# USB Proceedings

# 2014 International Conference on Electrical Machines (ICEM)

Andel`s Hotel Berlin
Berlin, Germany
02 - 05 September, 2014

Sponsored by

The Institute of Electrical and Electronics Engineers (IEEE)
IEEE Industrial Electronics Society (IES)

Co-sponsored by

ETG - Power Engineering Society withing VDI

# Design of an electrical motor with wide speed range for the in-wheel drive in a heavy duty off-road vehicle

S. Zhitkova, M. Felden, D. Franck and K. Hameyer
Institute of Electrical Machines
RWTH Aachen University
Email: svetlana.zhitkova@iem.rwth-aachen.de

***Abstract*—The electrification of the mobile machinery is often discussed. For agricultural tractors an electric drive can be an alternative to commonly used hydrostatic-mechanical power split drives. When compared to the hydrostatic drive, the electric motor with an efficiency above $90\,\%$ offers advantages. For a meaningful comparison the complete drive train (generator, gearbox, power supply, electric motor) has to be considered. Generally, a particularly limited space is available for the integration of an electric drive. This requires a compact design of the electric motor. Therefore, a permanent magnet synchronous motor is the best candidate, due to its high power density and high efficiency. A particular challenge when designing an electric motor is a special requirement on the driving cycle of the agricultural tractor. The electric motor has to provide a high torque for the working operation off-road and a high maximal motor speed for the transportation operation to move the vehicle on road. For this research a shiftable transmission gear is omitted. The design process of the electric motor with special characteristics is described. The challenge of the motor design for a wide speed range is the main subject of this paper.**

***Index Terms*—electric machines, high speed, wide speed range.**

## I. INTRODUCTION

Today the hydrostatic-mechanical power split drives, used in modern agricultural technique, present the technical state of the art and provide a high efficiency according to [1]. Several studies about the hybridization and electrification in the branch of agricultural machines are discussed in [2], [3]. The rising prices of fossil fuel and legal regulations for reduction of the $CO_2$ emission motivate the studies about the efficiency improvement by electrification. Several studies [4], [5] state the high potential to the application of electric drives in such application.

The major advantage of the electric drives in comparison to the hydrostatic drives is, besides the higher efficiency better controllability. An example for the integration of the electric motors in mobile machinery is the tractor concept Belarus Typ 3023, presented on Agritechnica 2009 in Germany. This concept contains an induction motor as a central drive [6]. The described concept promises a higher efficiency when compared to the hydrostatic drive, but lower overall efficiency compared to hydrostatic power split transmission [7]. A further promising concept is the integration of in-wheel drives. One example is the Rigitrac tractor concept, developed by the Technical University Dresden, Germany [8]. In this case the main challenges are the specific drive requirements, which generally include two speed ranges for farm work and transportation operation [1], [9]. A typical torque versus speed diagram for an agricultural tractor is shown in figure 1. The resulting wide speed ratio for an electric motor is shown in figure 2.

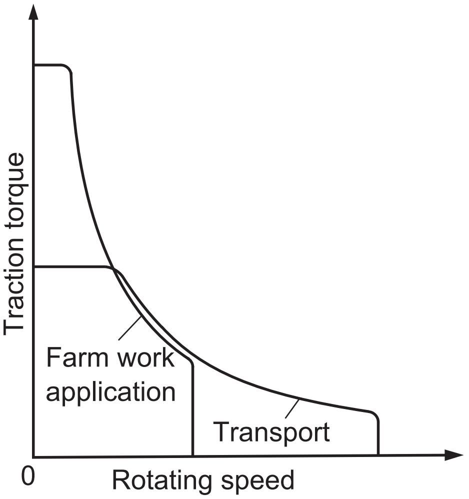

Figure 1. Torque versus speed for an agricultural tractor with two ranges[1].

The speed ratio in the modern tractors can reach the value of 1:15 [7]. In general a shiftable gearbox with two variable speed ranges is beneficial. However, the integration of a shiftable gearbox is excluded by the manufacturer. Therefore, in this study a shiftable gearbox is omitted. The presented research discusses the design of the electric motor with a fixed speed ratio of 1:11 (user requirements). A similar speed ratio for the PMSM is presented in [10]. A DC-link voltage of $650\,\mathrm{V}$ is employed.

The study focuses on the design of an in-wheel motor drive concept, consisting of an electric machine and a gearbox, for the agricultural tractor.

## II. REQUIREMENTS ON THE ELECTRIC MOTOR

The specific requirements on the traction drive for agricultural tractors are the high torque for farm work operation and high traveling speed for transport. It should be mentioned that available space for the integration of the electric motor is

978-1-4799-4775-1/14/$31.00 ©2014 IEEE

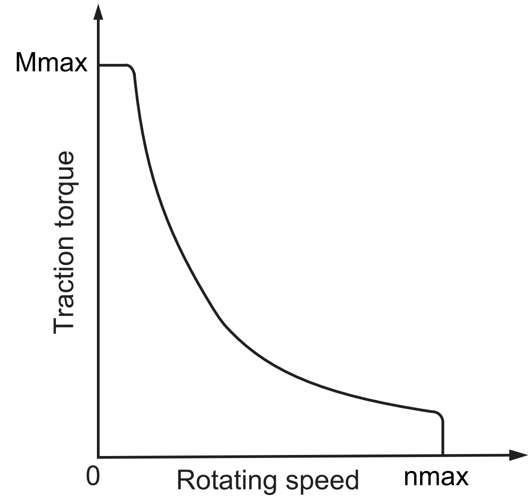

Figure 2. Operation range of an electric drive with fixed gear ratio.

