EXPERIMENTAL TEST RESULTS OF TANGENTIAL THRESHING CYLINDER WITH FUNCTIONALLY INTEGRATED ELECTRIC DRIVE IN COMBINES

M.Sc. Aumer, W.
Faculty of Mechanical Science and Engineering – Dresden University of Technology, Germany
wolfgang.aumer@tu-dresden.de

Abstract: *Research on electrical drives in agricultural machines rose in the last 20 years and is still continuing. Electric drives have the potential of better controllability and higher degree of efficiency compared to hydraulic and mechanical drives. However, power density is a disadvantage and needs to be compensated with additional functionality and higher reliability in the systems approach seeking for an overall advantage compared to current drive trains for propulsion and functional elements of mobile machines. Electric drives allow a high degree of integrating of the drive into a functional element, which would allow freeing up space needed for the combine working channel. At the chair of Agricultural Systems and Technology was developed an electric drive integrated in a tangential threshing cylinder as an example of an alternative drive solution for future combines. Following, tests with grain in the laboratory under field conditions were completed.*

Keywords: ELECTRIC DRIVE; INTEGRATED ELECTRIC DRIVE; COMBINE; AGRICULTURAL MACHINE; EXPERIMENTAL TESTS; COMPARISON OF DRIVE TRAINS

1. Introduction

The productivity improvements in combines are characterised by the increase of maximum feedrate at given quality parameters as well as functional improvements in order to decrease specific power requirements. The engine power has been growing in average by 3 % per year for the last decade [1]. Fig. 1 shows the trends of the increase of engine power in self-propelled harvesting machines. The performance of straw walker combines rose annually on average 5 kW. For the rotor combines, which have higher power consumption than walker combines, the power enhancement is more than 8 kW per year.

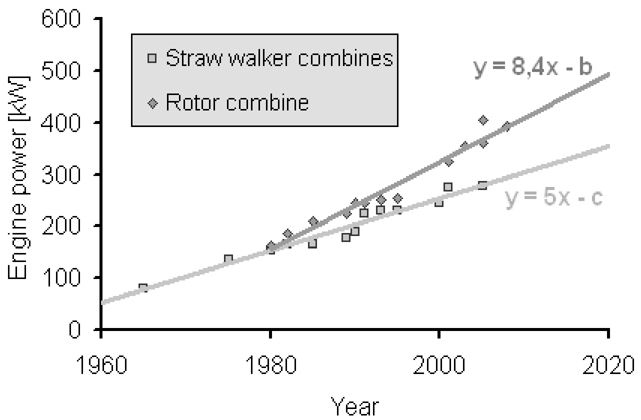

Fig. 1: *Development of power requirements for self-propelled harvesters*

Combines for the harvest of various crops have currently 150 to 470 kW engine power. Accommodation of machine components within the legal restricted envelope starts to become the biggest challenge for development of combines with continuously increased productivity. The drive trains of combines are complex.

A lot of space is needed for the transfer of the power for the various drives. Besides hydraulic components the main power distribution is realised by shafts, gear boxes, belts and chains. Depending on the power demand, component location or speed variability, machines are equipped with mechanical or hydraulic drive systems to distribute power. Mechanical and hydraulic drives are currently used to supply high-power consumers with power. Hydraulic drives are used for high power applications in traction drives and for medium power applications in decentralised systems. Actuators and low-power consumers are driven by 12 V DC drives. Due to the large number of drives, numerous transmission elements are needed which results in a complex drive train. Electrical drives offer an alternative. The number of transmission elements, which can be a measure of the complexity in harvesting machines, can be reduced by 60 % by using electrical drive technology [2]. Additional advantages are higher efficiency and better controllability. The electrical drives enable new management strategies. With the available information, such as torque and speed, the power flow within the drive train can be monitored and controlled. Individual and continuous speed and torque settings enable a flexible dimensioning of the drive units [3, 4, 5].

2. Function- and System Integration of Electrical Drives

The three main power consumers in a combine are ground drive, separator and straw chopper. A group of functional elements is needed for the separation. The power for the threshing cylinder, as shown in Fig. 2, is transferred from power take off, through countershaft, variator for the speed adjustment and a gearbox to the cylinder.

