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System-wide electrification and appropriate functions of tractor and implement

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The advantages of electric drive technology in industrial applications have been known for a long time. In addition to the flexibility and variability for the system integration, the very good controllability and the overload capacity should be mentioned. To increase the effectiveness of agricultural machinery and equipment crucially, the different electrical/electronic systems, drives and functions have to be interconnected machine internally and also externally, based on a system-wide approach. Thereby single machinery, machinery combinations and finally complete harvest chains can be used in a smarter and more efficient way. Using the example of a tractor-swather combination the suitability of electric drives itself and of the hybrid and interface concept is proven. Newly developed functions for overload protection and prediction of the working process are presented and their integration into the machine overarching energy and operational management is described. The transferability of the results and solutions to cognate applications is ensured.

Keywords
Electrification, hybridization, high voltage, tractor-implement interface

"The electricity will be the moving force in the coming century [...]" – this was what the magazine DER MOTORWAGEN wrote in 1898 – looking back on vehicle development a clear misjudgement. In fact, around 1900 about 40% of all vehicles in the United States were electrically driven (Eckermann 2015). In 2009, this number was only around seven percent (US Census Bureau 2012). In Germany, in 2015, for cars this number amounts to only 0.3%, including hybrid vehicles (Kraftfahrtbundesamt 2015). Also, the idea to realize functions of agricultural machinery and equipment electrically is not new. Already in the 1950s, a tractor with side-mounted generator driven via a belt drive with a connected load of 12.5 kVA, and an appropriate baler with electric drive was promoted in a brochure (International Harvester 1957). The propagated areas of application and general advantages – mobile power source for commercially available tools, emergency generator in case of power failure and simple connection and disconnection of devices – were also valid for the electrification efforts in the recent past, described for example in (Wilmer 2007). With the wide availability of modern and efficient electronics and semiconductor devices, the technology is currently experiencing a renaissance. Complex drive solutions can be implemented and tested efficiently and accurately. The focus is on the functional advantages and potentials of interacting machine functions and operating strategies and the interaction with the environment in the context of an efficient process management.

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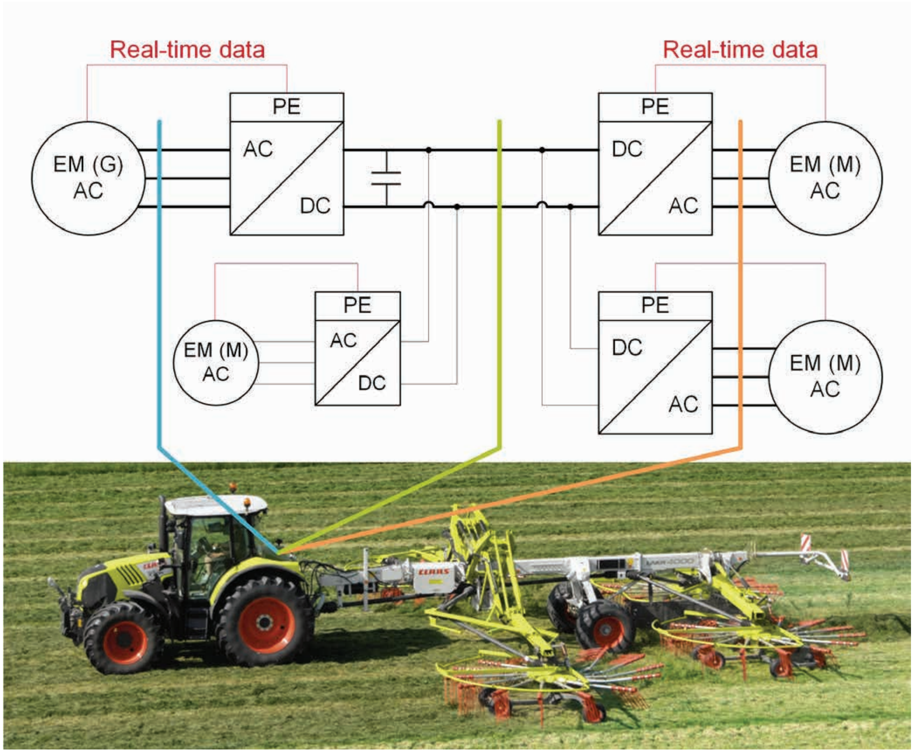
Motivation for the electrification and hybridization of a tractor-implement combination

Due to the extensive process technology present in a combine harvester, it is obvious to use such a vehicle as the basis for electrification. The machine combines many drives and process steps that need to be coordinated. For mobile machines electric drives are therefore already used. Using the vehicle system voltage (12 V) large mechanical or hydraulic services are controlled and regulated by means of adjusting motors for variators and hydrostats within certain limits. The use of big electrical power will be a next step. However, in the present study, the electrification of a self-propelled harvesting machine was still not functional. On the one hand because of the short harvest window and thus very limited testing period. Secondly, such a system – with the exception of the front-sided harvesting equipment – is fully encapsulated so that it was not possible to examine the appropriate interfaces for power and communication flows between “foreign” (multivendor) subsystems fundamentally. Considering Precision Farming, many attachments also offer a high potential for advanced, intelligent features, which could be realized with the classical concepts of power supply inadequately or at enormous expense. It is therefore expected that implements will be the first serial applications for electric drives. The tractor can be used as an adjusted and versatile, mobile energy source. This thesis was confirmed also by others (Herlitzius 2010). For these reasons, the objectives and motivations for the electrification of a tractor implement combination underlying for CLAAS can be derived:

- Representing and solving the general challenges in the development of electric vehicles and implements.
- Detailing and releasing the specific tasks and challenges of a multivendor usable (“open”) interface for power and communication, including safety concept.
- Make a long harvest season accessible as a test period for both the tractor and the implement for functional testing and proof the benefits of electric drives in the course of various boundary and ambient conditions.
- Transferability of solutions to self-propelled harvesters.
- Creation, integration and testing of networked machine functions and control strategies (machine-internal and interface across).