highly limited. This is due to the fact that the existing vehicle concepts are designed for the integration of the hydrostatic motors, which have a higher power density in comparison to the electric motors. Meanwhile, the high maximal torque requires the sufficient sizing of the machine in order to ensure the continuous operation at high torques and high speeds. The relationship between the torque and the dimensions of the electric machine is described in literature [11]. Particular attention should be paid to the choice of the suitable electric motor concept. Previous research has shown that a permanent magnet synchronous machine (PMSM) is favorable for the in-wheel drive of an agricultural tractor due to its higher power density and high efficiency in comparison to the other common electrical machines. Similar research is presented in [12]. Due to a better field weaking capability, a rotor with v-shaped internal magnets is chosen for the application with wide speed range [13]. In [14] a comparable PMSM application is described.

In the required driving cycle both high copper losses (maximal torque operation point) and high iron losses (maximal speed operation point) occur. A compromise between high speed and high torque operation has to be found. Therefore, the overall driving cycle has to be considered. The driving cycle is specified by the manufacturer. The weighted efficiency is chosen as evaluation criteria for the motor design. The efficiency at particular operating point will be multiplicated with time portion, relating to this operating point in the drive cycle. The resulting weighted efficiency provides better information about the overall performance than the efficiency calculated at each operation point. Based on these results, the motor efficiency can be improved in the most relevant operating points.

## III. INITIAL DESIGN OF THE ELECTRIC MOTOR

The main dimensions of the machine are determined by roughly estimating the specific force density $\sigma$, which displays a relation between the mechanical power $P_n$ and the outer dimensions of the machine.

$$P_n = \sigma \cdot \pi^2 \cdot D^2 \cdot l \cdot n \tag{1}$$

Where $D$ is the rotor outer diameter, $l$ is the active length and $n$ is the rotational speed. Typical values for the specific force density of the particular type of the electrical machine are presented in [15].

The next important parameter for the motor design is the number of pole pairs $p$ . It impacts the main dimensions and the losses distribution in the machine.

Basically, high torque motors are designed with a higher number of pole pairs. This helps reduce the stator outer diameter due to the inverse proportionality of the pole pairs to the yoke $b_{yoke}$ and teeth width $b_{tooth}$ of the electrical machine.

$$p \sim \frac{1}{b_{yoke}}, \frac{1}{b_{tooth}} \tag{2}$$

A higher number of pole pairs ensures thinner yoke and teeth and therefore smaller machine dimensions [15]. The number of pole pairs determines the fundamental frequency of the magnetic field $f$.

$$f = n \cdot p \tag{3}$$

Consequently, in high speed application a high number of pole pairs can be crucial due to the field frequency dependent iron losses, which can cause overheating at high speeds.

In this work three concepts with different number of pole pairs $p$=2, $p$=3 and $p$=4 are evaluated. All machines are designed with the same outer dimensions (overall length and outer stator diameter). For an accurate comparison a finite element method (FEM) has been utilized. All possible design candidates are simulated at different operating points. The influence of the number of pole pair is presented in the next section.

## IV. VARIATION OF THE NUMBER OF POLE PAIRS

Figures 3, 4 and 5 show the resulting efficiency maps for the different motor concepts. The efficiency calculation includes copper losses, iron losses and air friction losses. The eddy current losses in the permanent magnet materials are estimated to be neglected, because in case of the internal magnets these are very low, as it is shown in [16] for the similar machine topology. The electrical steel M235-35A and permanent magnets N45SH at a temperature of $120\,^{\circ}\mathrm{C}$ were utilized for the motor design. Due to the high centrifugal forces in the rotor at maximal speed operation a high strength rotor material is applied [17]. The machine is designed with a distributed symmetrical winding. The winding is adjusted for the particular number of pole pairs. For the copper losses calculation a copper fill factor of $k_{cu}$=48 %, which is common for machine wound windings, was assumed.

According to the figures 3, 4 and 5 it can be concluded that the concepts with higher number of pole pairs have higher efficiency at high torque operation, while the concepts with lower number of pole pairs have higher efficiency at high speed operating points. The impact of the number of pole pairs on the weighted efficiency of the machine is shown in figure 6.

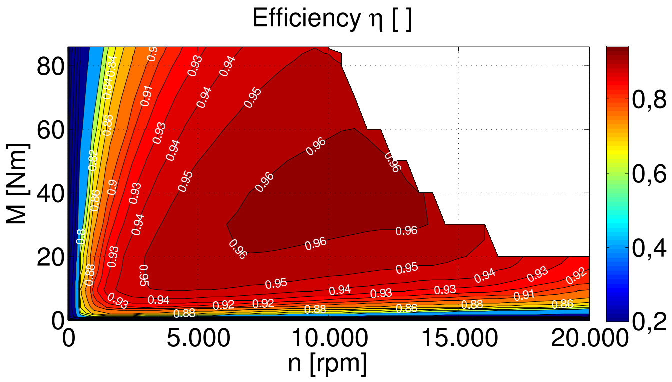

Figure 3. Efficiency of the electric motor with p=2.

