System comparison of hydraulic and electrical traction drives in self-propelled harvesters

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Abstract

The concept of a diesel-electric traction drive of a self-propelled sugar beet harvester is presented. Main focus is the comparison with the previously used hydrostatic drive. A simulation of the electrified drive that is based on load cycles collected with the conventional hydraulic driven machine delivers first estimates on behavior, dynamics, power consumption and degree of efficiency. Particular attention is paid to the efficiency analysis and a cost-benefit estimate of both drive systems. Eventually the feasibility of a production implementation is discussed.

KEYWORDS: diesel-electric, self-propelled harvester, efficiency

1. Introduction

Today modern agriculture is utilizing self propelled harvesters, such as combine harvesters for grain, forage harvesters or harvesters for beets and potatoes. 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 is including reverse operation and quick stop without the need of switching gears or hitting breaks. Other requirements for ground drives in self-propelled agricultural harvesting machines are fast response, high torque at low speeds, transport speeds from v = 20 km/h up to 40 km/h, high efficiency at all load conditions and slip and traction control.

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 narrow band of high efficiency causing low efficiency values farther away from the designed operating point. The occurring spectrum of load cycles in the operation of self propelled harvesters is characterized by a very broad distribution of operating points, which makes the optimization of a high overall efficiency fairly impossible. Under the aspect of installed engine capacities in a range between 200 and 800 kW and rising fuel costs this becomes an important dissatisfier.

Electric drives are characterized by a higher efficiency compared to hydraulics with a very slow decrease in efficiency towards the partial load range. Excellent controllability and dynamic behavior exceed the capabilities of mechanical or hydraulic drives. Additional advantage is the built-in current and voltage measurement, which delivers information about drive torque at any time and usually with less than 5 % error.

Analysts expect that in the future electrification of dive trains will be used in mobile agricultural machinery and implements with the purpose of efficiency increase and functional enhancements. Electrified ground drives of self propelled harvesters are an important step in that direction.

Figure 1: beet harvester in field operation

2. Initial situation

In a collaborative project Sensor-Technique Wiedemann GmbH, ROPA vehicle GmbH and TU Dresden are designing and demonstrating a diesel-electric ground drive system at a beet harvester. This machine is characterized by an empty weight of about 30 tons, which increases up to 60 tons when harvested beets have fully filled the intermediate storage in the middle of the machine. The high payload is required to keep the machine running between the unloading cycles. Harvesting operation takes place mainly between autumn and winter; sometimes under very difficult ground conditions. As a result and in comparison to other self-propelled harvesting machines there is a high power demand on the traction drive ranging from 100 kW – 300 kW with a very broad distribution of operating points. Under these conditions, improvements in overall efficiency have a good potential to compensate the extra investment for the electric components.

2.1. Conventional system with hydraulic ground drive

The hydrostatic drive train of the self-propelled, three-axle beet harvester ROPA euro-Tiger V8-3 uses a variable displacement hydraulic pump, which is mounted to the main transfer gear box located behind the flywheel of the diesel engine together with another twelve hydraulic pumps driving variable speed functional components. The hydraulic pump to drive the vehicle is a variable displacement swash plate design with a rated power of P = 343 kW. The hydraulic power is consumed from two hydraulic motors in bent axis design, where one motor has a fixed displacement and the other is a variable displacement motor. The beet harvester has a central drive, which permanently powers all three axle-differentials. The hydraulic motors are placed on the central gearbox, which is summing up the two motors and is switching on demand between field mode and transport gear. First gear has a speed of 0 – 13 km / h and second gear covers the whole range between 0 – 20 km / h, optional up to 25 km / h compromising some torque at the lower speeds. Transmission output goes into two Cardan shafts deploying power to the front and the two rear axles. The front axle is designed as a portal axle with a central differential gear, planetary final drives and is equipped with tires 800/65 R32. The first and second rear axle have differential gears and a planetary final drive. Tire equipment is 1050/50 R32 in the middle and 1050/50 25R32 in the rear. The wheels of both the rear axles features kingpin steering and in addition an articulated steering placed behind the front axle.