On this basis, the defined exemplary machine combination consists of a standard tractor Arion 650 with the consolidated own CVT EQ200 and the four-rotor swather Liner 4000. According to the definition of system boundaries and interface variables, the subprojects “Tractor” and “Swather” were edited largely independent of one another. After single commissioning and pre-testing the combination was tested in the field.



Legend:

EM Electrical machine
G Usually acting in generator mode
M Usually acting in motor mode
PE Power electronics
DC Direct current voltage
AC Alternating voltage

AC uncontrolled
DC (un-) controlled
AC controlled

Figure 1: Basic structure and potential solutions for interface of an electric drive system

Electrical architecture of the overall system

Controllable electrical drive systems always consist of power electronics (PE) for forming of the supplied energy and associated electrical machines (EM) linked to the functional device. To ensure a highly dynamic, needs-based power supply, data must be transferred in real time between PE and EM. Between the regenerative- and the motor-working parts the common DC link is formed, which may be considered as a central hub ("busbar"). The three possibilities to separate this basic structure for interfacing overarching electrification (Figure 1) have already been discussed extensively in the literature, e.g. in Lindner et al. (2011), Baldinger (2011), AGCO Fendt and John Deere (2011).

Table 1 illustrates relevant criteria for assessing the interface concepts for agricultural vehicles. It takes into account both aspects of the overall system as well as aspects to individual applications. The interface concepts are assessed on the basis of the formulated project objectives and the selected sample application. The feasibility of an open and multivendor solution is the most important goal. Depending on the framework conditions in other project considerations and objectives preferential alternative solutions are conceivable, e.g. for special applications with limited equipment variance.

Table 1: Relevant aspects as evaluation criteria of interface concepts

No	Criteria	Annotations, aspects
1	Reconfigurability of tractor equipment	Easy identification and initialization of the paired subsystems and drive units (PE/EM)
		Uncomplicated use of components from different manufacturers on both sides of the interface
		No drive calibration after coupling of tractor and mounted implement
2	Complexity of the interface	Low complexity and effort for performance and signal transmission
		Low demands on the used bus system, in particular renouncement of necessary real-time capability
3	Sustainability	Use of robust, sensorless machines with high performance and efficiency in a “open-loop” control concept in the tractor and/or implement
4	Electrification range on both sides of the interface	Possible number of independent electric drives in the subsystems
		Upgradeability of the electrical architecture of the system
		Number of required electrical sockets
5	Amortization of system costs	Reusability of system components
		Cheap system costs with an optimum specification, configuration and topology for the application
6	Using of existing systems	Further use and expand of proven and widespread systems and functions, e. g. ISOBUS drive control
		Access to existing cooling systems
7	Clear defined responsibilities	Clear separation of energy supply and process responsibility; security management
		Operating, load and energy management are optimally matched to the application
8	Potential for optimization of the overall system and the subsystems	Components are matched to the application and administration; No under- or over-specification
		Optimal coordination of LE and EM, so that “multigrade operation” and performance classes are disclaimed
		Cooling is optimally adapted to the needs

Table 2: Evaluation of the interface concepts with reference to the criteria of Table 1

	No. of the criteria							
	1	2	3	4	5	6	7	8
AC uncontrolled	-	-	o	-	-	-	o	o
DC (un-) controlled	+	+	+	+	o	o	+	+
AC controlled	-	-	o	-	+	o	-	-

- = poorly fulfilled
o = average fulfilled
+ = well fulfilled

The transfer of an unregulated AC voltage is not meaningful because of poor possibilities of amortization of the system costs. It is even more important that protective and isolating devices must be kept, as is known from the prior art for electrical high-voltage systems, e. g. ISO6469-3 (DIN 2011) and ISO/FDIS 16230-1 (DIN 2015). The initial effort regarding energy supply is therefore in any case high, so it should be possible to implement the tractor internal electrification. According to Table 2, the DC power transmission proves to be the most appropriate interface solution. Especially in light of the stronger weighting aspects of interchangeability and arbitrary combinability of tractor and implement (and thus of the installed components and their numbers) over a wide performance and operating range, this type of power transmission without demands on frequency and amplitude is advantageous. With reference to this principal claim and the necessary number of drives for the four-rotor swather, the DC transmission was called advantageous also from the published study by Geissler and Herlitzius (2014). The commissioning of the drive units is carried out once, by the tractor or implement manufacturer. They will not be separated during their lifetime, so no unknown pairings may arise. Elaborate identifications by transfer of all machine and inverter parameters via the interface are omitted. Also, a teach-in of drives with single-turn encoder or without encoder for determining the initial rotor position and the model of the motor inductances by the end user is not necessary. Apart from the time and the potential dangers of runaway of the drive, such an operation in systems with transfer of a regulated AC voltage is only possible with newest and therefore expensive technology, provided that the application allows only one direction of rotation. However, when using classic hardware both directions of rotation must always be driven. When the component costs for the optimal design of the drives with separate subsystems in the common DC link fall as predicted (Breu 2014), the first obvious cost advantage of an AC system will be lost even in systems with few drives prospective.

