**Klimentew, Lars; Krüger, Jan and Meyer, Henning J.**

# Influencing factors of the gearbox in efficiency of electrical traction drives

The usage of electrical drives in agriculture has reached mobile machines with drag force requirements, e. g. tractors. There are suggestions to optimize the electrical powertrain of passenger cars to reduce the energy consumption. During the optimization process the whole system, consisting of electrical and mechanical components, has to be considered. Effects of important factors and indicators are discussed in the following article.

**Keywords**
**Overall gear ratio, number of gears, electrical traction drive, degree of drive-efficiency**

**Abstract**
**Landtechnik 68(2), 2013, pp. 130–134, 9 figures, 1 table, 12 references**

Most traction drives in on-road applications are implemented as three-phase drives, especially asynchronous machines (ASM) and permanent magnet synchronous machines (PMSM). One of the most important reasons for using three-phase drives is its high power density, i.e. a low ratio of mass to drive power. **Table 1** compares the two types of electrical machines.

An exemplary characteristic curve of a controlled electrical device is shown in **Figure 1**. Through closed loop control of the power electronics, it is possible to maintain a constant drive torque $M_{nenn}$ over a certain speed range (hereinafter referred to as basic speed range BS) (**Figure 1**, a). If the speed is increased beyond the BS, the drive's nominal torque is reduced with increasing rotation speed, due to the fact that the magnetizing current falls if a constant voltage is applied. This area is referred to as the field-weakening area FW. The characteristics of the motor current in this area depend on the machine typ (e.g. ASM or PMSM) and the design of the electrical drive. As a result, the characteristic curve of the machine has areas of increasing power and areas of constant power (**Figure 1**, b).

At a given voltage and a finite thermal load capacity of the electric drive, a maximal torque $M_{max}$ can be produced (see **Figure 1**, a). In this state, the machine is heating up, until after a certain time a destruction of the machine can be expected. At a continuous torque $M_{nenn}$ however, a permanent operation is possible. The increase of the drive torque beyond the nominal torque is hereinafter referred to as overload operation.

Both types of electrical drives differ in their efficiency. PMSM achieve higher efficiency at lower rotation speeds and in partial load range. ASM can be advantageous at high rotation speeds [1]. For both types, an optimal efficiency range exists regarding either power or rotation speed.

Table 1

*Comparison of permanent magnet synchronous machine and asynchronous machine*

| **PMSM** | **ASM** |
|---|---|
| Hohe Leistungsdichte<br>*High power density* | mittlere Leistungsdichte<br>*medium power density* |
| Sehr gute Regelbarkeit<br>*Excellent controlability* | sehr gute Regelbarkeit<br>*excellent controlability* |
| Mittlerer Regelaufwand<br>*Medium control effort* | geringer Regelaufwand<br>*small control effort* |
| Hoher Aufwand bei der Auslegung<br>*High design effort* | aufgrund großer Erfahrung mittlerer Aufwand<br>*medium design effort due to high knowledge* |
| Hohe Kosten zum aktuellen Zeitpunkt<br>*Currently high costs* | geringere Kosten gegenüber PMSM<br>*lower costs than PMSM* |

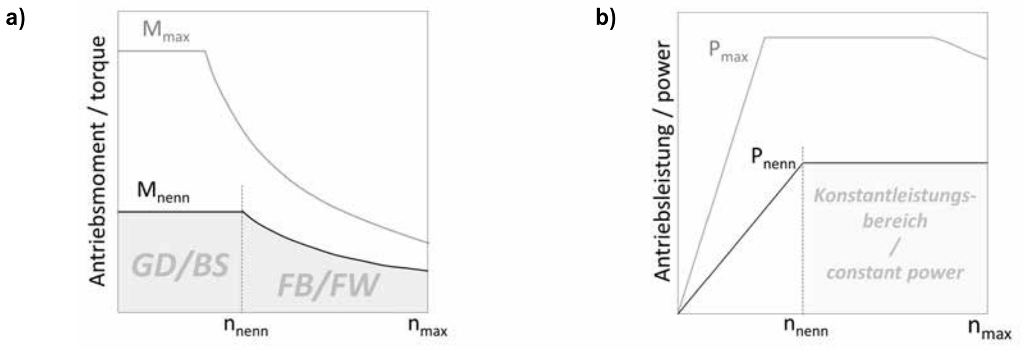
## Electrical drives in on-road applications