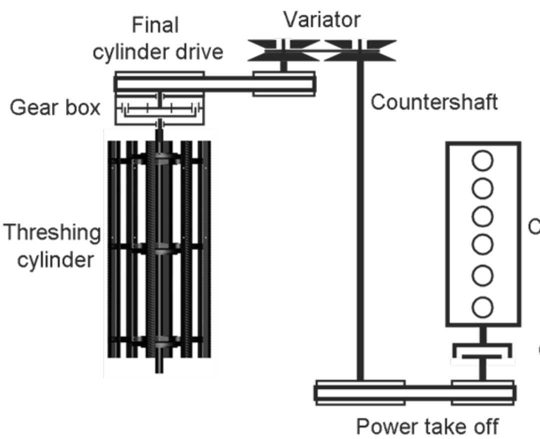

Fig. 2: *Drive train threshing cylinder*

A high number of rotating parts accumulates a considerable moment of inertia and losses. The transmission elements require space and weight. Requirements for future drive train systems can be addressed with electric drive systems. Productivity improvements for drives focus on:

- Overall increase of efficiency, reduction of losses at low speed.
- Reduction of weight to manage legal restriction, cost and soil compaction.
- Improved manufacturability by modular and simple design.
- Compactness and functional integration to save space.

Power electronics enable local intelligence allowing decentralized drives to have a specific and independent control. Electric drives enable new strategies of drive train management. With the available information, such as torque and speed, the power flow in the drive train can be monitored and controlled. Individual and continuous speed and torque controllability allow maximum flexibility of function and design of driving elements. A threshing cylinder with integrated electric direct drive was developed in a feasibility study in cooperation with the University of Applied Sciences Dresden. Fig. 3 shows the electrical drive train for the threshing cylinder of a combine.

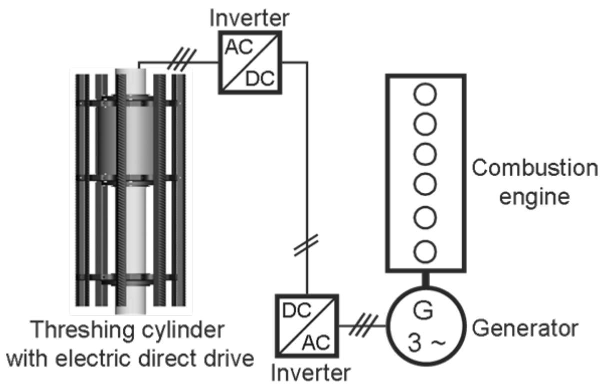

Fig. 3: *Integrated direct drive for the threshing cylinder*

The electric drive train for the threshing cylinder provides a better utilization of space needed for power transfer and speed adjustment. The generator is connected directly with the engine. The generated electrical energy is controlled by the inverter with DC circuit and transferred to the electric direct drive of the threshing cylinder. A capacitor located in the DC circuit absorbs short term load peaks. In later application electric motor and the inverter can be packaged within the threshing cylinder or separately installed [6].

3. Electrical Direct Drive for the Threshing Cylinder

The used motor is an individually designed and manufactured permanently synchronous motor with outer rotor. Synchronous motors are rotating field motors where the rotating field of stator and rotor rotates synchronously. A rotating field is generated by the spatial configuration of the stator coils and the timing of the input current. Compared to asynchronous motors, permanently synchronous motors have reduced mass and better efficiency. The synchronous motor has a smaller run-up time at no load due to the maximum motor torque and low inertia. A low inertia effects specifically in relation to the dynamics, but also has disadvantages at large external load torque peaks. The threshing cylinder with integrated permanently synchronous motor is shown in Fig. 4 as cut-away model and at the test bench.

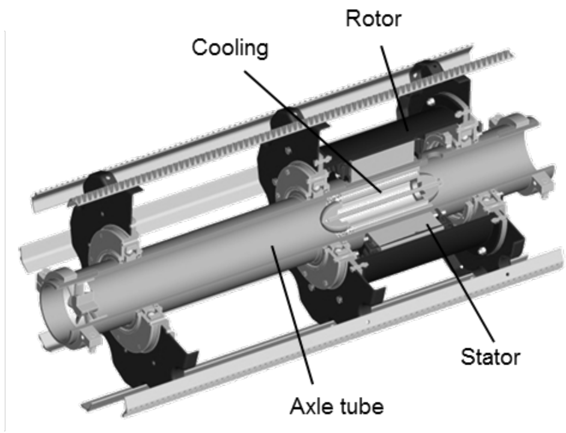

Fig. 4: *Direct driven threshing cylinder with permanently synchronous motor*

The external rotor transmits the torque and carries the rasp bars. Heat rejection is executed by an air stream going through the stator axle tube. The stator of the electric drive consists of the lamination stack and the stator winding. The rotor has the outer ring and the permanent magnets. The used permanent magnets are rare-earth material neodymium iron boron. These magnets provide excellent magnetic properties and can develop higher torque as ferrite magnets.

