power density, as with the e-tractor, this value can be increased to about 45 % by liquid cooling of the stator windings. This could be further optimized by cooling not only the stator windings but also the rotor and the inside of the stator. This leads to shear stresses of the cooling medium within the air gap. This can lead to losses as well as wear of the cooling medium, especially at high engine speeds.

If only the stator windings are cooled, it is possible to use a water-glycol mixture as it is realized for the cooling of the power electronics. The various temperature levels of the components has to be taken into consideration when the cooling circuit is installed, **FIGURE 2**. While the power electronics only allow a maximum coolant temperature of 70 °C, the electric motor will provide full performance up to approximately 80 °C. In order to keep the total coolant flow low, associated inverters and electric motors are connected in series. This allows the cooling medium from the cooler to lower the temperature of the power electronics and then the stator windings. The coolant pump is located in front of the filter, allowing the power electronics to be cooled at a lower input pressure to prevent damage.

Depending on the vehicle architecture, the control of the drive units varies in complexity. If, as in the e-tractor, two powered axles are used which are only coupled to each other via the ground, the control of the motors must be coordinated accordingly. It is important that a high number of inverters available on the market enable both torque and speed control. On one hand if both drive axles are controlled purely via their speed, even small deviations in the air pressure of the tires or in the ballasting of the axles can cause different rolling radii of the wheels. This results in a traction slip between the two drive axles and thus in reactive power, which has a negative effect on the system efficiency. On the other hand, if both axles are torque-controlled, it must be continuously adjusted to avoid slippage as a function of the axle load distribution and the ground conditions. The ideal system is one where a speed-controlled axle is defined as the primary axle which defines the vehicle speeds, while the secondary axle is based on the torque feedback of the primary axis and just supports the traction. This structure requires rapid communication between the inverters of the electric drive units to minimize the effect of a signal delay. Whether this can be successfully achieved in sufficient quality using conventional CAN bus networks or whether other real-time capable systems are required is yet to be proven systematically.

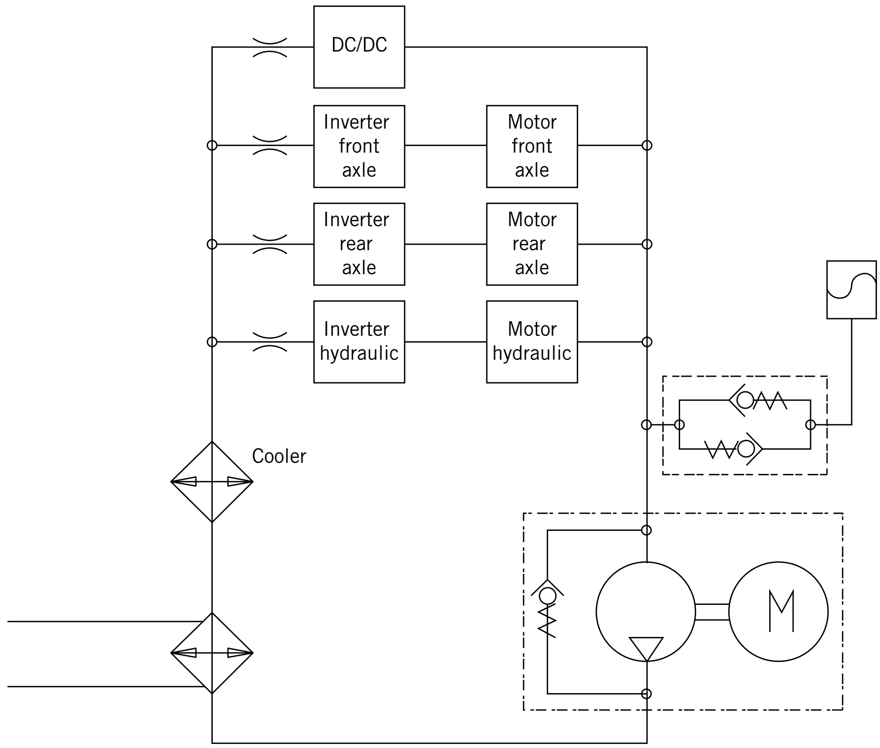

FIGURE 2 Exemplary cooling circuit of an electrically driven vehicle (© AVL)

INTEGRATION OF THE BATTERY

The battery represents the core component of a fully electric vehicle, not only because of the high cost factor. While battery failure equals total economic damage at today's price level, it also increases the likelihood of a hazardous situation especially if a battery fails during maintenance work or in the event of an accident. Safety systems such as double-sided HV relays and permanent insulation monitoring are employed. Additional sensors are used for voltage and current monitoring, **FIGURE 3**. These can be combined into one electronic unit which protects several battery modules.