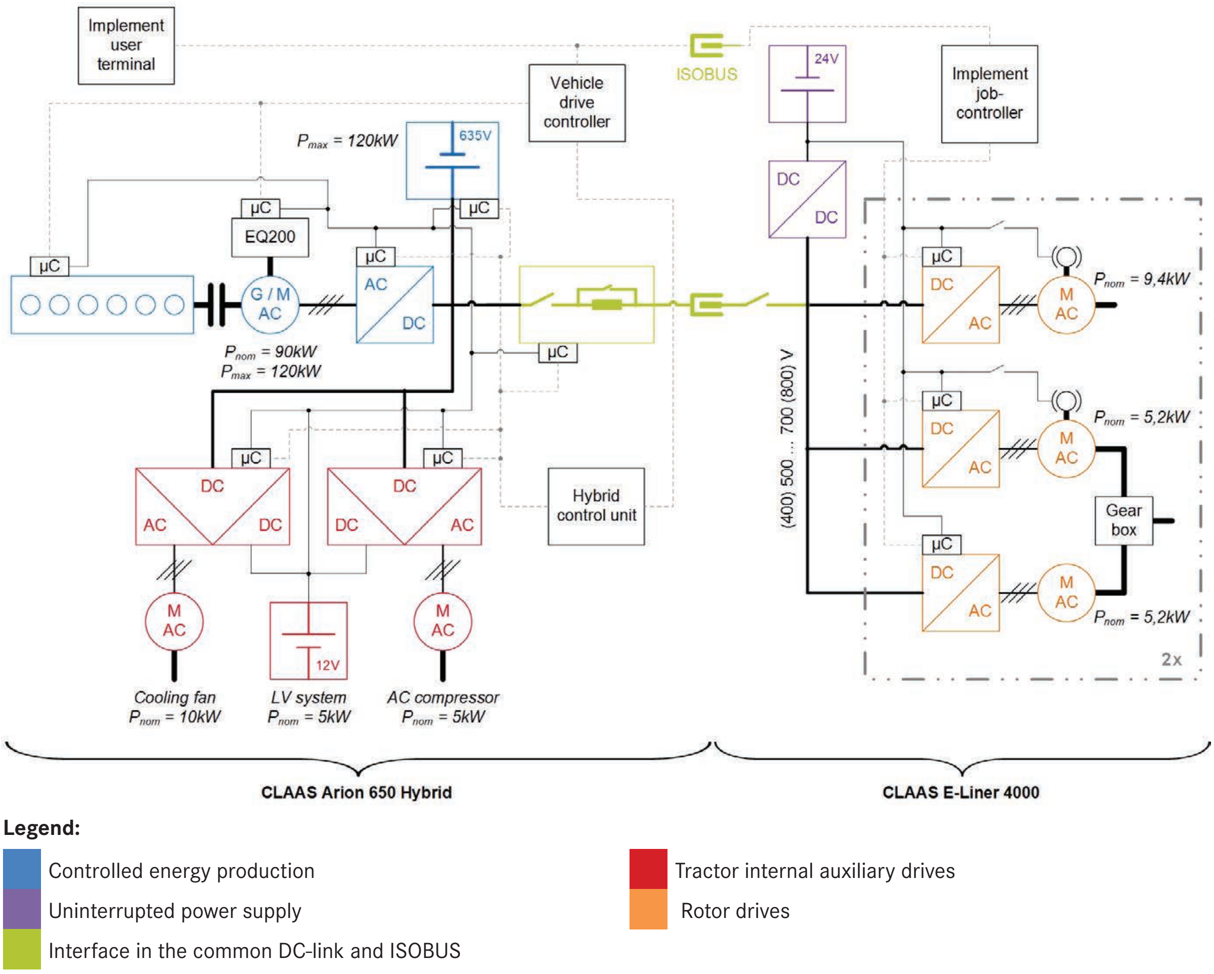


Figure 2: Block diagram of the total architecture of the electric system of the functional models

The consideration set out formed the basis of decision to draw up the overall system architecture of the prototypes. Figure 2 shows this as a block diagram and renames the performance data. Furthermore, the electric high-voltage system, the 12/24V control voltage supply and the communication networks are outlined. Not shown is the implemented 12V safety loop "HVIL" (High Voltage Interlock Loop) for basic coverage and system release. The bus communication between the tractor and implement is realized alone via the known ISOBUS.

Structure and function of the hybrid tractor

The electrified tractor based on the CLAAS Arion 650 is equipped with a crankshaft starter generator (permanently excited synchronous machine, PSM) between the diesel engine and continuously variable transmission. A high-voltage battery with 635 V rated voltage and a total capacity of 5.75 kWh (100 % SOC (state of charge)) is connected directly to the DC intermediate circuit and protected by separating contactors in the HV lines. The diesel engine can be uncoupled at the input side of the generator from the drive train, thus the vehicle is an extended parallel hybrid. Motor fan and air conditioning can be operated as exemplary chosen electrified auxiliary drives out of dual inverters (Figure 2). The 12V electrical system is fed by parallel connection of the two integrated DC/DC converters each with 200 A output current, whereby the availability is increased in the event of a defect. The high-voltage components are from companies of the Magna Group, which accompanied the installation and commissioning of the tractor with engineering services, too.

