Realization of a wide speed range for an agricultural tractor

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***Abstract*—The electrification of agricultural vehicles is often discussed. Several prototypes, which use electric machines as a traction drive, are known. However, design of an electric motor is a particular challenge because of the special characteristics of the drive cycle of the agricultural tractor. High torque at low speed and low torque at high speed are required. This results in a wide speed range, which represents a particular challenge for the machine design. This paper describes the possibilities to realize the wide speed range and its influence on the design of electric machines.**

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

I. Introduction

Nowadays, the hybridization of the personal cars is state of the art. Hybridization and electrification of agricultural vehicles are also often discussed [1], [2], [3]. Integration of the electric drives in the agricultural vehicle concepts can reduce the fuel consumption up to 30%, according to [4]. The main advantages of the electric drives, according to [5] and [6], are higher efficiency, better controllability and lower maintenance, when comparing to the hydrostatic drives, commonly used in agricultural tractors.

The examples of the agricultural tractors with an electric motor as a traction drive are tractor concept Belarus Typ 3023 [6] and Eltrac [7], which use an induction motor as a central drive. A Rigitrac tractor concept, described in [8], is an example for the in-wheel drive. Some studies note the advantages of the in-wheel drive concept for an agricultural tractor, such as individual adjustment of the wheel torque, better mobility and higher redundancy. Therefore an in-wheel drive for an agricultural tractor is considered in this study. This can be a possible alternative to the hydrostatic-mechanical power split drives, which present the state of art in the branch of power transmissions for modern agricultural tractors [9]. For this reason a typical drive cycle for agricultural tractor is assumed.

Generally, the drive cycle of an agricultural tractor includes two speed areas: for farm work and transportation operation [9], [10]. This results in a wide speed range of the motor. A high speed is needed for the transportation of the vehicle on the roads. In the farm work operation a high torque is required in order to avoid the wheel spinning in case of poor ground contact. For this reason a limited slip differential can be integrated. In the modern tractors, using hydrostatic-mechanical power split transmission, a hydrostatic transmission is utilized, when operating at high torque and low speed, and a mechanical transmission is utilized at lower torque and high speed. In case of an in-wheel drive, each motor has to be able to provide a maximum torque, without overheating. On the other hand safe operation at maximum speed has to be possible. For the given application the following requirements on electric motor exist: maximum operation torque of $85\,\mathrm{Nm}$ at $2.000\,\mathrm{rpm}$ and maximum speed of $20.000\,\mathrm{rpm}$, at which a torque of $12\,\mathrm{Nm}$ is required. This results in a speed range 1:10. The further constrain is a strongly limited space availability for the integration of an electric motor. A maximum outer diameter of $184\,\mathrm{mm}$ and maximum overall length of $200\,\mathrm{mm}$ are predefined.

Due to a maximum required torque and high power density, a permanent magnet synchronous machine (PMSM) with internal V-shaped magnets is chosen for this application [11]. The permanent magnet material NdFeB is chosen as a compromise between high remanence flux density and high thermal stability. The material data are given in [12]. For the copper fill factor a common value for a machine wound distributed winding of $48\,\%$ is assumed. The winding temperature is assumed according to the maximum value of an insulating class H [13], which is common for electric machines. For this study a cooling jacket is considered. The electric machine is operated from power converter. For the given application the maximum DC voltage is limited to $650\,\mathrm{V}$. A standard power converter has to be chosen for the control of the electric traction motor.

II. Realization of the required speed range

In order to describe the possibilities to realize a wide speed range the basic equations of the PMSM in the d/q coordinate system (power invariant) have to be analyzed. The torque can be calculated by standard formula [14]:

$$T = p \cdot (\Psi_d \cdot i_q - \Psi_q \cdot i_d) \tag{1}$$

where Ψ is the flux linkage of the machine, i the current and p the number of pole pairs. The flux linkage in the direction of the d-axis can be calculated as follows:

$$\Psi_d = L_d \cdot i_d + \Psi_{PM} \tag{2}$$

where L_d is the direct inductance and Ψ_{PM} is the flux of the permanent magnets. The flux linkage in the direction of the q-axis can be calculated as follows:

