SELF-PROPELLED HARVESTER WITH AN ELECTRICAL TRACTION DRIVE IN COMPARISON TO THE HYDRAULIC TRACTION DRIVE

Faculty of Mechanical Science and Engineering, Technische Universität Dresden, Dresden, Germany
E-mail: benjamin.striller@tu-dresden.de

Abstract: Sugar Beet Harvesters belong to self-propelled agricultural machinery for trimming, lifting, cleaning and collecting sugar beets. Like most harvesting machines such vehicles are equipped with hydrostatic traction drives to ensure a continuous variable speed adjustment for the harvesting process. These drives are state of the art but rather moderate in efficiency. For further enhancement of efficiency the hydrostatic system was replaced by a diesel-electric traction drive. The two different systems were tested and compared in simulation and field. As a result, improved driving performance at reduced fuel consumption could be achieved.

Keywords: DIESEL-ELECTRIC, HYDRASTATIC, SELF-PROPELLED HARVESTER, SUGAR BEET HARVESTER, EFFICIENCY

1. Introduction

Nowadays modern agriculture utilizes self-propelled harvesters, such as combine harvesters for grain, forage harvesters, harvesters for beets and potatoes or sugar cane and cotton harvesters. This type of harvesting machines is characterized by high productivity in terms of tons per hour or hectares per hour. The vast majority of these self-propelled harvesters are equipped with hydrostatic drive technology, which allows comfortable and fast adjustment of varying ground speeds according to the different harvesting conditions, and which includes reverse operation and quick stop without the need of switching gears or hitting breaks. Other requirements on the propulsion system of self-propelled agricultural harvesting machines are fast response, high torque at low speeds, transport speeds from \( v = 20 \text{ kph} \) up to 40 kph, high efficiency at all load conditions, and slip and traction control in terms of soil protection.

So far, hydrostatic drive systems have met these requirements best, specifically in consideration of weight and cost. However, a major disadvantage of hydraulics is the moderate efficiency \([1]\), especially in the part-load operational range. The spectrum of load cycles in the operation of self-propelled harvesters is characterized by a wide range of operating points which makes the optimization of a high overall efficiency fairly impossible. With regard to high installed engine capacities and rising fuel costs this is essential.

Electric drives are characterized by a higher efficiency compared to hydraulics and with a very slow decrease in efficiency towards the partial load range. Excellent controllability and dynamic behaviour exceed the corresponding capabilities of mechanical or hydraulic drives. Additional advantage is the built-in current and voltage measurement, which delivers information about the drive torque at any time and with high accuracy.

Analysts \([2]\) expect that in future electrification of drive trains will be used in mobile agricultural machinery and implements with the purpose of efficiency increase and functional enhancements. Electrified traction drives of self-propelled harvesters are an important step in that direction.

2. Initial Situation

In a collaborative project Sensor-Technik Wiedemann GmbH, ROPA Fahrzeug- und Maschinenbau GmbH, and TU Dresden implemented a diesel-electric traction drive system in a self-propelled sugar beet harvester (Fig. 1). This machine is characterized by a net weight of about 30 tons, which increases up to 60 tons when the hopper is completely filled with harvested beets. Harvesting operation mainly takes place between autumn and winter, sometimes under very difficult ground conditions. As a result and in comparison to other self-propelled harvesting machines, the power requirements of the traction drive are high, ranging from 100 kW – 300 kW with a very wide distribution of operating points. The annual harvesting area of a beet harvester is between 600 ha and 1200 ha, equivalent to about 75 000 t of sugar beets. An average fuel consumption of 40 to 50 l/ha leads to a fuel cost of about one third of the total operating costs.

3. Hydrostatic Drive Train

The conventional, hydrostatic drive train of the self-propelled, three-axle beet harvester ROPA euro-Tiger V8-3 uses a variable displacement hydraulic pump (Fig. 2, position 9), which is mounted to the main transfer gear box (Fig. 2, position 8). This gear box is located behind the flywheel (Fig. 2, position 7) of the diesel engine and drives another twelve hydraulic pumps for functional components with variable speed.