As they reach a higher power density, PMSM are used more often in mobile applications than ASM. Due to reasons of larger dimensions, wheel hub drives or direct drives are considered to be optimal in mini-vehicles. However, if more powerful engines are needed, central drive solutions are more and more predominant [2, 3, 4]. This results from a demand for high wheel torques to reach high accelerations on the one hand, as well as a demand for higher vehicle top speeds on the other hand.

The requirement for a high starting torque can be achieved by using a largely dimensioned and thereby heavy machine without a mechanical transmission, or using the overload operation of a "smaller" electrical drive.

The top speed depends on the wheel rotation speed. High rotation speeds do not pose a problem for electrical machines. Currently available PMSM are able to run in the field-weakening area at top speeds of 12 000 rpm and more.

Fig. 1




*Example characteristic curves of an electrical machine*

While the required drag force increases with the vehicle velocity, the drive torque decreases at higher rotation speeds, resulting in an operation point at which the vehicle reaches its top speed.

The battery is responsible for a significant share of the vehicles' production costs as well as its weight. Therefore at a given vehicle range, the energy consumption and the efficiency of the drive train are significant cost factors. It is an important aspect of the development of such vehicles to adapt the range with the highest efficiency of the electric machine to the power needs of the vehicle. Energy savings of up to 16 percent with regard to the particular driving cycle can be achieved [4].

For electrical traction drives in passenger cars, suggestions have been made to optimize energy efficiency of the electrical drive train [2].

## Drag force needs of a tractor

Mobile working machines can be categorized, according to their tasks, into machines with and without continuous drag forces. Tractors use a major share of the engine power for pulling purposes, which is why they are categorized as machines with continuous drag forces [5]. For further reduction of the energy consumption, electrical drives are more and more used in vehicles with a high share of continuous drag forces [6].

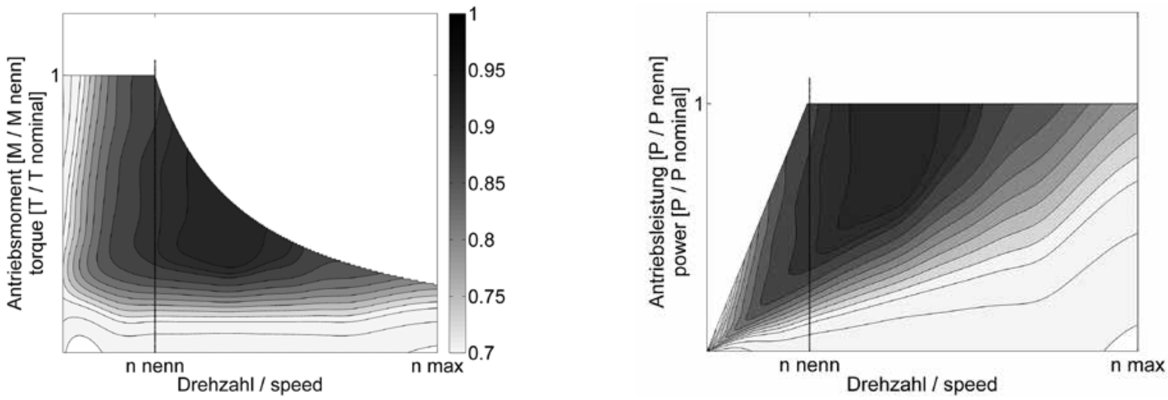
The demands on tractors shall not be discussed in detail in this paper, as they are already described in the literature, e. g. in [7]. To select a suitable traction drive, the vehicles' wheel rotation speeds as well as the necessary wheel torques have to be known. Due to the various applications of tractors, it is preferable to be able to convert the maximal engine power, at every vehicle speed, into traction power.