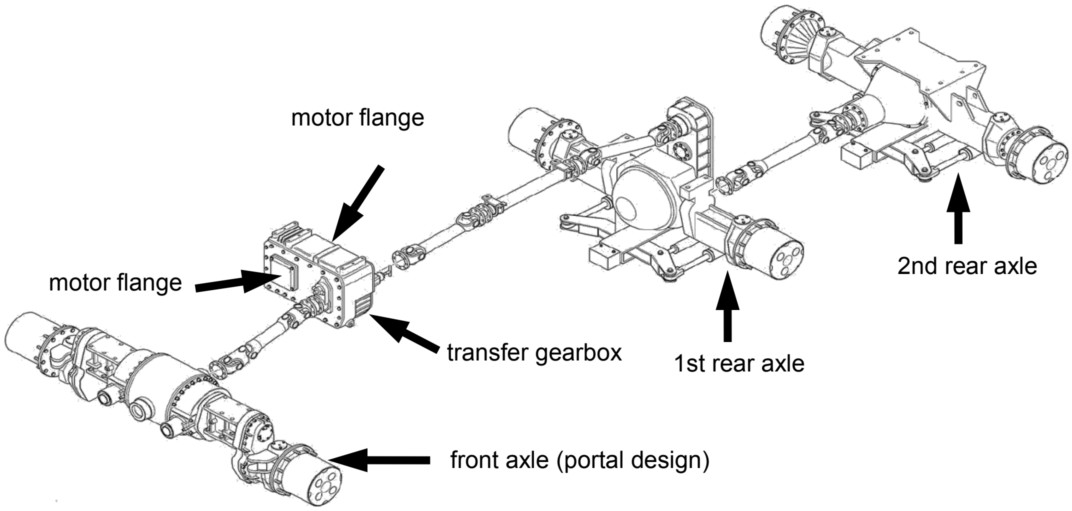

Figure 2: mechanical drivetrain

2.2. Measured load cycles

Loads were measured in order to understand the drive requirements on a conventional machine through the field season. During the beet harvest 2010 a total of about 200 h harvest and road operation was recorded (example **figure 3**). From this data load cycles and speed spectra have been developed. Drive line pressure and flow volumes were used to calculate drive performance and traction requirements. Data were analyzed and transformed into class frequency and residence time distributions (**figure 4**).