A constant torque is available up to the rated speed. The torque of the electric motor can rise up to multiples of his rated torque in short term. In Table 1 the characteristics of the direct drive of the threshing cylinder are described.

Table 1: *Characteristics of the permanently synchronous motor for the threshing cylinder*

Nominal power [kW]	62.5	Speed range [min^{-1}]	-1500–1500
Nominal speed [min^{-1}]	1000	Maximum speed [min^{-1}]	1500
Nominal torque [Nm]	597	Maximum torque [Nm]	1300
Open circuit voltage [V]	233	Frequency at nominal speed [Hz]	200
Nominal current [A]	108	Pole count [-]	24
Slots [-]	27	Weight [kg]	305

Investigations with a load motor were carried out to determine the speed stiffness and thermal behaviour of the threshing cylinder. Fig. 5 shows the characteristics of the electric direct drive for the threshing cylinder.

The torque-speed characteristic shows the nominal and maximum torque at the speed range. The speed is adjustable continuously and reversible from 0 – 1500 rpm for the settings of various crops. The permanently synchronous motor provides a constant torque up to its rated speed. The speed increase in the field-weakening range occurs by degradation of the stator current, which corresponds to a decrease in torque. In the short term range an overload is possible up to twice its rated torque, depends on the motor thermal behaviour. The characteristic of a permanently synchronous motor at constant frequency is the same characteristic without inverter at nominal speed. The speed of the motor is set by changing the frequency of the current. It is characteristically for electric drives that speed can be controlled independent from load, which is an advantage for the performance of the functional elements of a combine.

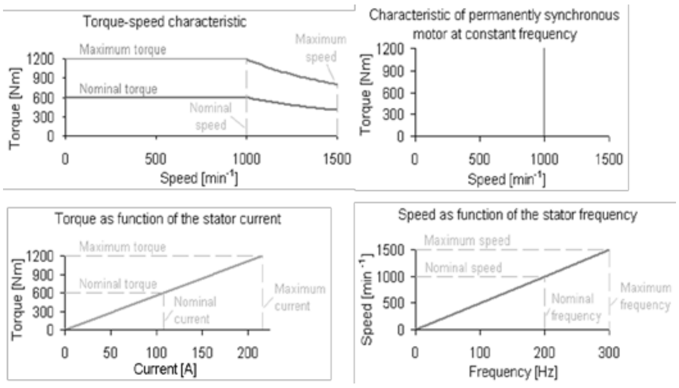

Fig. 5: *Characteristics of the electric motor for the threshing cylinder*

Frequency is proportional to speed and current of the motor is proportional to torque. With correlation and the available information such as torque and speed, the power flow within the drive train can be very precisely monitored and controlled.

4. Experiment at the Test Bench

For evaluation of the electric motor's characteristics parameters, the threshing cylinder was operated with nominal load at the test bench [7]. The load motor was directly coupled with the threshing cylinder via chain. Fig. 6 shows the setup of the test bench.

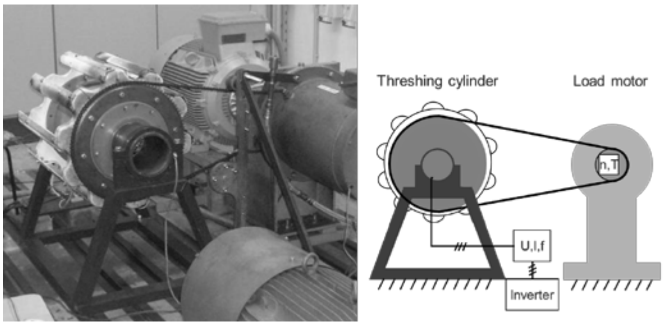

Fig. 6: *Setup of the test bench for the electric driven threshing cylinder*

The threshing cylinder runs in speed-controlled mode and the torque is set by the load motor. The heat loss of the electric motor is discharged in the axle tube. The electric motor windings temperature profiles are shown in Fig. 7.