$$\Psi_q = L_q \cdot i_q \tag{3}$$

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The phase current results of the direct and quadrature current components:

$$I = \sqrt{{I_q}^2 + {I_d}^2} \quad (4)$$

where $I_q = \frac{i_q}{\sqrt{3}}$ and $I_d = \frac{i_d}{\sqrt{3}}$. The current limits of the power converter have to be considered. The voltage can be calculated by following equations:

$$U_d = R_1 \cdot i_d + \frac{d\Psi_d}{dt} - \omega \cdot \Psi_q \quad (5)$$

$$U_q = R_1 \cdot i_q + \frac{d\Psi_q}{dt} + \omega \cdot \Psi_d \quad (6)$$

The phase voltage can be calculated as:

$$U = \sqrt{{U_q}^2 + {U_d}^2} < \frac{U_{DC}}{\sqrt{3}} \quad (7)$$

R_1 is the resistance of the stator winding and ω is the angular frequency, which is the product from the number of pole pairs p and the rotational speed n. The maximum voltage is limited by the DC-voltage of the power converter.

According to equations (4) and (7) current limitation can be presented by a circle in the $i_d - i_q$-plane and voltage limitation by an ellipse, as it is shown in the figure 1. When the rotational speed increases, the ellipse gets smaller. Vector I_{max} represents the current limitation of the power supply. Figure 2 shows the drive cycle of the studied application with wide speed range.

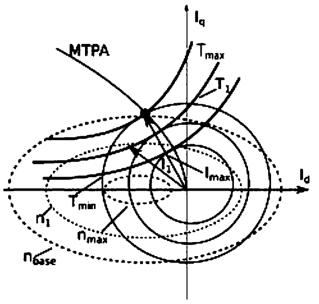


Fig. 1. Current and voltage limitation of the PMSM.

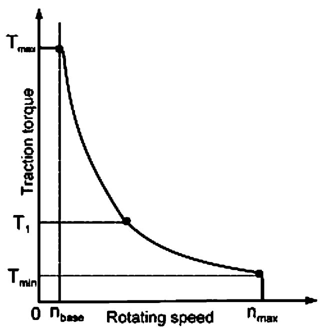


Fig. 2. Torque-speed diagram of the PMSM with wide speed range.

The torque in the $i_d - i_q$-plane can be described as a hyperbole. The point, at which the torque hyperbole touches the current circle without crossing is the optimal operating point, at which the required torque can be achieved with a minimum possible current. For each required torque there is a combination of i_d and i_q currents, at which a minimum current is resulted. Control strategy of electric motor can be adjusted for the reason to achieve a maximum torque per ampere (MTPA). MTPA control strategy is suitable for the given application in order to reduce the copper losses. MTPA trajectory is shown in figure 1.

The required torque T_1 at rotational speed n_1, which is higher than the base speed, cannot be achieved with a minimum possible current without exceeding the voltage limitation. This is also noted in the study [15]. For this reason current i_d has to be increased in the negative direction. Up to here field weakening operation area begins. From the figure 1 it can be concluded that required minimum torque (T_{min}) at maximum speed (n_{max}) cannot be achieved in spite of field weakening, when considering current and voltage limitation. This demonstrate the challenge of realization of wide speed range for given application. The possibilities to realize wide speed range have to be considered.

