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Comparison of energy efficiency by using simulation tools

Using electrical engines is one step to optimize the energy consumption of the power train. The adaption of mechanical elements of the power train to its task offers more options to reduce the losses. When simulation is used to compare different power trains with different gearboxes, the efficiency can be calculated already in an early stage of the conceptual design. Therefore a simulation model was build to compare different settings of electric drives with gearboxes.

Keywords
Energy efficiency, degree of efficiency for gearbox, simulationtool

Abstract
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Using drives for mobile applications postulate many requirements, which means especially low costs, high controllability, high efficiency and low mass. Electrical Machines achieve these requirements and in the consequence the spread of electrical drives rise in drive technology at mobile applications [1].

The use of these drives offers new additional tasks to optimize the power train. To reduce the energy consumption it is not the only way to enhance the motor but also the mechanical power train. It is necessary to adopt the power train to the mission and the drive to achieve low mass and high energy efficiency. With the usage of existing parts, this paper shows at the following example, how to reduce the energy consumption of the electrical drive in combination with a shiftable gearbox.

Weight to power ratio

In difference to fixed machines mobile agricultural machines have to handle the distance between different locations. Due to this requirement it is necessary that the used drives have the lowest mass as possible. With a drive of same power the ratio of mass to power should be low for carrying as less mass as possible on the mobile machine.

For the dimensioning of an electrical machine there is necessary information like power, speed and torque, which can be used with the equation 1.

Equation 1 delivers for a certain duty point, defined by a given power and speed, the diameter and the length of the electrical machine. The weight of the machine can be estimated with these values [2].

Comparing two machines with the same power, a higher torque at a lower speed leads to a higher weight and vice versa. Consequently engines with high speed can be combined with a reduction gear to reduce the weight-to-power-ratio. The use of a reduction gear to limit the weight of an electrical machine can be found in many fields of application and has been described by Geisler [3] for traction drive of self-propelled agricultural machines.

Whenever the power train needs to have a low speed and a high torque, a combination of engine and gearbox can be found to reach a low weight-to-power-ratio as explained above. It will be shown that there are more degrees of freedom regarding the optimization of the complete power train for a combination of engine and gearbox or the variation of the gearbox parameters.

With the following example it will be pointed out how the efficiency of an electrical drive in combination with a shiftable gearbox can be improved for one duty point compared to a single speed gearbox.

Drive selection

To fulfil the requested tasks, the electrical drive has to stand permanently the maximum requirements of each subtask of **Table 1**:

- Power of 92 kW
- Speed up to 1 000 rpm
- Maximum torque of about 1 060 Nm

Using equation 1 for the dimensioning of the electrical machine, an estimated mass of 250 kg follows for the electrical drive. For the same power and the fulfilment of all given requirements the use of a mechanical reduction gear lowers the weight even below 100 kg, depending on the chosen reduction.

The use of a drive in combination with a reduction gear will be discussed furthermore. A regular engine can be selected for this application. **Figure 1** illustrates the characteristic map of the engine. The maximum torque of the drive is plotted over speed, from which the efficiency can be found for each duty point.

Table 1

Maximum power for PTO type 1 [4]

PTO Typ *PTO type*	Durchmesser [mm] *Diameter [mm]*	Angegebene Drehzahl [U/min] *Rated rotational frequency [U/min]*	Maximale Leistung [kW] *Maximum power at rated engine speed [kW]*	Resultierendes Drehmoment [Nm] *Torque at rated engine speed [Nm]*
1	35	540	60	1062
	35	1000	92	879

Figure 1 also shows the isolines for a constant power at 60 kW and 90 kW. As the speed spread has to be within the characteristic curve of the engine, choosing only one transmission gives a restriction regarding the task to generate speeds of 540 rpm and 1 000 rpm. According to the chosen transmission the duty points 1 (at 540 rpm) and 2 (at 1 000 rpm) follow (**Figure 1**). Using a shiftable gearbox with two transmissions gives the possibility of choosing different transmission ratios, which leads to the points A and B at each specific power and speed for this example as shown in **Figure 1**. This additional degree of freedom in the conceptual design allows an influence on the duty points of the electrical engine and for this reason using duty points with higher degree of efficiency.