The hydraulic power unit to drive the vehicle for traction is a variable displacement pump in swash plate design with a rated power of \( P = 343 \text{ kW} \). The hydraulic power is converted by two hydraulic motors in bent axis design, one with constant displacement (Fig. 2, position 1) and the other with a variable displacement (Fig. 2, position 2). The beet harvester is all-wheel driven by a central gearbox (Fig. 2, position 3) with two gears where both the motors are directly mounted. The first gear enables vehicle speeds from 0 to 14 kph, the second from 0 to 20 kph, optional up to 25 kph.

Power is distributed by a cardan shaft to the front axle (Fig. 2, position 4) and the two rear axles (Fig. 2, position 5 and 6), respectively. The front axle is designed as a portal axle with a central differential gear and planetary final drives. In the first and second rear axle differential gears and planetary gears as final drives are integrated like in the front axle. Furthermore the last axle is equipped with an axle load control. All wheels feature kingpin steering whereas, additionally, an articulated steering is implemented between the front axle and the first rear axle \([4]\).

4. Determination of Load Collectives

For the changeover of the hydrostatic traction drive to the diesel-electric traction drive the current drive requirements on a conventional machine were determined. During beet harvest 2010 a total of about 200 h of harvest and road operation were recorded on two machines. Using drive train pressure and flow volumes, drive performance and traction requirements could be calculated. Data were analysed, transformed into class frequency and residence time distributions, and thus load collectives could be formulated. It was found that the vehicle speed during harvest ranges from 6 to 8 kph.


5. Electric Drive Train

For the electric drive the central drive concept of the hydraulic drive train was kept. The hydraulic pump was replaced by two generators with a rated power of $P = 140$ kW each at a speed of $n = 3000$ min$^{-1}$ [5]. A gearbox was implemented, which is flanged to the former pump drive, shifting the input speed of the generators to a higher range to assure a favourable efficiency of the electrical machines. The hydraulic motors were substituted by two electric motors with a rated power of $P = 140$ kW respectively at a speed of $n = 3000$ min$^{-1}$ [6]. Here as well a matching gear was mounted between the motors and the gearbox to run the motors at the desired speed. All the electrical machines are identically constructed, permanently excited synchronous machines cooled by isolating transformer oil. The overload capacity of the electric machines is 30 %. A brake chopper limits the maximum DC voltage in the DC link between the generators and electric motors working with a voltage level of 650 V. Additional energy storage in form of a battery or supercapacitor does not exist at the moment. Currently the mass ratio of electric to hydrostatic drive including the two matching gears is 3.3:1 without considering the cooling.

6. Simulation and Field Tests

In parallel to the integration of the electric drive system into a real machine, the conventional hydraulic and the alternative electric traction drive were simulated based on the load collectives determined. The simulated multi-body models represent the complete drive train including the diesel engine, the generators and the electric motors (electric drive train) or the pump and the hydraulic motors (hydraulic drive train), the mechanical central drive, and the contact between wheel and soil. The simulation provides comparative statements for the effectiveness, efficiency, and fuel consumption of the electric and the hydraulic system. The increase in efficiency of the drive train ranges from 20 % up to 30 % in accordance with the simulation results; therefore the fuel consumption is reduced about 20 %.

The first functional tests of the electrified machine were carried out during 2011 beet harvesting period. All driving functions for road and field operation were checked. Subsequently, in April 2012 the electric and hydraulic harvesters were compared in field tests by tractive force measurements, carried out with a tractor-cultivator combination as braking vehicle (Fig. 3).

To record the full-load curve in the operating diagram the maximum vehicle speed was approached in the respective gear. The braking vehicle increased the load continuously until the vehicle speed fell according to the tractive output hyperbola. For the determination of working points within the operating diagram specific vehicle speeds were set gradually as shown in Fig. 4 with bright colours. While increasing the load of the braking vehicle, the harvester speed fell when reaching the full-load curve. During these tests the parameters tractive force, GPS-based vehicle speed, fuel consumption, and performance data in the drive train were recorded, i.e. flow rates, pressures, temperatures, as well as currents and voltages. These parameters were used to calculate input and output power and to create a characteristic diagram for efficiency.