In **Figure 3**, a list of typical tasks for tractors and its corresponding vehicle speeds is given [8]. The resulting velocities range from about 4 until 40 km/h. The speed limit for tractors of today 50 km/h, is reached more and more frequently and an increase of the maximum speed is currently discussed [9].

If the drag force $F_{zug}$ is calculated according to equation 1 from the power $P_{nenn}$ provided by the engine, the curve in **Figure 4** can be plotted.

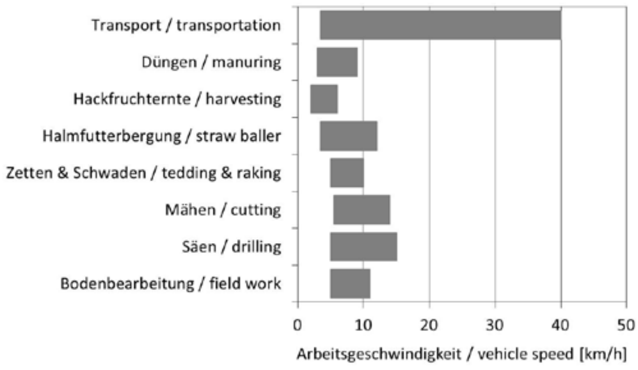
$$F_{zug}(v) = P_{nenn} \cdot v^{-1} \quad \text{(Eq. 1)}$$

Fig. 2



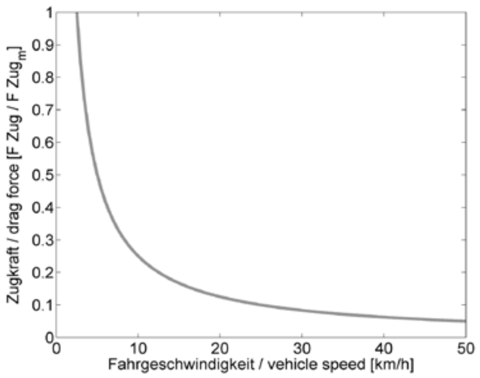

*Example efficiency map of an electrical machine*

Fig. 3




*Vehicle speed*

Fig. 4




*Drag force over speed*

An electrical machine with a large field-weakening area and an almost constant power in this area seems to be well suited for the task of drag force generation.

The hyperbola of the field-weakening area of an electrical motor fits almost ideally to the drag force hyperbola as both curves are based on a constant power supply at increasing rotation speed. (**Figure 1**, a and **Figure 4**)

To generate the necessary torque for a high drag force without using additional transmissions, the electrical drives would have to have a large and often unsuitable diameter as well as a high mass. This conflict has been discussed several times and was solved by [10] by using an additional gear reduction.

For a mobile working machine with continuous drag forces only the continuous load range of an electrical machine can be used. A short overload operation seems to be only necessary in certain situations with high drag force demands. It should be noted that the demand for a high torque overload capacity and a large field-weakening area cannot be fulfilled at the same time [11].

The overall gear ratio can be calculated using equation 2. For a speed range of 4–50 km/h as it is given in **Figure 3**, it is $\varphi_{Geschwindigkeit}$ = 12,5. This ratio (or spread) cannot be achieved with machines currently available on the market. PMSM and ASM that are suitable for automotive applications reach according to equation 3 a value of $\varphi_{Antrieb}$ = 3 (up to 4) in the field-weakening area at constant power output.

In order to use standard electrical motors, a possibility has to be found to adapt the overall gear ratio resulting from the different working speeds ($\varphi_{Geschwindigkeit}$) to the overall engine spread ($\varphi_{Antrieb}$). Normally, this can be done using a shift transmission that provides the additional spread according to equation 4. The following calculations are made according to [12].