In general, there are different cell types that are used for mobile applications, depending on the operating conditions and installation space. In order to use the installation space of the e-tractor optimally, and to be able to fully integrate the battery into the vehicle, round cells are used because of their shape. These nickel-manganese-cobalt-based cells provide high capacity that can only be charged with lower currents. The relatively low power output per cell is compensated by a battery capacity of sufficient size to achieve the cycle time required by the customer. In system design, the relationship between battery power and battery capacity, the so-called C-rate, is of high importance. For the e-tractor, the value of C = 0.6 due to the low current at each cell, which equates to a high capacity battery. By contrast, C-values of up to 80 are achieved with a battery from an automotive hybrid application or motorsport, where very high powers are needed at a low capacity.

For a series solution, the battery pack can be adapted to the vehicle specification via a targeted serial and parallel connection of round cells. The e-tractor has a nominal voltage of 700 V DC. For this voltage level, 191 cells are required at a nominal cell voltage of usually 3.65 V in a serial connection. This corresponds to a capacity of only 3500 Wh.

Using a total of 40 parallel systems, the target capacity of 140 kWh is achieved. Accordingly, 7640 single round cells in a 21700 format are to be accommodated and installed in the installation space to ensure both the voltage level and the cycle time of the vehicle. In the prototype stage such a high development and validation effort is often neither timely nor financially feasible. While safety electronics must be realized from the beginning, standard battery modules of lower capacity can be used for initial system designs. Even though the use of the available installation space by these modules is not comparable with packaging at cell level, the interconnection of several modules can achieve a substantial test capacity of more than 20 kWh while maintaining the voltage level of DC 700 V. Since an adequate number of modules cannot be realized in the given installation space of the e-tractor, the required voltage level is achieved by a DC/DC converter without any functional restrictions for the entire vehicle system. **FIGURE 4** shows the different packaging of a potential serial component with target capacity, **FIGURE 4** (left), and a low-cost prototype battery developed in a short period based on available modules, **FIGURE 4** (right).

CONTROL OF A HIGHLY AUTOMATED VEHICLE

The e-tractor offers additional applications not only by integrating the components in the power chassis, but also by providing a new and intelligent control. As shown in **FIGURE 1**, the operation of the vehicle from a driver's cab is still conceivable, but not mandatory. Since the power chassis includes a steer- and brake-by-wire system, it is capable of autonomy, which can optimize the work process, especially in the lower power classes up to 74 kW.

For operation in an urban environment, the highly automated e-tractor is oriented towards a guiding object or a person which is detected by camera systems. However, various tasks are performed and supervised in a highly automated and autonomous manner. For example, when mowing a slope, the telescopic arm can be equipped with additional cameras for object recognition and with position sensors for automatic tool alignment. At the same time the environment is detected using radar or ultrasonic sensors which are mounted on the vehicle to avoid danger. On highway construction sites systems are in testing to realize a convoy function as highly automated trucks follow a lead object at a constant distance.

In the future, the sensor technology installed on an e-tractor will enable autonomous operation. This technology will allow the vehicle to independently orientate itself to external influences and to complete tasks without intervention or guidance by means of objects. While such an operation still represents a safety concern in the automotive sector because of its interaction with other road users, the agricultural sector has the potential to work in closed and non-public areas with machinery capable of autonomy. The tractor can be used as a nursing or harvesting vehicle in a vineyard, where the machine is assigned a specific work process for a defined