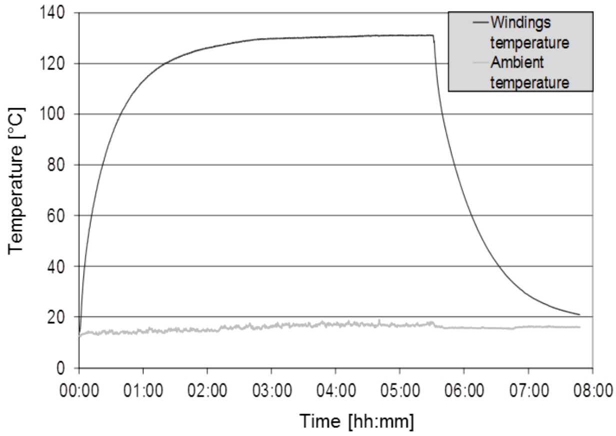

Fig. 7: *Temperature of the electric drive and the threshing cylinder in sectional view*

The steady state temperature of 130 °C is reached after a time of 5 hours. For cooling medium, the ambient air was used at 16 to 18 ° C. The difference of the temperatures is 112 K. The ambient air was used as cooling medium with a temperature of 16 to 18 ° C which leads to a temperature difference of 112 K.

5. Laboratory Tests

For laboratory tests the threshing cylinder with the electric drive was implemented in a conventional threshing system, see Fig. 8.

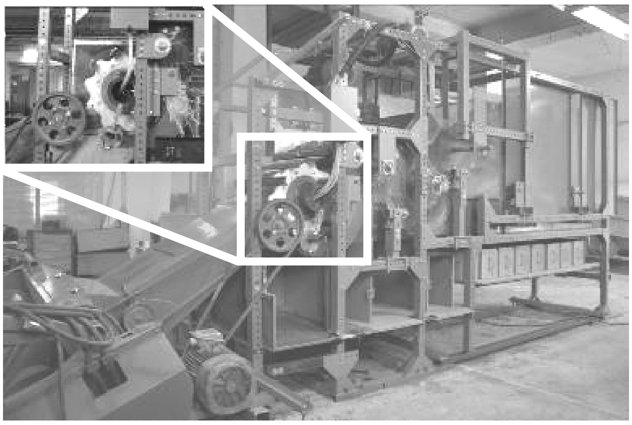

Fig. 8: *Electric driven threshing cylinder at the laboratory tests*

Due to the fact, it was stationary tests, real-life conditions were replaced (stand density of grain, driving speed) and the crop fed in defined amounts. Thus, the load conditions at various crops fed throughput could be determined. Fig. 9 and Fig. 10 shows the speed, torque and power curve of the threshing cylinder for a lab test. At the test time of 3 s the threshing drum is fed with a feedrate of 25 t/h, based on realistic field conditions. The drive system controls the torque very quickly in order to maintain the speed at the target rotational speed of 850 min^{-1}. The performance curve is similar to the torque due to the rapid speed control.

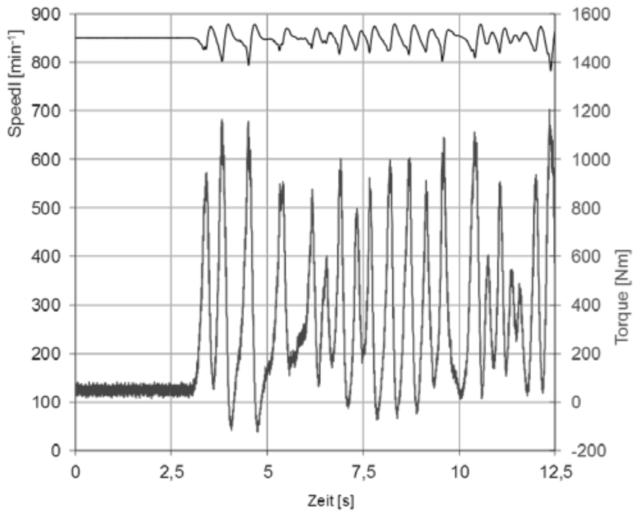

Fig. 9: *Torque and speed of the threshing cylinder with electric drive at a feedrate of 25 t/h*