III. Influence of Wide Speed Range on the Machine Design

In the next step the influence of the motor requirements on the machine design is demonstrated. Firstly, it should be mentioned that due to strong limited volume, wide speed range has to be realized with one electric motor. This means that the designed electric motor has to be capable to achieve the high torque at low speed and low torque at high speed. Considering the equations above, can be noted that a high current is needed for the maximum torque operation, according to equation (1). A high number of turns can increase the flux linkage and therefore torque capability of the machine. On the other hand, for a maximum speed operation a low number of turns is most suitable to avoid exceeding the voltage limits, according to equation (6). A low number of turns results in higher currents at maximum torque operation. Current limits of the power converter have to be considered. A higher number of pole pairs can decrease the current requirements at high torque application, according to equation (1) and therefore high copper losses, which are proportional to the square of the current of the electric machine. The same effect can be achieved by choosing permanent magnets with higher remanence flux density. In this case a higher permanent magnet flux linkage can additionally reduce the current requirements and therefore copper losses. According to equation (6) a lower number of pole pairs reduces the angular frequency and is more suitable at high speed operation. In addition, iron losses are more significant when operating at high speed. Considering that iron losses depend on electric frequency of the magnetic field and of the flux density in iron, a lower number of pole pairs in combination with a lower remanence flux density of magnets are suitable for high speed operation. Contrary differences between requirements on high speed and high torque operations are summarized in the table I.

TABLE I
Requirements of different operating points.

High torque	High speed
High number of pole pairs	Low number of pole pairs
High number of turns	Low number of turns
High magnet flux density	Low magnet flux density
High current	High voltage
High copper losses	High iron losses

Considering the requirements, two different machines are designed for high torque and high speed application in order to demonstrate the conflict between two crucial operating points. Machines are designed under consideration of the volume limits and maximum DC-voltage of 650 V. For the high speed application a minimum possible number of pole pairs p = 2 is chosen. A lower number of pole pairs results in larger dimensions and does not fulfill the volume limitation. For a high torque application a number of pole pairs p = 4 is preferred, because a higher number of pole pairs is not suitable due to limited outer diameter. In general, electric machines with high number of pole pairs are designed with large outer diameter and short active length (example: hydro-generator). Electric machines for high torque application are generally designed with larger rotor volume. It can be explained by the relation between output power and machine dimensions. The output power of electric machines can generally be described by:

$$P = \sigma \cdot V_{rotor} \cdot n, \tag{8}$$

Here σ is the utilization factor of electric machine [16]. By increase of the required rotational speed a lower torque and, therefore, lower utilization and rotor volume are needed. High speed machines are designed with smaller dimensions. In addition, when designing electric machines for a high speed application, a mechanical safety has to be considered. In order to avoid the damage due to high centrifugal forces, a smaller rotor diameter has to be chosen. It is because the centrifugal force is proportional to the rotational speed and square of diameter of the rotating body.

$$F = m \cdot \frac{{D_r}^2}{4} \cdot \omega \tag{9}$$

Here m is the mass of the rotating body. The highest mechanical stress occurs in the magnet bridges, which is shown in figure 3, since generally bridges are designed thin in order to reduce the leakage flux. The magnetic circuit has

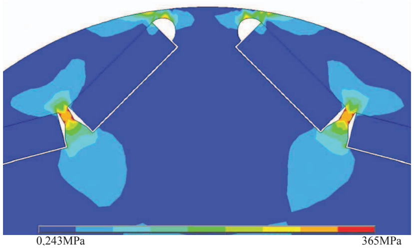


Fig. 3. Mechanical stress in the rotor of the electric machine.

also be designed differently. For high speed machines larger tooth width b_t and jocke height h_y are suitable in order to reduce the flux densities in the magnetic circuit and therefore iron losses. Flux density in the tooth and yoke of electric machine can be calculated by equations (10) and (11).

$$B_t = \frac{1,03 \cdot \tau_n \cdot B_g}{b_t}, \tau_n = \frac{\pi \cdot D_r}{N_{slot}} \tag{10}$$

$$B_y = \frac{1,05 \cdot \tau_p \cdot B_g}{2 \cdot h_y}, \tau_p = \frac{\pi \cdot D_r}{2p} \tag{11}$$

Here N_{slot} is the number of slots respectively teeth and B_g is the air gap flux density. In contrary, for the high torque machine thinner teeth and yoke are more suitable in order to ensure a sufficiently-dimensioned slot area and therefore to avoid the overheating due to high copper losses. Parameters of two electric machines for high torque and high speed operations are presented in the table II. The cross-sectional area of the magnetic circuit of both machines are shown in figures 4 and 5.