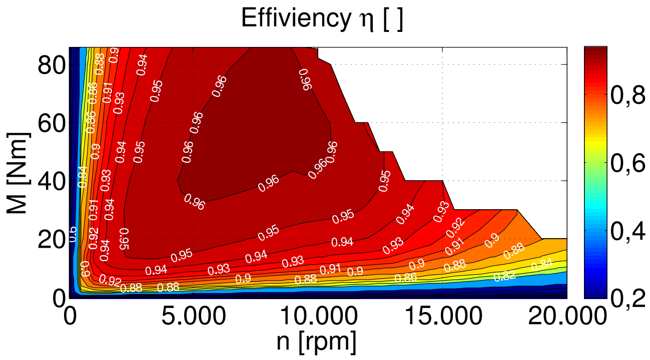

Figure 4. Efficiency of the electric motor with p=3.

Lower number of pole pairs provides the highest weighted efficiency, due to the drive cycle considered here.

Figures 7- 9 present the distribution of copper and iron losses in particular operation points as well as their relative occurrence. The operating points are sorted in descending order by the speed. It can be seen that the operating points with the high portion of iron losses occur more frequent during the driving cycle. Therefore, the concept with lower number of pole pairs, providing lower iron losses, results in the higher weighted efficiency. The detailed assessment provides the results, listed in the table I.

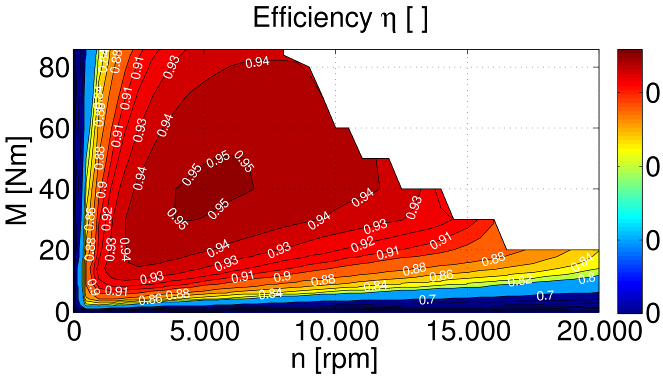

Figure 5. Efficiency of the electric motor with p=4.

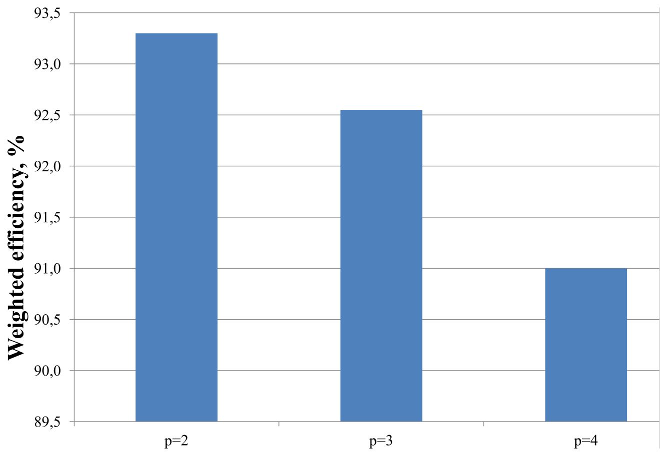

Figure 6. Weighted efficiency for different number of pole pairs.

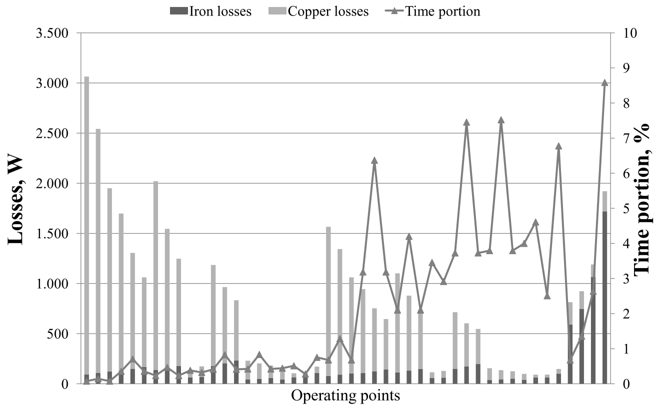

Figure 7. Distribution of losses with $p$=2 during drive cycle.

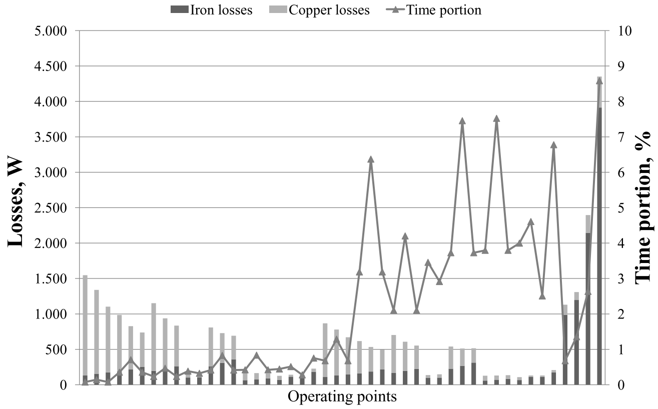

Figure 8. Distribution of losses with $p$=3 during drive cycle.