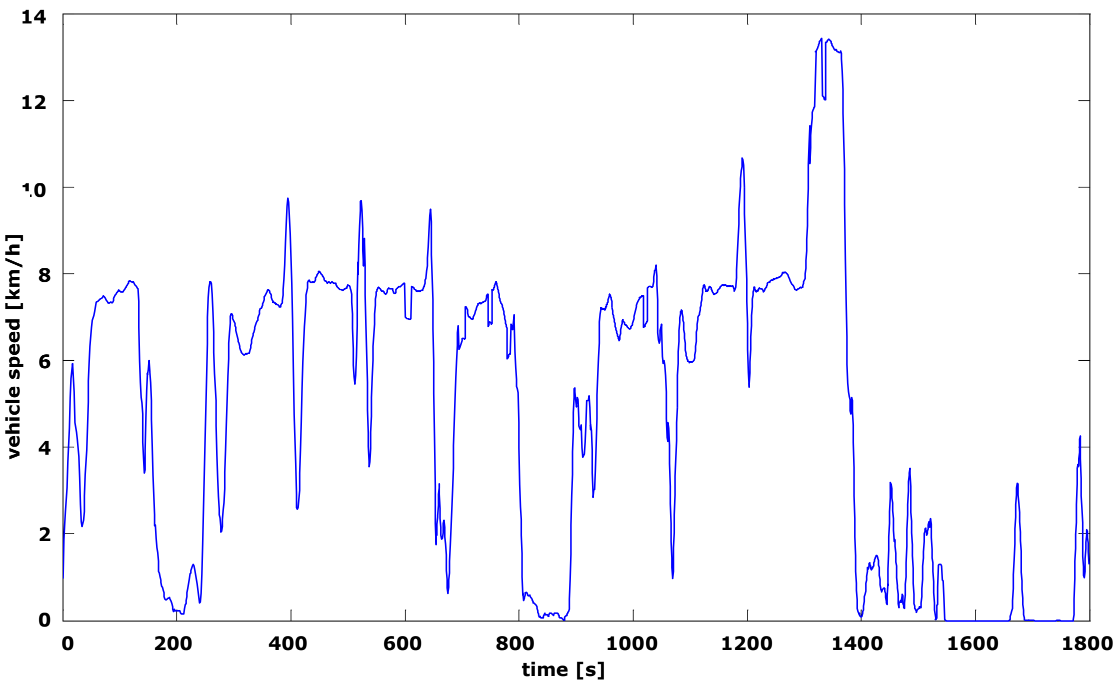

Figure 3: ground speed while harvesting beets

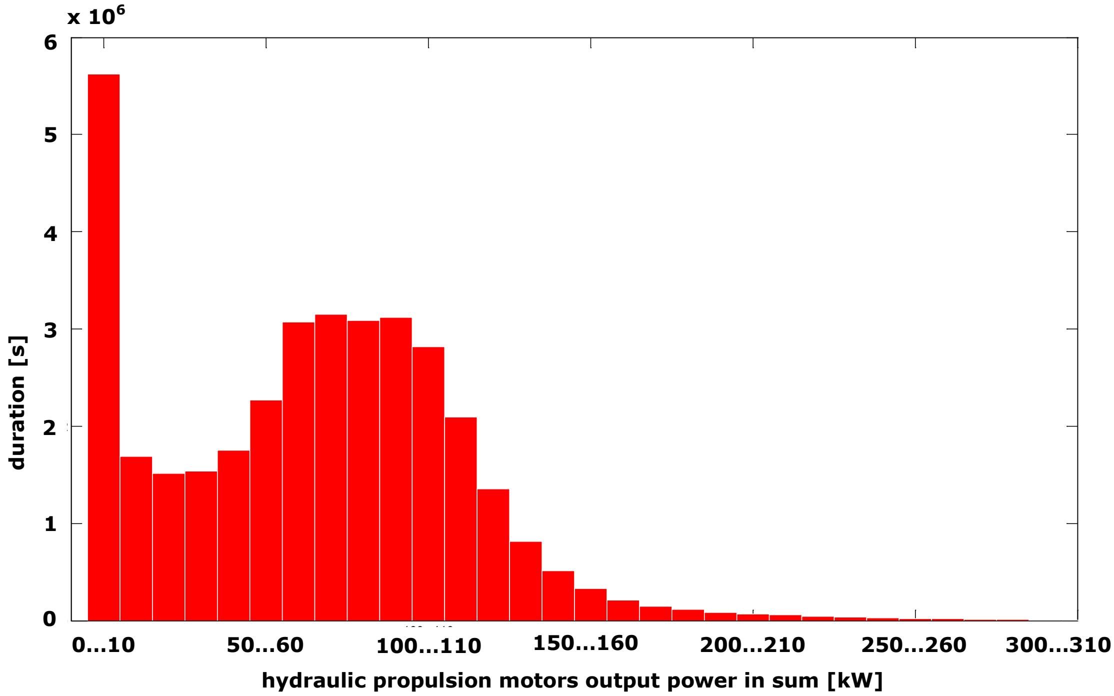

Figure 4: mean residence time of propulsion motors output power

3. Alternative system with electrified drives

For the electric drive the central drive concept was maintained. The hydraulic pump has been replaced by two generators with a rated capacity of P = 140 kW each at a speed of n = 3000 min^{-1} (**figure 5**). A gearbox was implemented, which is flanged to the former pump drive, to bring the input speed of the generators into the desired higher range where a favorable efficiency of the electrical machines can be warranted.

The hydraulic motors were replaced by two electric motors with a rated capacity of P = 140 kW each and at a speed of n = 3000 min^{-1}. The existing gearbox that was summing up and transferring the hydraulic power to the axles was connected to an additional gearbox with a higher transmission ratio that allows running the motors at the desired speed. All the electrical machines are permanently excited synchronous machines cooled by isolating transformer oil, which allows bringing the fluid directly onto the windings. The overload capacity of the electric machines is 30 %. A chopper limits the maximum DC voltage in the DC link between the generators and electric motors. Additional energy storage in form of a battery or super capacity does not exist at the moment. For a production intent the double generators and electric motors would be replaced by bigger machines.