The transmission's gear spread ($\varphi_{Getriebe}$) has to be divided into gears so that an uninterrupted drag force hyperbola approximating the ideal drag force hyperbola can be implemented (**Figure 4**). Using gear transmissions implies that an integer number of speeds has to be used. Applying a constant gear step without overlapping rotation speeds of the drive in different gears the number of gears can be calculated according to equation 5.

$$\varphi_{Geschwindigkeit} = v_{\max} / v_{\min} \quad \text{(Eq. 2)}$$

$$\varphi_{Antrieb} = n_{\max} / n_{nenn} \quad \text{(Eq. 3)}$$

$$\varphi_{Geschwindigkeit} = \varphi_{Antrieb} \cdot \varphi_{Getriebe} \quad \text{(Eq. 4)}$$

$$z_{Gang} = \log_{\varphi_{Antrieb}}(\varphi_{Getriebe}) + 1 \quad \text{(Eq. 5)}$$

One possibility to implement an integer number of gears is to choose an oversized electric drive and use the nearest lower integer number of gears. Thereby, the usable engine spread can be extended as the required power output is reached at rotation speeds below the corner speed ($n_{nenn}$) (**Figure 5**). A higher drag force could be used if a machine with higher power output would be chosen, provided that this would not be limited by the energy source or the traction limit.

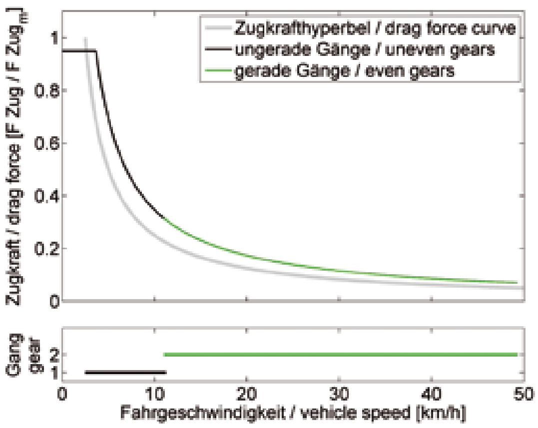
The second possibility is to choose the nearest higher integer number of gears. The drag force curve aligns with the ideal drag force hyperbola over the whole speed range (**Figure 6**). As a result of the adaptation of the gear steps, the speeds overlap in the different gears (**Figure 5**, at the bottom).

The velocities that can be reached in each gear using the nominal power are displayed below the drag force curves (**Figure 5** and **Figure 6**).

## Optimization approach

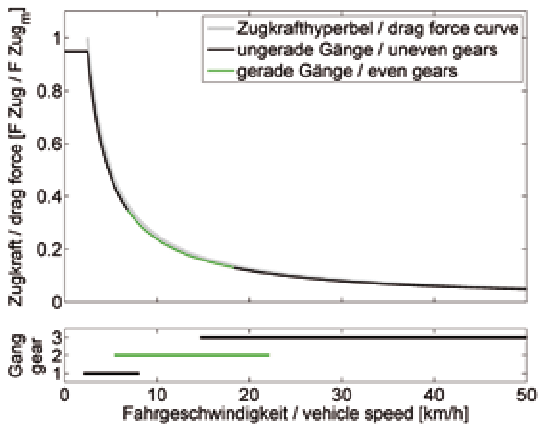
To reduce losses of the electrical machine, it is useful to operate it in the range of optimal efficiency. By increasing the number of gears, the drive could be operated in its optimal rotation speed range. **Figure 7** shows a drag force curve for a 5-speed drive. An example using two, three and five gears demonstrates how the efficiency of the electric drive as a function of vehicle speed changes, using only a small part of the constant power area of the drive with the highest drive efficiency. **Figure 8** shows that increasing the number of gears allows to operate the