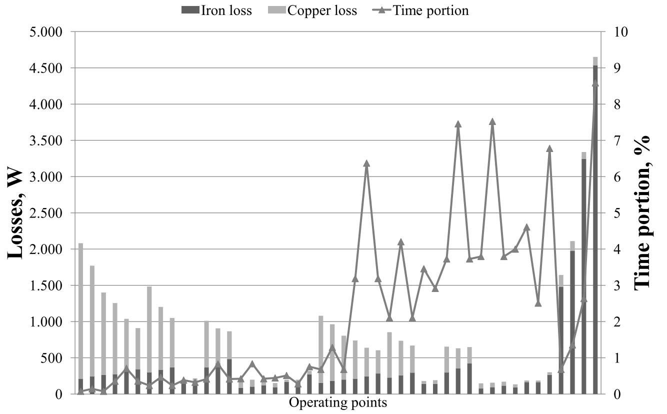

Figure 9. Distribution of losses with $p$=4 during drive cycle.

Table I

COMPARISON OF THE DIFFERENT MACHINE CONCEPTS WITH THE SAME OUTER DIMENSIONS.

| **Number of pole pairs** | **p=2** | **p=3** | **p=4** |
|---|---|---|---|
|  | **Electrical data** |  |  |
| Rated power | 20.000 W |  |  |
| **Operating point** | **Maximum torque** |  |  |
| Copper losses | 2,97 kW | 1,40 kW | 1,87 kW |
| Iron losses | 0,09 kW | 0,13 kW | 0,20 kW |
| Efficiency | 83,00 % | 90,00 % | 88,00 % |
| **Operating point** | **Maximum speed** |  |  |
| Copper losses | 0,20 kW | 0,44 kW | 0,12 kW |
| Iron losses | 1,70 kW | 3,90 kW | 4,50 kW |
| Efficiency | 90,00 % | 81,00% | 79,50 % |
|  | **Geometrical data** |  |  |
| Number of teeth | 24 | 36 | 48 |
| Tooth width | 7,0 mm | 5,5 mm | 3,8 mm |
| Slot area | 213,3 mm$^2$ | 163,6 mm$^2$ | 140,7 mm$^2$ |
| Core length | 110,0 mm | 130,0 mm | 145,0 mm |
| End windings length | 85,0 mm | 65,0 mm | 50,0 mm |
| Outer diameter | 184,0 mm |  |  |
| Overall length | 195,0 mm |  |  |

According to table I and figure 6 it can be concluded that the concept with $p$=4 is an unsuitable candidate for the given application. The mentioned concept provides low efficiency at both high torque and high speed. This is because the large number of pole pairs results in thin slots and consequently a higher current density is required to achieve the maximum torque, leading to the higher cooper losses. The high number of pole pairs causes high iron losses at the high speed.

When comparing the concept with $p$=2 and $p$=3, it is clear that the concept with $p$=2 has the maximal power losses at high torque operation, whereas the concept with number of pole pairs $p$=3 has the maximal power losses at high speed operation. According to the weighted efficiency comparison, the $p$=2 concept appears more favorable. However, the high power losses can present a thermal problem. In this case it has to be examined, which kind of the power losses is more crucial for the electric motor. Therefore, a thermal analysis is required for the fair comparison between the concepts. Based on the results of the thermal simulation the final decision for a suitable concept can be made. The results of the thermal simulation are described in the next section.

## V. THERMAL ANALYSIS

The thermal analysis of the electrical machine is the next important evaluation step in the design process. It helps to evaluate, if the machine can be operated at specified conditions. It should be noted that due to high power losses and limited dimensions an air cooling is not suitable for the continuous operation in the required operating point. For this study a cooling jacket is considered. In the presented work the thermal analysis is based on an analytic approach and is provided using the lumped-parameter model of the electrical machine. Similar thermal calculations are presented in [18], [19]. The following boundary conditions are assumed for the thermal analysis for this study: the rotor temperature is estimated to be $120\,^{\circ}\mathrm{C}$ (maximal allowed operating temperature of the permanent magnets) in each operating point, the temperature of the coolant is $70\,^{\circ}\mathrm{C}$(specified by the user), the average temperature on the housing surface is constant and reaches $75\,^{\circ}\mathrm{C}$. The thermal simulation was implemented in the two most crucial operating points of the machine: at maximal torque and at maximal speed. The temperatures, occurring in the electric machine are compared to the different design concepts. The results are presented in figures 10 and 11.

For the $p$=2 concept the highest temperature occurs at maximal torque operation in the end winding. The temperature reaches the value of $380\,^{\circ}\mathrm{C}$ and exceeds the maximal permissible value of common insulating class H [20] for the electric machines. Therefore, the concept with $p$=2 is not suitable for this application.