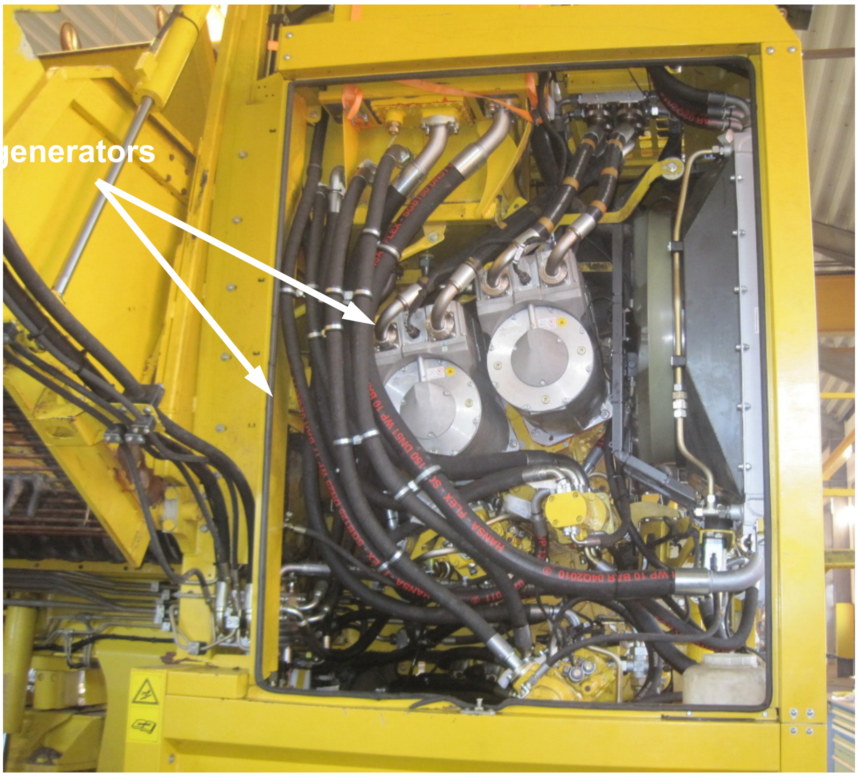

Figure 5: generators

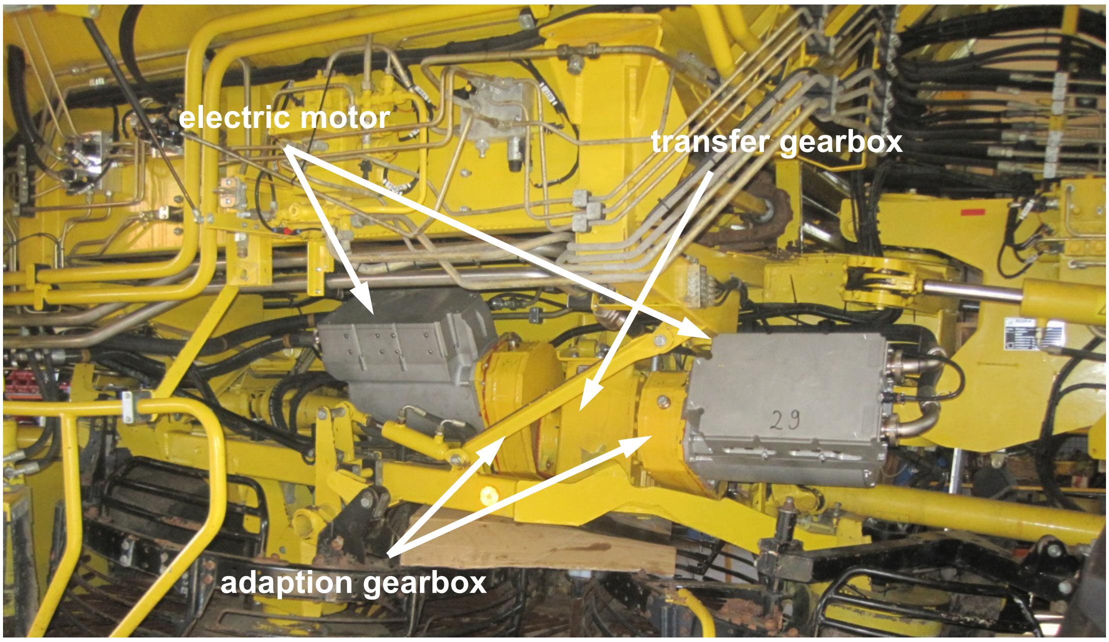

Figure 6: electric drive motors

The doubling is mainly due to the availability of electrical machines. The old gearbox inherited from the hydraulic drive and the additional gearbox for achieving the higher ratio would be combined into one gearbox, which would reduce the mass ratio between electric and hydrostatic drive. Without consideration of cooling and including the two gearboxes the current mass ratio is 3.3 : 1.

4. Results

4.1. Simulation

The drivetrain of the conventional hydraulic and electric system is simulated via Matlab/Simulink. Therefore load cycles, measured at the conventional machine, are used for real stress simulation. The simulated models reflect the complete electric drivetrain consisting of diesel engine, generator, electric motor, mechanical central drivetrain (gearboxes, driveshafts, axles) and the contact between wheel and ground. Instead of the electrical components a hydraulic pump and a motor are used for the common drivetrain. The simulation provides comparative statements about the effectiveness, efficiency and fuel consumption for the electric and the hydraulic system. The increase in efficiency of the drivetrain ranges from 20 % up to 30 % in accordance with the simulation results. The fuel consumption can be reduced in the simulation up to 30 % (table 1). These data are used for a business management. In assumption of a fictive series production all main operating and investing costs are considered. As a result an amortisation of the electric drivetrain can be achieved within a realistic time (see 4.2).