The components are integrated into the tractor architecture (Figure 3). Only the cooling for PE, EM and the HV battery are installed on the vehicle roof. The system is an IT network with single-failure tolerance in accordance with the design guidelines of DIN VDE 0100-410: 2007-0 (DIN 2007). All cables carrying voltages above the safety extra-low voltage are marked orange in accordance with the general guidelines and difficult to access for the user. Covers and housings are included in the inner-vehicle safety loop HVIL, which shuts down the system power in cases of interruption. To the socket of the implement a second HVIL is provided. When the high-voltage system is active, the in-

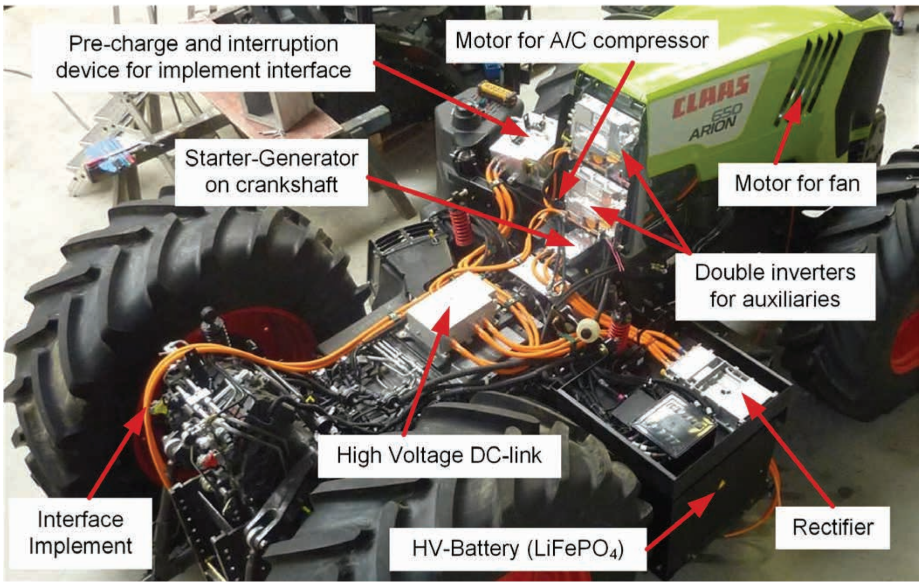


Figure 3: High Voltage system in the CLAAS Arion 650 Hybrid (cooling not shown)

sulation resistance against the vehicle chassis is permanently monitored, an attached implement is included therein. Appropriate fault reactions are triggered if the actual value becomes lower than the permissible limits noted in ISO 6469-3 (DIN 2011).

The shown structure as a parallel hybrid ensure complete electric, hybrid, and conventional operation of the drive train, the hydraulic facilities and of course the electrical consumers. In particular, the following hybrid functions are implemented (Heymann 2015):

- Electric boosting and recuperation
- Start/stop of the diesel engine at standstill and while driving
- Pure electrical operation with or without an electric implement

The boost function rather serves to shift the operating point and phlegmatization of the diesel engine than to increase the overall performance (Figure 8). Different from a conventional tractor, the torque can be increased to the shaft as a load increase occurs, without relieving the powertrain by adjusting the gear ratio before. Instead, the transmission ratio remains constant and the tractor does not lose speed. Thus, the resetting of the working point of the diesel engine can be done under the maximum load because the internal combustion engine is relieved by the generator that is fed from the battery.

The hardware for a start/stop function is directly included in the system. On the software side the function has been implemented in the prototype control unit to identify and examine hybridization potential, e. g. in the context of an air conditioning in standstill, an electrical shunting or suitable driving situations. Depending on the system and operational conditions of the tractor (e. g. total load in the drive train and the vehicle speed) and the electrical system (e. g. state of charge of the HV battery, current consumption of the electrical loads), the diesel engine is automatically switched off. When the vehicle is stationary, the idle speed of the transmission input shaft through the generator is set up to about 600 rpm, to receive the hydraulic pressure. When re-coupling the diesel engine, the rotational speeds of the internal combustion engine and generator are synchronized to protect the clutch against damage. The motor is therefore not dragged during start/stop, but started using the conventional starter by supercapacitors. Of course, the start/stop function can be deactivated by the driver at any time.

For temporary purely electrical operation of a tractor different applications are possible: In farmyard work, for example, for zero-emission driving through the barn, or in field operations during set-up times, such as the setting and preparation of implements. In fact, a purely electric usage of the swather over several hundred meters is possible (Figure 4). During this shown experiment the speed has increased simultaneously.