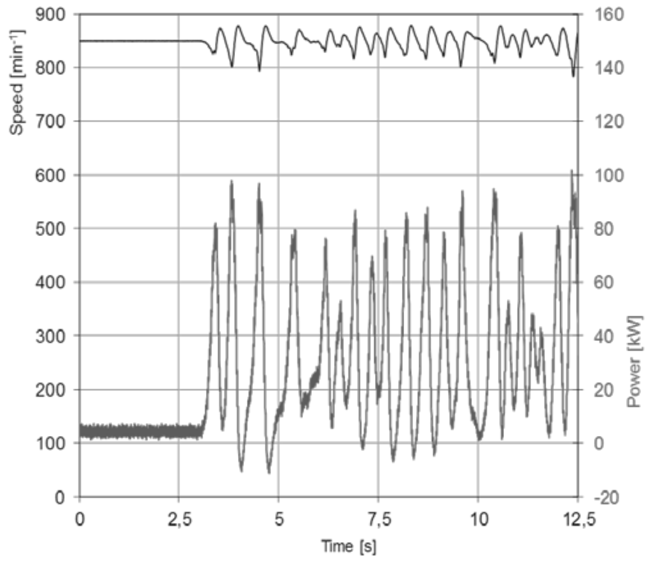

***Fig. 10:** Power and speed of the threshing cylinder with electric drive at a feedrate of 25 t/h*

The effective torque is 470 Nm and the maximum torque 1200 Nm. Thus, the required overload factor is calculated to 2.55.The effective power is 39 kW and the maximum power 100 kW. The data obtained the design, while still reserves are available.

While the mains power supply enables fast control times in the laboratory, a higher inertia in the electric system is expected with diesel-electric power on the mobile machine. Laboratory experiments with a diesel-electric powertrain and field tests in a combine are intended for the future.

6. Efficiency of the Electric System

A quantitative efficiency comparison of a combine mechanical and electrical 150 kW threshing drum drive train is shown in Table 2.

***Table 2:** Efficiency of mechanical and electrical threshing system drive train*

Mechanical drive train [2]		**Electrical drive train**	
Belt	0,94	Generator	0,96
Shaft + Bearing + Variator	0,94	Rectifier	0,98
Intermediate drive + Shaft + Bearing	0,94	Wire	0,99
Reduction gear (optional)	0,99	Motor inverter	0,98
		Electric drive	0,92
Total	0,82	Total	0,84

The efficiency of the electric drive system is only slightly higher than the mechanical. The electrical drive system has more mass and higher costs. The higher costs of an electric drive system, which will be reduced in the future, become attractive by higher system integration and a higher customer value.

The efficiency of the used electric drive is shown in Fig. 11. At the nominal point with speed of 1000 min^{-1} and torque of 597 Nm, the efficiency is $\eta = 0.926$. An increase of the efficiency can be achieved by reducing the rotor mass, increasing the flux density and lower-loss shaft seals.

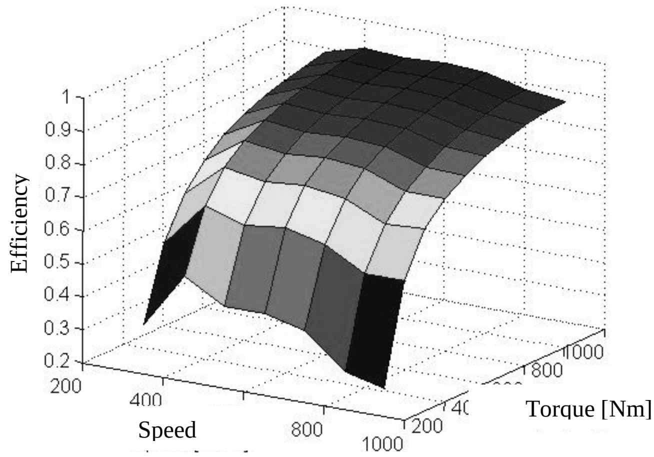

***Fig. 11:** Efficiency of the electric drive in the threshing cylinder*

5. Conclusion

With the function-integrated electric drive in the threshing cylinder and the comparative studies with the conventional system showed advantages of function-integrated electric drive in the threshing cylinder which could be confirmed in laboratory tests. It is shown that electric drives can be an alternative to increase productivity and efficiency in self-propelled harvesting machines by their function specific, decentralized and modular designed units. In addition to the electric driven threshing cylinder, more decentralized drives in the combine are useful to drive electrically. Higher investment can be amortise by reduced specific fuel consumption, less maintenance, increased reliability and productivity.

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