Electric mechanic power split PTO for implements

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Abstract
In standard tractors, the mechanical PTO is used to drive high power demanding implements. Its current design as a mechanic, manually switchable transmission enables efficient power transmission, but does not provide the variability needed for automated optimization of the operating points of the engine and the implement. In this paper the development and testing of an electro-mechanic power split transmission as PTO drive for agricultural machinery is being presented. This transmission offers variable speed control with efficiencies of 90% in the main operating range.

Introduction
The mechanical power take-off shaft has established itself in standard tractors for driving agricultural implements. Two nominal speeds, 540 and 1000 rpm, are mainly used for power transmission. Up to two additional stages offer these speeds at reduced engine speed in order to reduce fuel consumption and noise emission during partial load operation [1]. However, in order to adapt the attachment speed continuously and automatically to changing environmental conditions during operation or to stop it during the turning manoeuvres on the headland an infinitely variable transmission is required. Due to the mechanical coupling between PTO and engine, the speed adaption can only be met by actively adjusting the engine speed of the tractor [2]. This is not only less practicable, but also prevents the optimisation of the whole working combination’s operating point. Variable-speed drive concepts for attachments offer great potential for improvement with regard to the efficiency and quality of the working process.

As an alternative to the established mechanical drives, hybrid and fully electric drive concepts for implements are being tested increasingly. Due to the good controllability of electric drives, this drive technology is suitable for various applications such as fertilizer spreaders,
sowing machines or potato harvesters. Since established standard tractors do not have the correspondingly powerful electrical energy sources and are therefore not suitable for the conversion-free operation of electrical attachments, only a few electrical attachments exist so far [3].

**Approach**

In order to both eliminate the speed coupling of the combustion engine to the implement and to offer a retrofittable electrical power source for tractors, a joint research project carried out by Müthing GmbH & Co. KG and Pulsgetriebe GmbH & Co. KG with the Professorship for Natural Materials Technology of TU Dresden and the Institute for Machine Elements and Systems Engineering of RWTH Aachen University developed an electric power-split transmission for the power take-off drivetrain. The aim of the project is to develop a variable and easily controllable implement drive, which allows to operate the implement at optimum speed without changing the speed of the engine of the tractor. For this purpose, the transmission is equipped with two electric machines, which are used as a generator-motor combination for continuously variable speed transmission. Both can also be used as generators to power electrically driven implements or as a drive motor for the attachment. The power-split transmission structure reduces the electrical machine power to be installed, so that smaller and more cost-effective units can be used. Furthermore, compact high-speed machines with operating speeds above 10,000 rpm are used to allow a compact design and competitive cost.

As seen in Fig. 1, four operating modes are provided. The *ininitely variable PTO* allows the PTO speed to be controlled independently of the tractor engine speed between 0 and 1090 rpm. The main operating range of the PTO of the tractor is 800 to 1000 rpm, which allows the optimization of the operating point of the engine. The *Generator* mode can be used to equip current tractors with an electrical power interface. The *Hybrid* mode offers a variable PTO and an electrical interface simultaneously. In order to drive a mechanical implement locally emission-free the unit can also be used as an electric motor using external power supply.

![Operating modes](image_url)
The drivetrain has been designed using a drivetrain synthesis tool developed at the Institute for Machine Elements. This tool simulates the power flows in the transmission and optimizes the individual transmission components with regard to the efficiency and the loads on the components. Both input and output coupled power split drivetrains have been simulated and evaluated. The structure shown in Fig. 2 has been determined with the aim of operating the electric machines at their optimum efficiency and using as few components as possible.

![Diagram of transmission structure](image)

Fig. 2: Favoured transmission structure

The implement drive is developed as a modular system which is available in four power classes with 30 kW, 70 kW, 120 kW and 200 kW mechanical power output. In order to be compatible with as many implements as possible, the unit is designed as an independent implement with a frame to transmit external forces and be adaptable to existing implements. Depending on the power class, different frames with different interfaces are available. All frames are equipped with a three point hitch as standard. The variants for the smaller power classes are theoretically available as plug-on variant without a separate frame by being mounted directly to the PTO shaft of the tractor and therefore will have less influence on the centre of gravity of the machine combination. Installation directly in the drive train of the implement is also conceivable and offers the option of partially electrically operating more complex implements.