For the $p$=3 concept the highest temperature occurs at the maximal speed operation and reaches $214\,^{\circ}\mathrm{C}$. In this case the hot spot of the machine is the tooth tip of the stator. The common temperature capability of insulation coating is defined in [21]. According to [21] the maximal temperature of the machine core should not exceed over $180\,^{\circ}\mathrm{C}$. As it can be seen, both concepts can result in overheating at different operating points. However, it should be noted that the p=2 concept reaches a higher peak temperature in comparison with the p=3 concept.

As a consequence, the high copper losses are more crucial for the electric machine compared to the iron losses of the

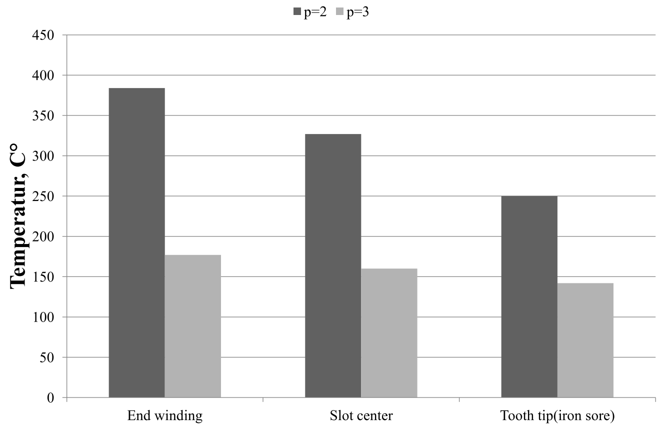

Figure 10. Temperatures in the electric machine at maximal torque.

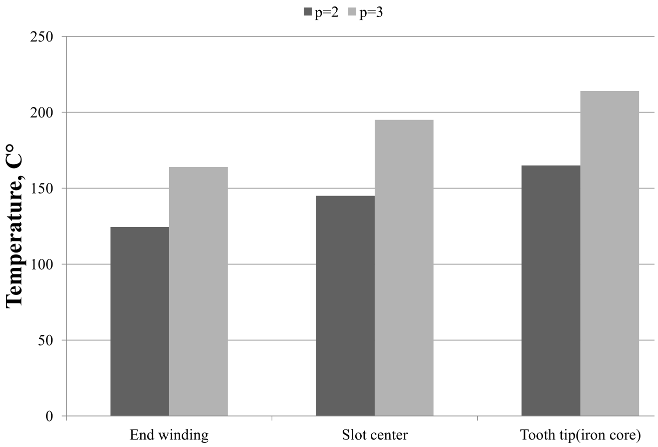

Figure 11. Temperatures in the electric machine at maximal speed.

same value. It means that the iron losses can be dissipated more effectively from the machine surface. For this reason, the concept with number of pole pairs $p$=3 is chosen for the given application. However, in order to avoid overheating at high speed operation the iron losses have to be reduced. This can be achieved by choosing another steel grade. Several sorts of the electrical steel were evaluated. The results of the comparison are presented in the next section.

## VI. COMPARISON OF DIFFERENT CORE MATERIALS

The choice of the electrical steel is the next important step. The goal is to reduce the iron losses and to improve the overall efficiency. Electrical steel impacts the torque capability and the iron losses in electrical machines. The iron losses occur in the stator and rotor of the electrical machine. The resulting iron losses in the stator and rotor of the machine are listed in II.

Table II
IRON LOSSES OF THE RESEARCHED MACHINE.

| | Stator iron losses | Rotor iron losses |
|---|---|---|
| Value | 3.418W | 150W |
| Percentage of the overall losses | 96% | 4% |

The rotor iron losses are only 4 percent of the overall iron losses. Therefore we focus on the reduction of the stator iron losses.

For iron losses estimation the 5-Parameter-IEM-Formula, described in [22], [23] is used:

$$P_{Fe} = P_{hyst} + P_{eddy} + P_{excess} + P_{sat}, \tag{4}$$

where $P_{hyst}$ describes hysteresis losses, $P_{eddy}$- eddy current losses, $P_{excess}$- excess losses and $P_{sat}$ saturation losses. The iron losses components can be calculated according to the following formulations:

$$P_{hyst} = a_1 \cdot B^{\alpha} \cdot f \tag{5}$$

$$P_{eddy} = a_2 \cdot B^2 \cdot f^2 \tag{6}$$

$$P_{excess} = a_5 \cdot B^{1.5} \cdot f^{1.5} \tag{7}$$

$$P_{sat} = a_3 \cdot a_2 \cdot B^{a_4+2} \cdot f^2 \tag{8}$$

$B$ is the amplitude of the flux density, $a_i$ is a material independent parameter. which is determined based on the measurement in an Epstein frame for a large frequency range [22]. The flux densities are evaluated based on FEM simulations. The eddy current losses, which are proportional to the square of the field frequency, are most crucial at high speeds. Figure 12 represents the iron losses distribution at high speed. The eddy current parameter $a_2$ depends on the sheet thickness [22], therefore electrical steel with lower sheet thickness has to be used for the designed PMSM. Several lamination materials with different sheet thickness are compared: M250-35A, NO-30 and NO-20. The identified parameters for the evaluated materials are presented in the table III. It should be mentioned that the reduction of the sheet thickness provides a lower stacking factor, which increases the copper losses. Due to reduction of the magnetic flux a higher current density is required to achieve the required torque. As a result a higher temperature is expected at high torque operation. To avoid overheating, the core length is increased. The typical stacking factors for particular sheet thicknesses are used in the simulation and shown in table III. The results of the stator material variation are presented in the table IV. The impact on the weighted efficiency is shown in the figure 13.