Degree of efficiency and energy consumption

As per definition a machine converts one form of energy in another [5] and in this example electrical energy into mechanical energy. Power is the ratio of energy divided by time and within that power is a time-discrete dimension, which is suitable for describing a process over a space of time or transient processes. Dividing the useful power of a machine by the quantity of power, the result is the degree of efficiency. The difference between the power values is the energy loss, which is usually not useable for the process. Due to that it is possible to calculate all powers and energies by the knowledge of the degree of efficiency, the actual power and the time.

Power train

In this paper the power train includes an electrical machine, a gearbox und the load, as a variable magnitude. The regulation in this task is for adjusting the torque at the drive in that way, that the speed is constant.

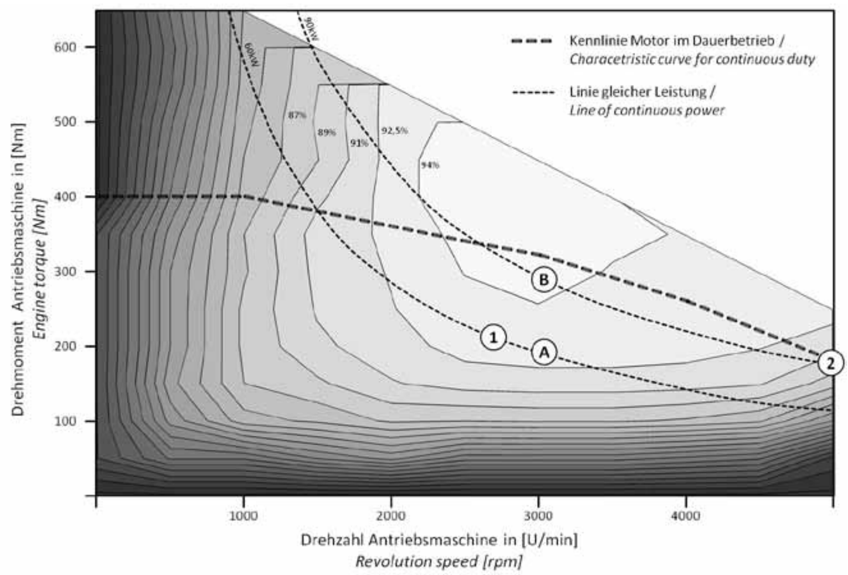
After the choice of the electrical machine two different gearboxes were designed. The concept 1 has a fixed ratio and the concept 2 is shiftable two speed gearbox. Booth concepts are designed with equal lifetime and durability for bearings and gears. The weight of the concept 2 is about 20 % higher than the weight of concept 1, because of the shiftable ratio there are more parts in concept 2. **Figure 2** shows booth concepts with the given ratio.

Simulation

To compare these different power trains there was a simulation model developed, which displays the energy consumption and especially the losses addicted to speed and load.

This model was built in SimulationX and attends the losses of the drive and the gearbox for the whole power train. To