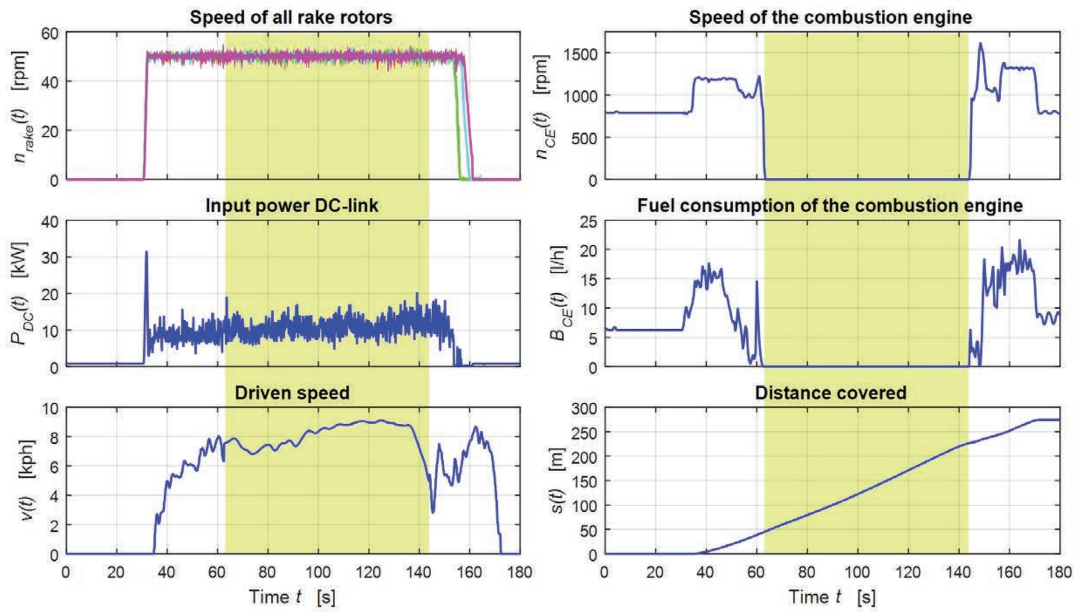


Figure 4: Emission-free use of the swather (green indication) in the used SOC region (25 %)

Structure and function of the four-rotor swather

The mechanical drive train for the rotors of the swather has been completely replaced by a variable drive system according to the patent suggestion in Claas (2010). All other systems are adopted as it stands in the standard machine. The electrification was carried out exclusively with standard air-cooled components. The permanent-magnet synchronous machines with resolver are flanged directly onto the specially developed swath gearbox. The gearbox is identical on all rotors. As it is shown in the block diagram (Figure 2) and Figure 5, on each outer rotors one machine and on the inner rotors two smaller units are installed. In addition to an optimal use of space, thereby a test environment

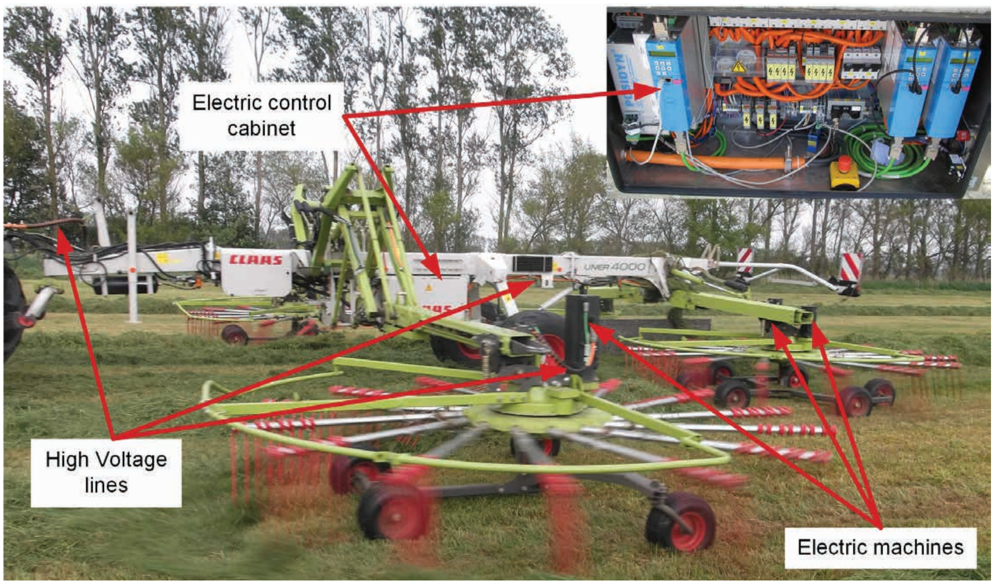


Figure 5: Function model CLAAS E-Liner 4000

for testing mechanically coupled drives was created, how they can be useful in other machines. This double drive operates on a real-time coupling (EtherCAT) on the master-slave principle with variable-speed routing guiding machine and torque follower. The logic is such that in case of failure of the master, the slave automatically switches to speed control, thus the availability of the working device is increased.

From the block diagram (Figure 2) it is seen that the drives are supplied from an uninterruptible power supply (UPS) with control voltage. The voltage level of 24 V is chosen according to the system components used. First, the drives are supplied out of the UPS after shutting down the HV system for a certain time with control voltage. Therewith the already existing choppers and brake resistors are used for an active discharge function of the DC link, as is generally required in the prior art (e. g. ISO 6469-3). Furthermore, it provides a service facility for releasing the holding brake of the rotors for maintenance by means of a switch. The holding brakes meet the requirements of the Machinery Directive (Directive 2006/42 / EC (EU 2006)), Annex 1, point 1.3.9: "It has to be prevented that a stopped part or device of the machinery moved from its rest position without acting at the actuator component. As "interchangeable towed machinery" that extends the function of the drawing vehicle, the swather is proper in the scope of the so-called Tractor Directive, Directive 2003/37/EC (EU 2003). Since the risk of uncontrolled movements of standstill machine parts is currently not covered by Directive 2003/37/EC, the Machinery Directive 2006/42/EC is valid (recitals point (8) in Directive 2006/42/EC).