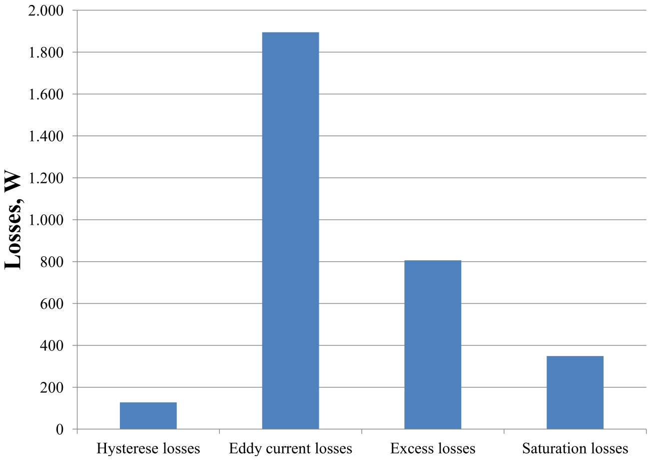

Figure 12. Iron losses distribution at maximal speed.

Based on the presented results, it can be concluded that the NO-20 electrical steel is most suitable for the motor design. According to the figure 13, the reduction of the sheet thickness to 0.2 mm has a significant impact on the machine

Table III
IDENTIFIED PARAMETERS FOR THE DIFFERENT MATERIALS.

| | **M235-35A** | **NO-30** | **NO-20** |
|---|---|---|---|
| Sheet thickness | 0,35 mm | 0,30 mm | 0,20 mm |
| Stacking factor | 97,00% | 96,50% | 95,00% |
| Core length | 130,00 mm | 130,50 mm | 132,50 mm |
| $a_1$ | $13,88 \cdot 10^{-3}$ | $20,63 \cdot 10^{-3}$ | $16,10 \cdot 10^{-3}$ |
| $a_2$ | $44,78 \cdot 10^{-6}$ | $39,98 \cdot 10^{-6}$ | $14,30 \cdot 10^{-6}$ |
| $a_3$ | 0,17 | 0,26$\cdot 10^{-3}$ | 0,14 |
| $a_4$ | 2,95 | 1,76 | 5,53 |
| $a_5$ | $0,52 \cdot 10^{-3}$ | $0,45 \cdot 10^{-3}$ | $0,33 \cdot 10^{-3}$ |
| $\alpha$ | 1,98 | 2,00 | 2,00 |

Table IV
RESULTS FOR DIFFERENT STATOR MATERIALS.

| | **M235-35A** | **NO-30** | **NO-20** |
|---|---|---|---|
| Operating point | **Maximum torque** | | |
| Copper losses | 1,41 kW | 1,43 kW | 1,46 kW |
| Iron losses | 0,13 kW | 0,15 kW | 0,10kW |
| Efficiency | 90,00% | 90,00% | 90,00% |

| Operating point | **Maximum speed** | | |
|---|---|---|---|
| Copper losses | 0,44 kW | 0,40 kW | 0,38 kW |
| Iron losses | 3,90 kW | 3,00 kW | 1,40 kW |
| Efficiency | 81,00% | 84,00 % | 91,00% |

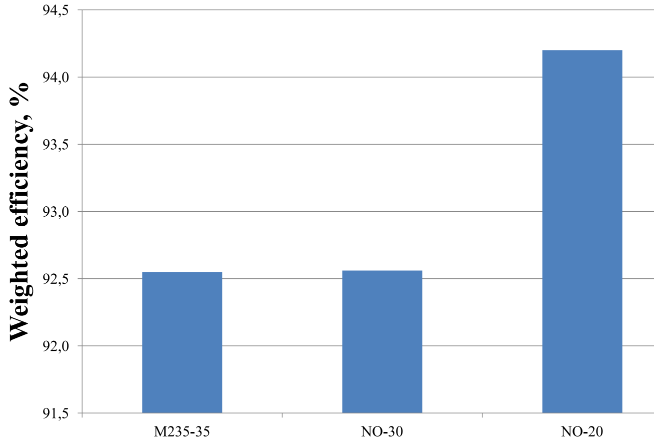

Figure 13. Impact of the different stator core materials on the weighted efficiency.

performance, increasing both the efficiency at high speed operation as well as the weighted efficiency. The thermal analysis provides the following results:

Table V
TEMPERATURES IN THE ELECTRIC MACHINE WITH NO-20 ELECTRICAL STEEL.

| **Operating point** | **Maximal speed** |
|---|---|
| End windings temperature | 126°C |
| Tooth tip | 144°C |
| Slot center | 137°C |

Using NO-20 electrical steel, the thermal loading of the machine is in the permitted limits in both relevant operating points.