Fig. 5



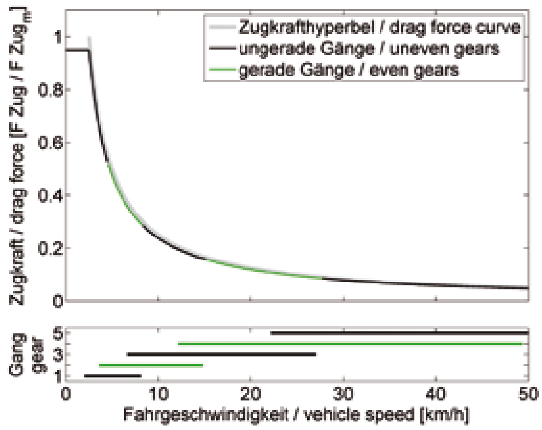

*Example of drag force curve for 2-speed drives*

Fig. 6



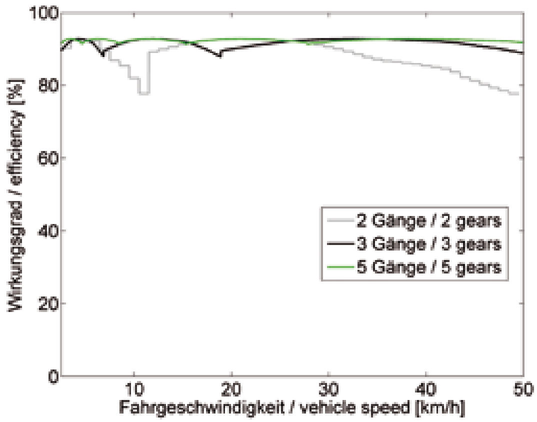

*Example of drag force curve for 3-speed drives*

Fig. 7



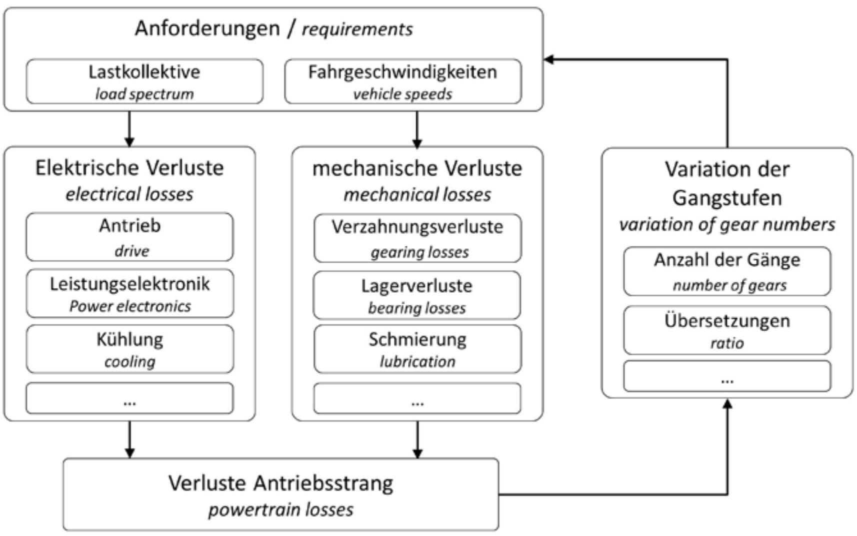

*Example of drag force curve for 5-speed drives*

Fig. 8




*Efficiency comparison for different numbers of gears*

Fig. 9




*Optimization procedure*

drive over a wide range of vehicle speeds in its optimal drive efficiency area.

As every gear pair causes mechanical losses, an optimum for motor and gearbox losses has to be found. An iterative strategy based on simulation results taking into account electrical and mechanical losses according to **Figure 9** is proposed.

## Conclusions

Electrical drives that provide a large constant power area are well suited to reach a close approximation to the ideal drag force hyperbola using a small number of gears. Increasing the number of gears allows adapting the drives' operating points to the vehicle speed enables the use of the high efficiency of electrical drives even better. The estimation of mechanical and electrical losses in the drive train is an essential information for the optimization process. An iterative strategy to optimize the energy consumption is proposed.