In fact, the holding brakes increase security during maintenance work in the HV cabinet because turning any rotor (voltage induction by PSM) is only possible in combination with pressing the service button. Comparable to the tractor, the high-voltage connectors and the doors of the cabinet are included in the interlock loop HVIL. The latter can be bypassed for diagnostic work using a key switch. Also all high-voltage lines are sheathed and marked in orange color. Particularly in the area of the articulations of the booms they are equipped and secured with additional strain relief devices. However, the cables on the implement – in disparity to the tractor – cannot completely be sealed off because of the supply line to the electrical socket. Therefore the implement should only be used with a tractor or PTO generator with insulation monitoring device according to ISO/FDIS 16230-1 (DIN 2015).

Integration of the implement in the operating and energy management of the tractor

As the block diagram shows in Figure 2, the tractor cannot individually limit the current in the HV line to the implement interface. Only a precharge unit, current measurement and the main contactors as basic protection are installed. Considering developments to series application of electric drives, this simplification is advantageous. With the realized interface and communication concept by Tetzlaff (2014) in addition to the uncomplicated system handshake, a dynamically acting overload protection can be easily implemented. The load monitoring and, if necessary, the power limitation is based on a signal with regard to the tolerable nominal load current on tractor side and the coded load management on implement side (Figure 6). The implement control unit sets this power value by using information about the current drive capacity/operating grade and setpoint changes to feedforward for best drive performance. Figure 7 illustrates the initial situation and the approach of this load management for the swather: For an optimum process performance within the available total power the underutilized drive makes its reserve available at the higher-loaded drive, thus sufficient reserves are available at all rotors even under special conditions and power restrictions. Because the control unit of the implement knows the work process and the current system state best, this solution is very advantageous from application perspective. The strict separation between energy management (tractor) and process-load management (swather) is also beneficial for reasons of functional safety and producer responsibility. The areas of responsibility defined in this way can be maintained under all circumstances, because the tractor can switch off the socket in any case of disregard of the load requirements and will protect themselves (main contactors in the HV-lines). Conversely, the swather will open its main contactors in the HV-lines self-dependent for basic coverage, if necessary.

As a counterpart to the overload protection the rake can send requirements about the expected power consumption and time response to the tractor (Figure 6). Accordingly, this adapts its internal operation and energy management for effective power supply whenever possible. For instance, such prediction of the expected load can be part of a headland management. An integration of these information flows in further TIM strategies (Tractor Implement Management) is another way to optimize the system load and to relieve the operator at the best possible rate, especially taking into account the driving speed.