## VII. RESULTS

The design of the electric motor with wide speed ratio for the integration as in-wheel drive, consisting of an electric machine and a gearbox, for an agricultural tractor is presented in this paper. A permanent magnet synchronous motor (PMSM) has been chosen for the application due to its high power density. It is shown that the required high maximum torque and high maximum rotational speed are a particular challenge for the motor design. Both high copper losses and high iron losses occur at corresponding operating points. Therefore, a compromise between reducing copper losses and iron losses in the design of the electrical machine is necessary. For this reason the comparison of the different concepts with different number of pole pairs over the weighted efficiency is implemented to consider a suitable motor concept. The concepts with the number of pole pairs $p$=2 and $p$=3 are possible for the given application, where the concept with $p$=2 provides a higher weighted efficiency. However, the concept with $p$=2 is not applicable due to the high end-windings temperature of 380 °C at high torque operating point. For the concept with $p$=3 the highest temperature occurs at maximal speed operation due to high iron losses. However, the thermal analysis shows that iron losses at high speed operation ($p$=3) can be dissipated more effective than copper losses at high torque operation ($p$=2). A design concept with $p$=3 is therefore chosen as most suitable. The designed permanent magnet synchronous motor is presented in figure 14.

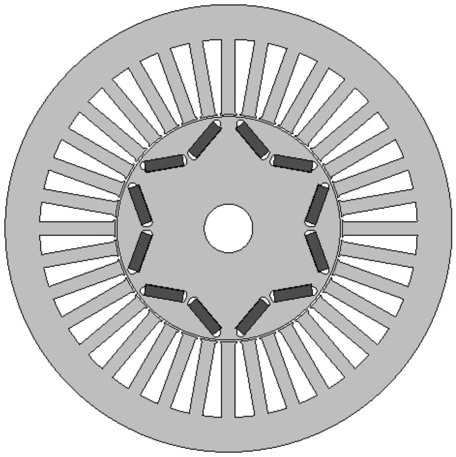

Figure 14. The studied PMSM with p=3.

It was found that the conventional electrical steel grades are not suitable due to high iron losses with the risk of overheating at high speeds. The main reason being high eddy currents losses, depending on the sheet thickness. In order to decrease the iron losses the comparison of different electrical steel sorts with different sheet thickness was performed. An electrical steel NO-20 with sheet thickness of 0.2 mm was chosen. The reduction of iron losses is necessary to avoid the overheating at high speed operation and also improves the weighted efficiency of the machine. In order to prevent the temperature increase at high torque the core length is increased. The resulting dimensions and values of the final geometry are listed in the table VI.

Table VI
THE FINAL MACHINE DATA.

| | |
|---|---|
| Number of pole | 6 |
| Number of slots | 36 |
| Stator outer diameter | 184,0 mm |
| Rotor outer diameter | 92,0 mm |
| Air gap length | 0,75 mm |
| Core length | 132,5 mm |
| Stacking factor | 95,0 % |
| End windings length | 65,0 mm |
| Overall length | 197,5 mm |
| Weighted efficiency | 94,2% |

It should be mentioned that the design of the high speed electric motor can also improve the power density and reduce the machine dimensions. However, the wide speed ratio and consequently required high maximal torque leads to the large outer dimensions. In this case the utilization of a shiftable gearbox can be meaningful. The drive unit, including a high speed electrical motor and a shiftable gearbox will be examined in further research.

## VIII. CONCLUSIONS

Mobile machinery is a promising branch for the application of electric motors, which have the potential to improve the efficiency of the vehicle. This study shows the potential of integrating an electric motor to an in-wheel drive, consisting of an electric machine and of a gearbox, fulfilling the particular requirements of an agricultural tractor.

Results presented in this work are intended to provide guidelines for design of the permanent magnet synchronous machine for both high torque and high speed application simultaneously. The design aspects, having the most significant influence on the machine dimensions and efficiency, are described.

## REFERENCES

[1] K. T. Renius and R. Resch, “Continuously variable tractor transmissions,” *Asae distinguished lecture series no. 29*, 2005.

[2] T. Minav, L. Laurila, and J. Pyrhönen, *Effect of an Electric Motor on the Energy Efficiencyof an Electro-Hydraulic Forklift, Energy Efficiency - A Bridge to Low Carbon Economy*, D. Z. Morvaj, Ed., 2012.

[3] P. Immonen, “Energy efficiency of a diesel-electric mobile working machine,” Ph.D. dissertation, Lappeenranta University of Technology, 2013.

[4] E. A. Burning, “Electric drives in agricultural machinery-approach from the tractor side,” *EIMA International-Proc. conf.*, 2010.

[5] S. Pick, S. Müller, P. Bach, and T. Zenner, “Effizienzpotenziale durch Elektrifizierung bei mobilen Arbeitsmaschinen,” *ATZoffhighway*, vol. Issue 2, 2013.

[6] “Electro-mechanical drivetrain for vehicles,” *Ruselprom, Russian electrotechnical concern.*

[7] K. T. Renius and M. Geimer, “Tractor engines and transmission,” *Jahrbuch Agrartechnik*, 2012.

[8] M. Geiler, W. Aumer, and M. Lindner, “Elektrifizierter Einzelradantrieb für Landmaschinen,” *In: VDI-Bericht Nr. 2138, VDI-Verlag GmbH*, 2011.

[9] K. Hahn, “Einsatzmöglichkeiten elektrischer antriebe für landwirtschaftliche maschinenkombinationen,” Ph.D. dissertation, Institut für Agrartechnik Hohenheim, 2010.