Fig. 1



Characteristic curve with efficiency map

Fig. 2

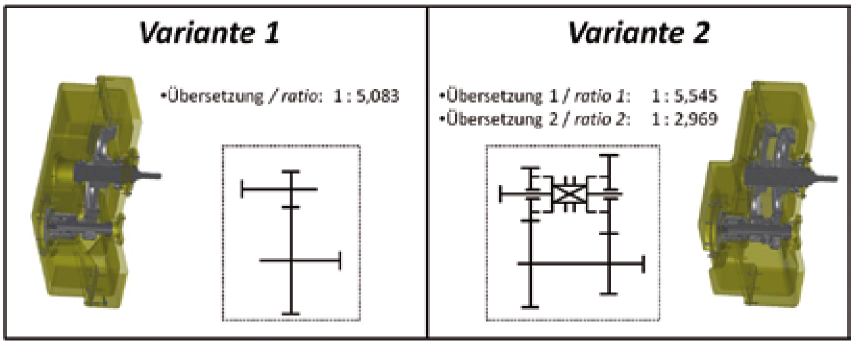
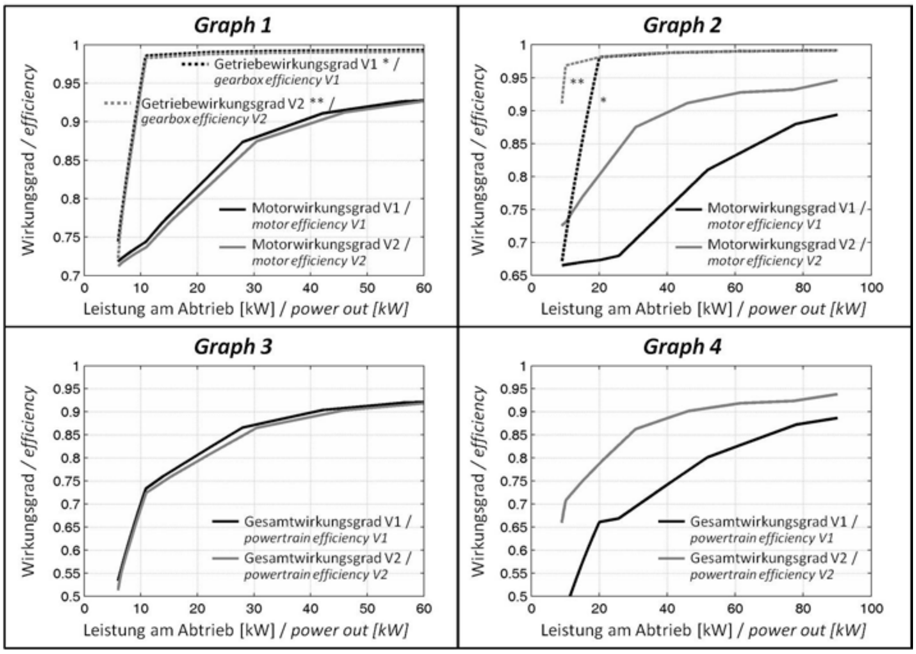


Illustration of the gear concepts 1 and 2

Fig. 3



Results of the simulation

reduce the complexity of the model, the model uses the characteristic curves containing the energy efficiency in function to speed and load.

The control element is a proportional element, which adjust the torque that way the speed keeps constant at 540 respectively 1000 rpm, while the load changes continuously from part load to full load. The needed characteristic curves were created by calculations and given data specifications from the respective manufacturer.

The characteristic curve of the electrical drive was interpolated from the data sheet and transferred the simulation model.

The data of the gearbox concepts were calculated by different programs (e. g. KiSSsoft) to get the losses for the bearings, the tooth contact and all friction places. These results were transferred in the simulation program. With the simulation program the characteristic curve and the losses for the gearbox were created.

Result

The energy efficiency grades of the concepts are compared to each other, for analyzing the results.

In relation to the load speed and the power the graph 1 in **Figure 3** shows the efficiency grade of the gearbox. The efficiency grade of gearbox in concept 1 with only one gear pair is higher than the efficiency grade of concept 2 at a load speed of 540 rpm, because booth concepts rotating with the same speed but in concept 2 there are more rotating parts which cause losses.

The energy efficiency grade of the electrical machine is almost equal for the use in booth concepts. There are only little differences due to the different ratio.

At a load speed of 1 000 rpm and the second gear in concept 2 the efficiency grades of the concepts are equal (cf. graph 2 **Figure 3**). There are higher losses in concept 1 due to the lower ratio and the higher rim speed of the tooth contact. The efficiency grade of the electrical machine at a load speed of 1 000 rpm is for concept 2 higher than for concept 1, because in concept 1 is a higher speed of the drive.

According to the overall efficiency of the power train (graph 3 & 4 in **Figure 3**), the concept 2 has a better efficiency grade, a lower energy consumption and due to that an advantage over concept 1 at a load speed of 1 000 rpm.

Conclusions

The used elements are available or were designed according to the requirements. The comparison of the gearboxes is based on a new simulation model, which creates the energy efficiency depending on the used machine elements and whose arrangement. The gearbox efficiency is non-constant but a function of the load and the speed. Optimizing the energy efficiency means to look at the whole power train and the task to find a variation of the lowest energy consumption.

The given task can be solved with one drive and a single stage gearbox. Due to the different speeds at the load it is not possible for the drive to work always in its point of best efficiency. By using a two speed gearbox the overall efficiency increases while the efficiency of the gearbox itself decreases. In that way there is a reduction of the energy consumption by using the two speed gearbox.

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