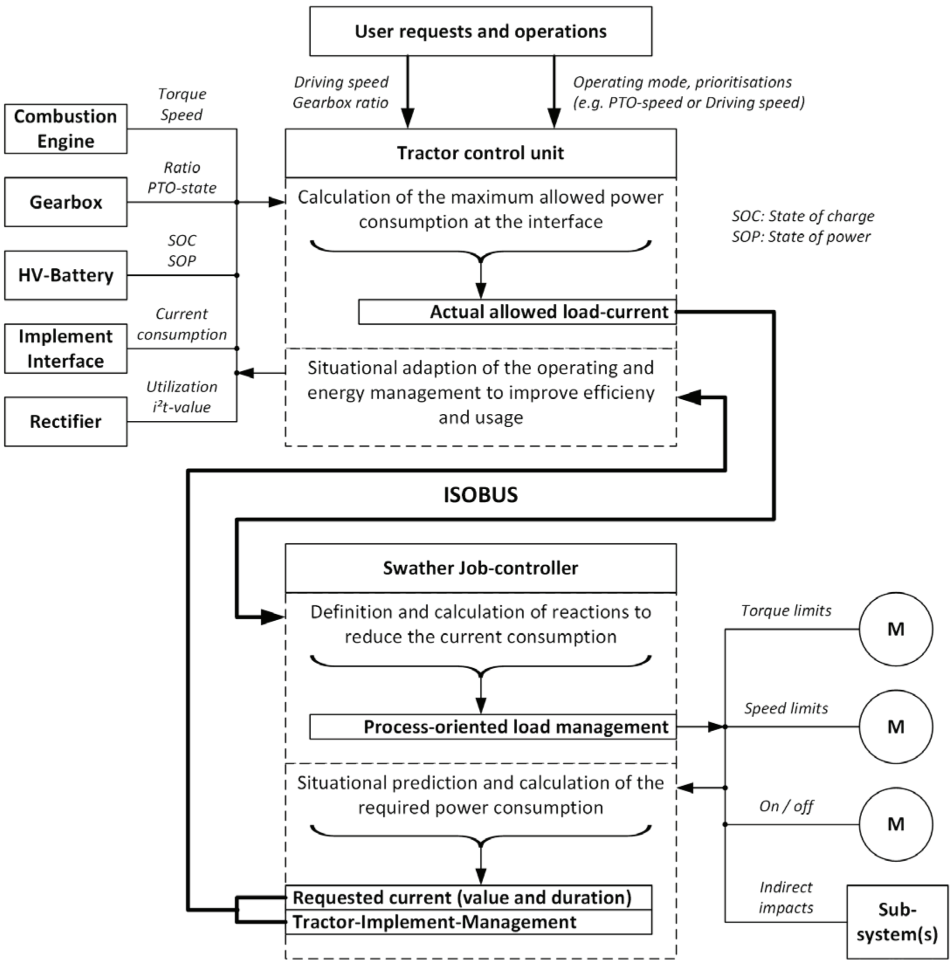


Figure 6: System-wide approach for load limitation and load prediction

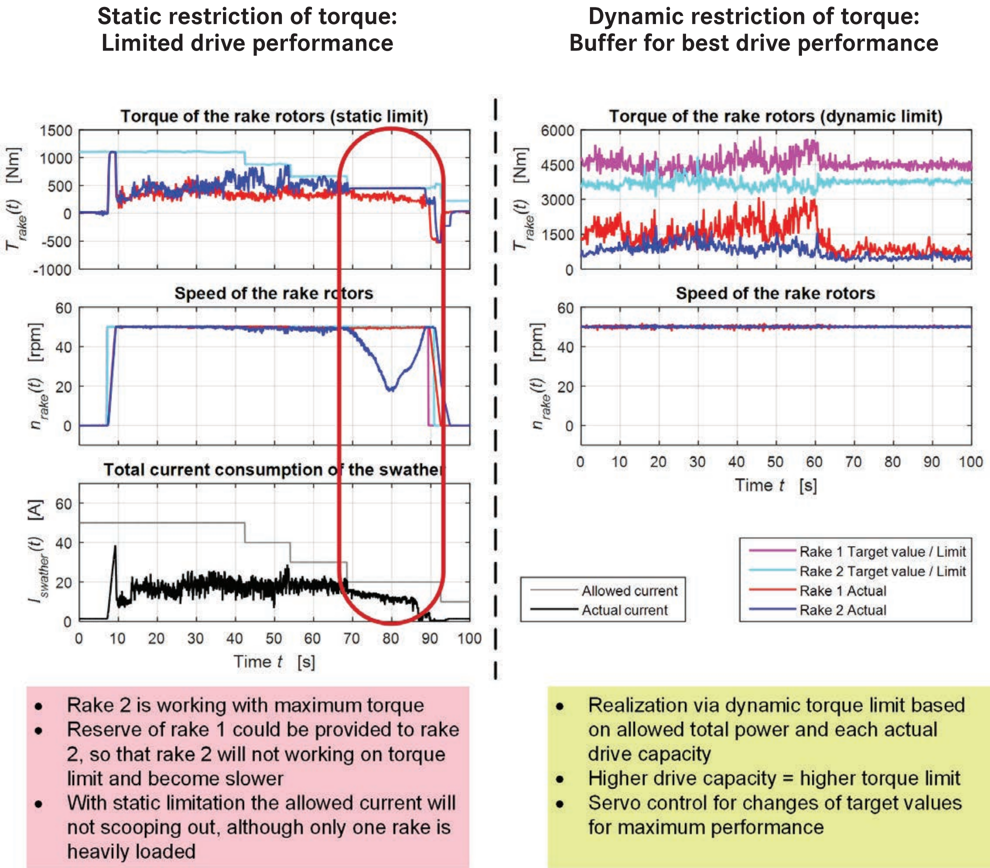


Figure 7: Explanation of the dynamic load management using the example of two rotors of the swather

The signal flows for load limiting and prediction of the load described before are executed cyclically or on request. Due to the overload capability of electrical systems no real-time data transfer is required, the use of the established and proven ISOBUS is sufficient. During the system initialization and comparison of the performance requirements of tractor and implement a basic coverage against peak currents is always done.

The described solutions for the overload protection and prediction of the load are universal. For example the increasing power demand over time during pressing a round bale is predictable, too. Together with the proposals for a three-step system identification, initialization and failure monitoring using the ISOBUS (Tetzlaff 2014), the approaches became an important basis for the current discussions about multivendor systems and a suitable interface specification in the project group 7 “High Voltage” of the AEF (Agricultural Industry Electronics Foundation). The proposed functional models currently use proprietary signals and messages.

Further results of the testing in the field

Upon the initial operation of the electric swather in 2013 and the hybrid tractor one year later, extensive functional tests were performed. The swather was used both with a PTO generator as well as the hybrid tractor. Thus, interdependencies during the development process could be resolved, if necessary. On the other hand, there was the opportunity to test the interface concept with two system configurations. The swather can be operated without modifications with both energy sources, only the software supplied functions (prediction of load, TIM) are restricted when using the PTO generator. Because the load management is fully implemented and running on the implement, this function is always available and thus an important advantage of electric drive technology.

The previous tests were done under various environmental conditions. In addition to function tests continuous operations were performed. Even at high outside temperatures, the systems and components worked smoothly, despite the industrial components primarily used in the swather. Due to the automatic switch-off of the rotors energy savings of approximately 8 % (length of the swath 200 meters, turn time 20 s) can be obtained in the headland depending on the position of the booms. Of course, the saving increases in short fields and high turning proportions. Since the excavation of the booms is performed sequentially or at least staggered, the accumulating braking energy is made available to the other rotors via the common DC bus. Even when using the PTO generator (without a high-voltage battery) no power is revoked out of the system, with the exception of losses.