**Concept validation**

To validate and test the concept of the electric mechanic power-split transmission, a demonstrator for a flail mower application is set up. The power class has been set to 120 kW maximum power. Due to the power split transmission structure, the variator transmits a maximum power of 40 kW and less than 30 kW average power during the main operating range. The unit is mounted in a CAT 3 suitable frame. This frame also carries the power electronics, oil...
pump for the gearbox and cooling system (see Fig. 3). The transmission in this design requires a length of 350 mm between tractor and implement. In order to allow the full stroke movement of the three-point linkage without inadmissible deflection angle of the driveshaft during operation, the frame is overall 900 mm long. The integration of the transmission into the implement or tractor offers here significant saving potentials in terms of installation space. This unit is designed for speeds up to 1000 rpm and up to 1150 Nm of torque. The electric interface is set up for up to 90 kW of electrical power.

Fig. 3: Model of the 120 kW variant

The controls of the module has been designed and tested by the Institute for Natural Materials Technology. Since the electric machines were used in a back-to-back arrangement, capacitors are used to stabilize the DC link. All auxiliary consumers (coolant pump, fan, oil pump and controls) are supplied by a 12V on board power system and are switched on as required. The maximum input power for all consumers combined is less than 1 kW. This power is supplied by a DC-DC converter from the DC-Link during operation. Additionally, the power for the control can be supplied by the tractor during start up and shup down. This ensures the power supply and the tractor's on-board power supply is only used if necessary. The implement drive is controlled via ISOBus. Here, the operating mode and the output speed are specified and information about the input and output speed and torque as well as the DC-Link voltage can be output. In addition, the operating temperatures and speeds of the electrical machines are monitored.

The gearbox has been designed and manufactured by Pulsgetriebe. The complete unit has been calibrated and measured on a test bench of the Institute for Machine Elements. Repeated start-up processes from standstill up to 120 % of the drive speed were successfully...
tested up to a load torque of 700 Nm. The maximum output torque is continuously available at output speeds above 200 rpm. The prototype achieved the desired output speeds. Fig. 4 shows the efficiency of the implement drive including the auxiliary consumers for different input speeds and different output speeds.

Fig. 4: Efficiency of the transmission

Overall, the implement drive achieves an efficiency of over 80% for the most part. In the main working range between 800 and 1000 rpm input and output speed, the efficiency is around 90% and reaches up to 94%. The reduced efficiency at lower output speeds can be attributed to the reduced total output power at constant auxiliary power consumption. With the same output power, the efficiency changes only slightly for different input speeds and therefore offers potential for the operating point shift of the tractor in particular.

After this test bench phase, field tests are currently being prepared at Müthing (Fig. 5) and the Institute for Natural Materials Technology, where the unit is used to drive conventional flail mowers. Further measurements during these tests are planned, in particular to investigate speed control and torque monitoring under real conditions.
Conclusion

In this paper the design and testing of a power-split power take-off transmission module that varies the drive speed of the implement and also allows the implement to be operated electrically has been introduced. A prototype has been manufactured, calibrated and measured on a test bench. It offers a high efficiency during partial and higher loads. The unit is capable of stopping and starting the implement without adjusting the PTO of the tractor, therefore it can be used as a driveline for continuous and automatic speed adjustment for implements. To be as compatible as possible to existing tractors and implements, it has been designed in four power classes with three-point interfaces. It is controlled via ISOBus and also displays the current loads of the implement. Installation directly in the drive train of the implement or tractor is also possible and offers advantages regarding the installation space. In the next steps, the advantages of the attachment drive in the various variants for different areas of application will be evaluated with regard to improved process control and efficiency optimization. Further tests with the prototype are also planned.
Literature