[10] A. El-Refaie and T. M. Jahns, “Comparison of synchronous PM machine types for wide constant-power speed range operation,” *Industry Application Conference, (IAS)*, vol. 2, pp. 1015–1022, 2005.

[11] J. Pyrhönen, T. Jokinen, and V. Hrabovcova, *Design of rotating electrical machines*. John Wiley&Sons, Ltd, 2014.

[12] T. Finken, M. Felden, and K. Hameyer, “Comparison and design of different electrical machine types regarding their applicability in hybrid electrical vehicles,” *Electrical Machines, 2008. ICEM 2008. 18th International Conference on*, vol. 5, 2008.

[13] T. Finken, M. Hombitzer, and K. Hameyer, “Study and comparison of several permanent-magnet excited rotor types regarding their applicability in electric vehicles,” *Emobility - Electrical Power Train*, 2010.

[14] Iung Moo Seo, Y.-K. Kim, I.-S. Iung, and H.-K. Iung, “Permanent magnet synchronous motor for electric tractor of 35 horsepower,” *ECCE Asia Downunder*, 2013.

[15] K. Vogt, *Elektrische Maschinen: Berechnung*. VEB Technik Verlag, Berlin, 1972.

[16] S. Y. Oh, S.-Y. Cho, J.-H. Han, H. J. Lee, G.-H. Ryu, D. Kang, and J. Lee, “Design of ipmsm rotor shape for magnet eddy-current loss reduction,” *IEEE Transactions on Magnetics*, vol. Vol. 50, No. 2, 2014.

[17] M. Tietz, F. Herget, G. von Pfingsten, S. Steentjes, K. Telger, and K. Hameyer, “Effects and advantages of high-strength non grain oriented (ngo) electrical steel for traction drives,” *Electric Drives Production Conference (EDPC)-Proc. Conf*, 2013.

[18] N. Rostami, M. R. Feyzi, J. Pyrhönen, A. Parviainen, and M. Niemela, “Lumped-parameter thermal model for axial flux permanent magnet machines,” *IEEE Transactions on Magnetics*, vol. 49,No. 3, 2013.

[19] G. Guemo, P. Chantrenne, and J. Jac, “Application of classic and t-lumped parameter thermal models for permanent magnet synchronous machines,” *Electric Machines and Drives Conference (IEMDC)*, 2013.

[20] *Electrical insulation -Thermal evaluation and designation*, IEC 60085:2007 Std.

[21] *Magnetic materials-Classification of surface insulations of electrical steel sheet, strip and laminations*, EN 10342:2005 Std.

[22] D. Eggers, S. Steentjes, and K. Hameyer, “Advanced iron-loss estimation for nonlinear material behavior,” *IEEE Transactions on Magnetics*, vol. Vol. 48, No. 11, 2012.

[23] S. Steentjes, M. Lessmann, and K. Hameyer, “Advanced iron-loss calculation as a basis for efficiency improvement of electrical machines in automotive application,” *Electrical Systems for Aircraft, Railway and Ship Propulsion (ESARS)*, 2012.

## IX. BIOGRAPHIES

**Svetlana Zhitkova** received her Dipl-Ing. degree in electrical power engineering from the State University of Aerospace Instrumentation, Saint-Petersburg, Russia. She has been working as a research associate at the Institute of Electrical Machines of RWTH Aachen University, Germany since January 2012. Her research interests include new arts of electrical machines, simulation and performance improvement of the electrical machines.

**Matthias Felden** received the Dipl.-Ing. degree in electrical engineering from RWTH Aachen University, Aachen, Germany, in September 2007. After that he has been working as a research associate at the Institute of Electrical Machines. His main research interests include design of the electric machine for the application in the automotive branch.

**David Franck** received the Dipl.-Ing. degree in electrical engineering from RWTH Aachen University, Aachen, Germany, in March 2008. After that he became of staff (research associate) at the Institute of Electrical Machines. Since 2011 he has been working as chief engineer of the Institute of Electrical Machines. His main field of research is the acoustic behavior of the electrical machines.

**Dr. Kay Hameyer** received his M.Sc. degree in electrical engineering from the University of Hannover and his Ph.D. degree from the Berlin University of Technology, Germany. After his university studies he worked with the Robert Bosch GmbH in Stuttgart, Germany as a Design Engineer for permanent magnet servo motors and vehicle board net components. Until 2004 Dr. Hameyer was a full Professor for Numerical Field Computations and Electrical Machines with the KU Leuven in Belgium. Since 2004, he is full professor and the director of the Institute of Electrical Machines (IEM) at RWTH Aachen University in Germany. 2006 he was vice dean of the faculty and from 2007 to 2009 he was the dean of the faculty of Electrical Engineering and Information Technology of RWTH Aachen University. His research interests are numerical field computation and optimization, the design and controls of electrical machines, in particular permanent magnet excited machines, induction machines and the design employing the methodology of virtual reality. Since several years Dr. Hameyers work is concerned with the magnetic levitation for drive systems, magnetically excited audible noise in electrical machines and the characterization of ferromagnetic materials. Dr. Hameyer is author of more than 250 journal publications, more than 500 international conference publications and author of 4 books. Dr. Hameyer is a member of VDE, IEEE senior member, fellow of the IET.