Another project goal – besides the general system and function testing – is to study the particularities of a hybridization. An energy storage in the tractor has two essential advantages for the development process (Figure 8):

- Presence of a test environment for the design, optimization and control of unbuffered DC links by “freezing” of the SOC (state of charge).
- Application-specific hybridization potential and appropriate energy and operating strategies can be identified and tested.

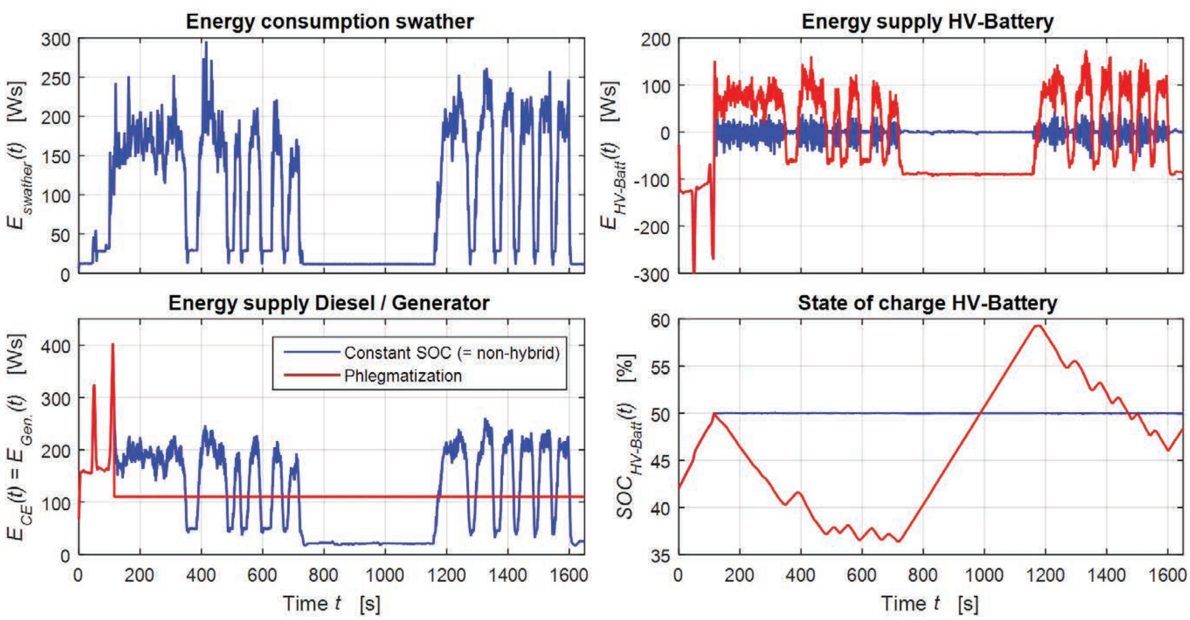


Figure 8: Operating of the tractor with fixed SOC and hybrid strategy derived from that

Initially the blue curves in Figure 8 show an operation with fixed battery SOC. After the initial charge to a target value that is kept constant during the following working process, this means that the battery current is switched to zero. So the behavior corresponds to a non-hybrid vehicle. It can be seen from the figure that strong load fluctuations are present, battery currents remain. This energy flows represent application-specific information for the design and interpretation of the DC link or its control for an electrified tractor without high-voltage storage device. For stable driving behaviour of a non-hybrid vehicle these amounts of energy need to be provided directly by the DC link.

For the same duty cycle, the red curves illustrate the targeted use of the HV battery for shifting the operating point and desensitization of the diesel engine. For a stationary operation of the diesel engine with constant output power and usage of the HV battery in an uncritical SOC range operating parameters for the swath process and the real built-up system can be determined. The load characteristics are primarily caused by the work process and provided by the battery as an offset to the base load of the diesel engine. In the headland and during a field change, the battery is charged and discharged at all other times. The range around 600 s illustrates, that the headland times are sufficient to keep the state of charge on a quasi-stationary level. Such kind of analysis provides the opportunity to develop various hybrid and operational strategies both for the single machine and the tractor-implement combination, depending on certain constraints and preferences to field and crop.

Conclusions

The electrified functional models are constructed according to the state of the art and have proven their ability to function in field tests. As shown in this work, both the swather and tractor electrification provide benefits. However, the interface overarching approach is of particular importance. The DC voltage interface provides advantages over AC transmission, due to – among other factors – the clear allocation of responsibilities for energy management and process oriented load management. Communication is carried out by the known ISOBUS. Strategies are specifically developed for protecting electrified agricultural vehicles against overloads and prediction of load. These strategies are implemented and tested, and have also become the subject of discussion of the standardization efforts of the AEF. By hybridizing the operational and functional strategies can be significantly expanded. Furthermore, non-hybrid systems are purposefully developed.

In present investigations, the system efficiency of the swather is compared with the conventional design of a comparable machine. The first results show, as expected, a higher system input power, but at a considerably increased utility, increased ease of use and enormous automation and networking potentials inside the single machine and in the machine composite. These are expanded and tested in the course of further investigations for the hybrid and tractor-implement management.

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