![Exemplary tractive force gear](image)
The comparison of the two tractive force diagrams (Fig. 5 and Fig. 6) shows in the first gear at low vehicle speed slightly higher maximum tractive forces for the machine with electric drive. In the upper speed range of the first gear higher vehicle speeds can be reached with the electric machine. It can be concluded that the electric drive train is as effective as the hydrostatic drive train; this means the performance limits of the machine with hydrostatic drive train can be realized and even surpassed by the machine with electric drive.

Fig. 5 Total wheel force, efficiency of hydrostatic drive train

![Efficiency η [%] - hydrostatic drive - gear 1](image1)

Fig. 6 Total wheel force, efficiency of electric drive train

![Efficiency η [%] - electric drive - gear 1](image2)

The efficiency of the drive train is calculated as ratio of tractive power and diesel engine output for the traction drive. For \( v = 6 \) kph, which is a vehicle speed representative for the harvesting process, and a full loading cycle of the hopper, the efficiency is \( \eta = 70.5\% \) for the machine with electric and \( \eta = 46.4\% \) for the machine with hydrostatic drive. Due to the high share of time of this operational range a fuel saving between 10 and 20 % is possible.

### 7. Cost-benefit Calculation

Under the following conditions, a cost-benefit calculation was made:

- general machine lifetime: 5 years
- annual use: 1000 hectares or 650 operating hours (oh)
- specific fuel costs: 1.30 EUR/l
- assumed rate of interest: 6 %

All quantities are shown in Table 1 and 2. It is found that the electrified system shows significantly higher investment costs compared to the hydraulically driven machine. However, looking at the annual operating costs, the electric system is more economic.

Based on the above mentioned general conditions, a payback period of approximately 3.6 years can be determined for the electric system compared to the hydraulic one.

### Table 1 Investment costs

<table>
<thead>
<tr>
<th></th>
<th>Electric [EUR]</th>
<th>Hydrostatic [EUR]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drives</td>
<td>32000</td>
<td>6400</td>
</tr>
<tr>
<td>Wires/tubes</td>
<td>2500</td>
<td>590</td>
</tr>
<tr>
<td>Safety equipment/pressure control valves</td>
<td>500</td>
<td>100</td>
</tr>
<tr>
<td>Power electronics/valves</td>
<td>Inclusive</td>
<td>150</td>
</tr>
<tr>
<td>Investment costs, total</td>
<td>35000</td>
<td>7240</td>
</tr>
</tbody>
</table>

### Table 2 Operating costs

<table>
<thead>
<tr>
<th>Operation costs</th>
<th>Electric [EUR]</th>
<th>Hydrostatic [EUR]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil change</td>
<td>250</td>
<td>100</td>
</tr>
<tr>
<td>Fuel consumption/1000 ha</td>
<td>49095</td>
<td>60249</td>
</tr>
<tr>
<td>Operating costs/year</td>
<td>49345</td>
<td>60349</td>
</tr>
</tbody>
</table>

### 8. Conclusion and Outlook

Based on the beet harvester ROPA euro-Tiger V8-3, which is conventionally hydrostatically driven, a machine was equipped with a diesel-electric traction drive. On the one side, both machines were compared in simulations with Matlab/Simulink using load collectives for field and road operation determined in advance. On the other side, field tests were carried out. Due to the higher efficiency of the electric system superiority in terms of fuel consumption could be shown. Despite of the higher investment costs, the current design of the electric system has shown an economic benefit. Furthermore, the ecological advantage of saving CO\(_2\) will become more important in future.

During beet harvesting periods of 2012 and 2013 the electrically driven prototype machine has been successfully used in practice. Load peaks and their frequency during operation could be detected by determining load collectives. Identifying the maximum power requirement and its duty cycle enables the extension of the current serial system to a hybrid system using energy storage. If the storage covers the energy requirements of the load peaks, the diesel engine only has to ensure a basic power supply (phlegmatization); so the load for the engine is smoothed [6]. A smaller diesel engine can be chosen if the basic power is supplied at full engine load (rightsizing).

### Literature