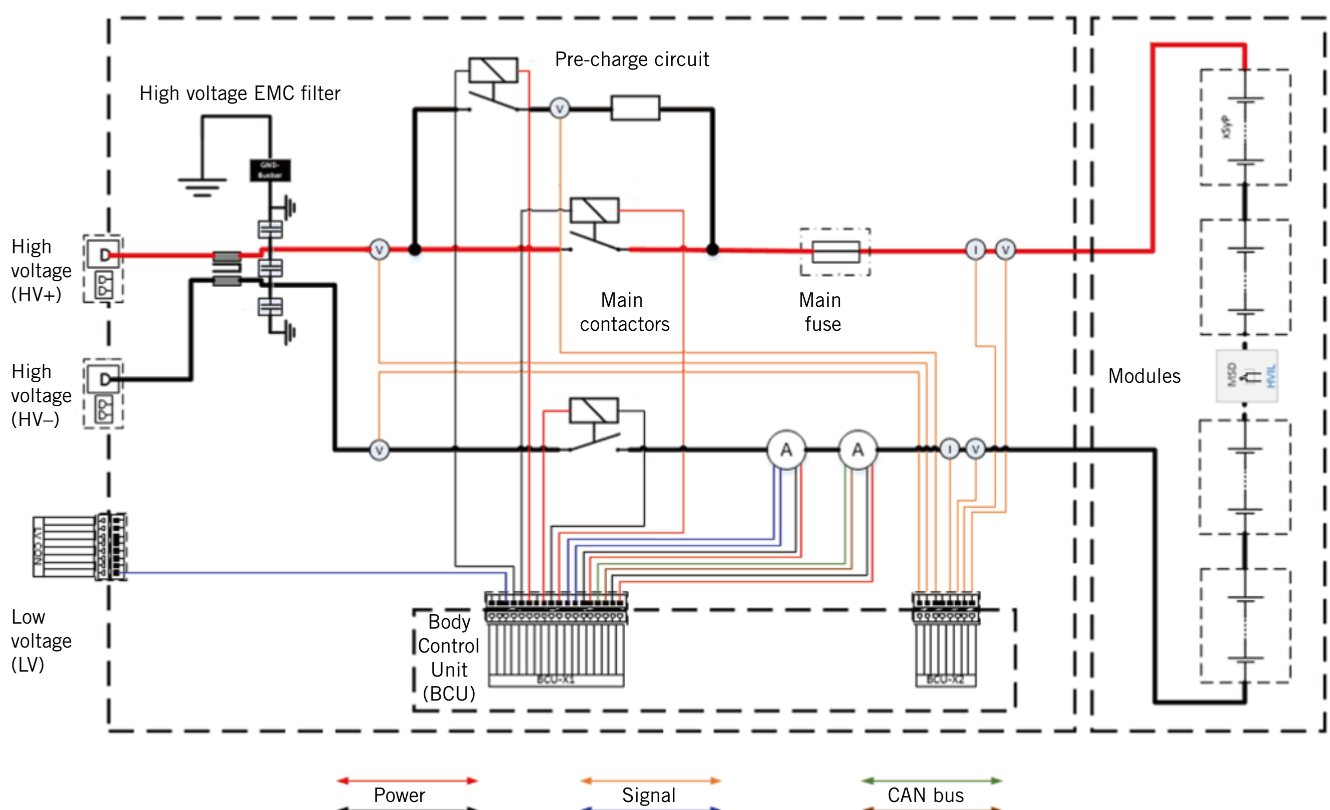

FIGURE 3 Exemplary electrical layout for high voltage vehicle batteries (© AVL)

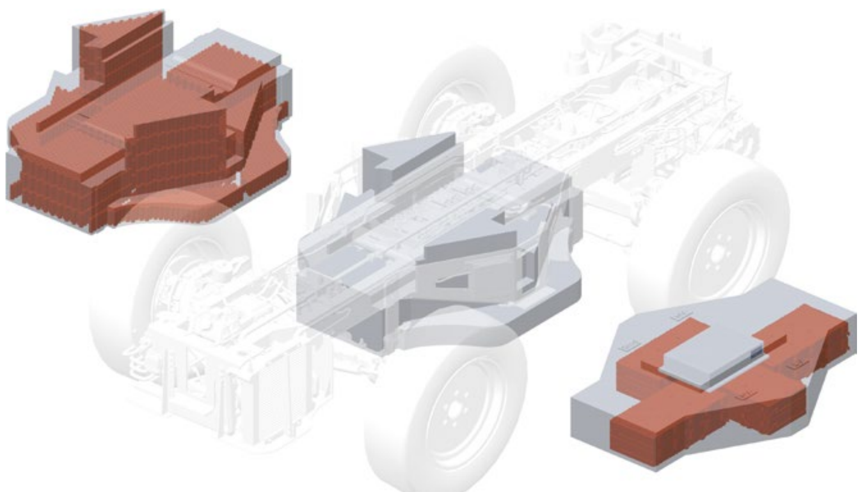

FIGURE 4 Comparison of a fully integrated serial battery (left) and a functional prototype battery (right) (© AVL)

period of time by a job computer. Real time-capable sensors, actuators and algorithms do not only enable vehicle or tool guidance, but also optimize the work process itself. For example, with the help of high-resolution cameras an optical assessment of each individual plant can be performed to optimize fertilization. In terms of swarm technology networking of such new tractors with each other and their environment is realistic. For example, on a large field, several small vehicles can perform the tasks of one large vehicle. The vehicle control integrated into the power chassis of the AVL e-tractor, which is also responsible for the coordination between the vehicle's own drives, is preceded by an additional module, which includes the sensors and communication hardware needed for autonomous operation and their control. The communication between the vehicles can be realized via the LTE network so that data from a cloud can be accessed. Work steps can be coordinated, the weather report can be taken into account or incorporate geostationary information can be respected within the work process.

SUMMARY AND OUTLOOK

For series production of battery powered vehicles, an application-specific design of the core components, especially the battery and electric motors, offers new integration capabilities through fully integrated solutions. In addition to the optimized use of installation space and the flexible power distribution of electric drives, the operation, if this is even necessary, or an intelligent control can be another unique selling point in the market keeping with the trend of transmission from the driver to the controller. Due to these new technical possibilities, work processes will change considerably in the coming years. On the basis of the e-tractor, AVL is planning to further examine the entire tractor/implement system in order to investigate possible process changes. This will identify improvements and demonstrate their constructional and control-technical influence on the actual machine as a logical consequence.