## References

[1] Schäfer, Uwe (2012): Elektrische Antriebe für Straßenfahrzeuge. Skript. Technische Universität Berlin, http://www.ea.tu-berlin.de/menue/lehre_elektrotechnik/modul_elektrische_antriebe_fuer_strassenfahrzeuge/vorlesung/, Zugriff am 31.1.2013

[2] Knödel, Ulrich; Strube, Alexander; Blessing, Uli Christian; Klostermann, Sven (2010): Auslegung und Implementierung bedarfsgerechter elektrischer Antriebe. Automobiltechnische Zeitschrift ATZ 2010(6), S. 462–466

[3] Roberts, Simon (2012): Multispeed-Getriebe für Elektrofahrzeuge. Automobiltechnische Zeitschrift ATZ 114(4), S. 298–303

[4] Schneider, Erik; Fickel, Frank; Cebulski, Bernd; Leibold, Jens (2011): Elektrische Antriebseinheit für E-Fahrzeuge. Hochintegrativ und Flexibel. Automobiltechnische Zeitschrift ATZ 113(5), S. 360–365

[5] Renius, Karl Theodor (2004): Hydrostatische Fahrantriebe für mobile Arbeitsmaschinen. Überblick zum Stand der Technik. In: Wissensportal Bau- und Baustoffmaschinen 3(1), S. 1–15, http://www.baumaschine.de/wissensportal-archiv/2004-01/wissenschaft-und-technik/fahrantriebe_dateien/fahrantriebe.pdf, Zugriff am 30.1.2013

[6] Renius, Karl Theodor; Geimer, Marcus (2012): Traktoren. Motoren und Getriebe bei Traktoren. In: Jahrbuch Agrartechnik 2012, Hg. Frerichs, Ludger, Braunschweig, Institut für mobile Maschinen und Nutzfahrzeuge, S. 1–9

[7] Renius, Karl Theodor (1985): Traktoren. Technik und ihre Anwendung. München, BLV Verlagsgesellschaft

[8] KTBL (2009): Faustzahlen für die Landwirtschaft. Darmstadt, KTBL

[9] Nadlinger, Manfred (2005): Fahrkomfort und Fahrsicherheit moderner Traktoren. Stand der Technik; Bedeutung im Praxiseinsatz, Anforderungen in der Zukunft. Landtechnische Schriftenreihe 223, Wien, Österr. Kuratorium für Landtechnik und Landentwicklung ÖKL

[10] Geißler, Mike; Lindner, Mirko; Aumer, Wolfgang; Herlitzius, Thomas; Budig, Peter; Steinbach, Heinz; Gräf, Heinz (2009): Dieselelektrisches Antriebssystem in selbstfahrenden Landmaschinen. Fachtagung Baumaschinentechnik 2009, Dresden, 14.-15.5.2009, Schriftenreihe der Forschungsvereinigung Bau- und Baustoffmaschinen 37, S. 134–144

[11] Canders, W. R.; Mosebach, H. (1999): Technologien und Grenzen von High-Torque-Antrieben. Jahresbericht TU Braunschweig, Institut für elektrische Maschinen, Antriebe und Bahnen (IMAB), https://www.tu-braunschweig.de/Medien-DB/imab/09-Jahresberichte/1999/03_Canders-Mosebach-Laube_1999.pdf, Zugriff am 16.01.2013

[12] Naunheimer, H.; Bertsche, B.; Lechner, G.; Ryborz, J.; Novak, W. (2007): Fahrzeuggetriebe. Grundlagen, Auswahl, Auslegung und Konstruktion, 2. Aufl., Berlin, Springer

## Authors

**Dipl.-Ing. Lars Klimentew** and **Dipl.-Ing. Jan Krüger** work as research assistants at the Department of Machinery System Design (Head of department: **Prof. Dr.-Ing. Henning J. Meyer**), Straße des 17.Juni 144, 10623 Berlin, e-mail: lars.klimentew@tu-berlin.de