	Electric	Hydrostatic	Ratio
Efficiency factor (field)	82,2%	54,7%	1,43
Efficiency factor (road)	82,3%	52,5%	1,57
Fuel consumption (field)	40,7l/h	51,0l/h	0,8
Fuel consumption (road)	24,3l/h	38,9l/h	0,62

Table 1: results of simulation

4.2. Field tests

The first functional tests of the electrified machine have been carried out. All driving functions for road and field operations were checked. In the upcoming field tests of both vehicles (which were not completed at the time of documentation), the conventional hydraulic machine and the electrified machine will be compared to each other.

Primary aims of field tests are:

- Statements of efficiency between electric and hydraulic machine
- determination and comparison of power limits (performance diagram)
- proof of fuel consumption while field and road operations

Based on these findings considerations of functionality, efficiency and versatility can be figured for the best system configuration. Furthermore, with the aid of results from field tests a verification of simulation seems possible. Also, simulation models can be validated.

4.3. Cost-benefit calculation

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

- general machine lifetime: 5 years
- annual use: 1000 hectares or 650 operating hours
- specific fuel costs: 1.20 EUR/l (agricultural diesel)
- adopted rate of interest: 6 %

All quantities are shown in **table 2**. It is found that the electrified system shows significantly higher investment costs compared to the hydraulic driven machine. Looking at the annual operating costs, the electric system is more economic, however.

Investment costs	Electric [EUR]	Hydrostatic [EUR]
Drives	32000	6400
Wires/ tubes	2500	590
Safety equipment/ pressure control valves	500	100
Power electronics/ valves	inclusive	150
Investment costs/ year	**35000**	**7240**

Operating costs	Electric [EUR]	Hydrostatic [EUR]
Oil change	250	100
Fuel consumption/ 1000ha	39600	46200
sum	500	100
Power electronics/ valves	inclusive	150
Operating costs/ year	**39850**	**49300**

Table 2: investment and operating costs

Taking into account of boundary conditions operating costs are obtained from **table 3**. A payback period of approximately 3.6 years can be determined for the electric system to hydraulic one. Due to a lower fuel consumption also environmental advantages are achieved by saving carbon dioxide. Certainly, this point cannot be accounted yet.

	Electric [EUR/oh]	Hydrostatic [EUR/oh]
Fixed costs (depreciation, interest, insurance)	13,13	2,72
Variable costs (reparation, maintenance, fuel)	59,76	74,04
Total costs per operating hour	**72,89**	**76,76**

Table 3: costs per operating hour

5. Summary

Based on the self-propelled sugar beet harvester “ROPA Eurotiger V8-3” a prototyp was fitted up with an electric drivetrain. A simulation was carried out for both machines while passing field and road operations. Therefore real load collectives were gained on common machines. Multi-body simulation models, including the whole drivetrain, were implemented to Matlab/Simulink. Due to the higher efficiency of electric drives an economical superiority was determined during machine operations. Especially, a reduction in fuel consumption has been demonstrated up to 30 % by simulation. As a result, the much higher investment costs of the electric system were amortized in less than 4 years. With the expected rising fuel costs in future, the amortization will be reduced accordingly. In addition, a significant environmental benefit is generated through reduction of carbon dioxide. Although this is difficult to quantify, but will be definitely gaining more importance forwards.

6. Continuing tasks

Covered by the measured load spectra, peak loads and their frequency can be detected very well. If the required maximum power as well as the associated duration is determined, a hybrid system can be build up by using an energy storage. After an initial estimation it seems that supercapacitors are the best way in that case. While peak power is provided by the storage, the diesel engine has only supply the basic power (phlegmatising), whereby the load for the diesel engine becomes smoother. If the requested basic load is supplied under full diesel engine power, the engine size can be done smaller (downsizing). In follow, the diesel engine runs in a more optimal efficiency range. To proof the positive effects of phlegmatising, the use of an appropriately sized energy storage is suggested at first. So, the complexity of design can be kept in an acceptable way.

7. Used formula

A	area	ha
m	mass	t
n	speed	min^{-1}
P	power	kW
$t_{operate}$	operating time	h
v	velocity	km/h