TABLE II
PARAMETERS OF ELECTRIC MACHINES FOR DIFFERENT OPERATING POINTS.

Parameter	High torque	High speed
Outer diameter, [mm]	184	167
Overall length, [mm]	183	200
Rotor diameter, [mm]	106	84
Active length, [mm]	129	120
Number of pole pairs	4	2
Number of teeth	48	24

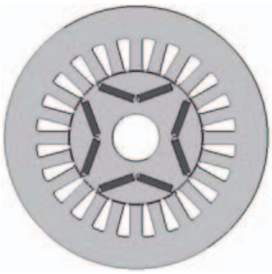


Fig. 4. PMSM for high speed operation.

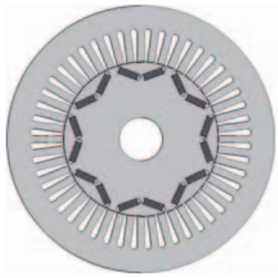


Fig. 5. PMSM for high torque operation.

The efficiency maps of two designed machines are presented in figures 6 and 7. Efficiency calculation includes copper losses, iron losses and mechanical losses. The eddy current losses in permanent magnets are not considered, because in interior permanent magnets significant high losses are not expected [17].

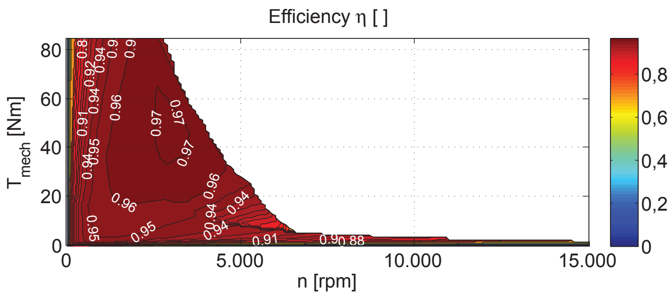


Fig. 6. Efficiency map of electric machine for high torque application.

From figures 6 and 7 it can be seen that the machine for high torque application achieves a high efficiency of 96% at high torque and low speed. At higher speed only low torque with low efficiency can be achieved. The maximum possible speed for this machine is equal to 12.000 rpm. In contrary, the machine for high speed application has high efficiency of 94% at maximum required speed. However, a maximum

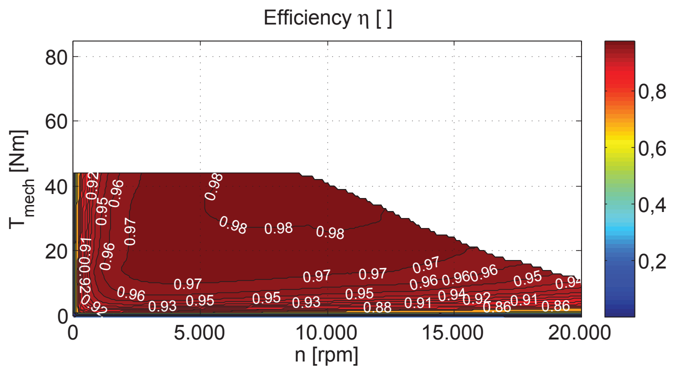


Fig. 7. Efficiency map of electric machine for high speed application.

required torque can be achieved by further increase of current, which results in high copper losses and overheating of the machine at this operating point. It can be concluded that in order to achieve high efficiency at both operating areas, two different machines are required, which is not possible. Therefore, an electric machine has to be designed, which can achieve both operating points. Here it should be mentioned that due to contradictory requirements a compromise has to be found.

A. Design of the drive unit with wide speed range

In the first step the suitable number of pole pairs is assumed. The maximum possible number of pole pairs p = 3 is considered for the given application. A higher number of pole pairs ensures higher iron losses, which can be crucial for the given application because of high required maximum speed. The influence of the number of pole pairs on the efficiency and operation of the given application is presented in previous research [18].

In the next step the suitable rotor dimensions have to be defined. The volume of the rotating part of the electrical machine is proportional to the torque capability $T \sim V_{rotor}$. On the one hand, the larger dimensions are needed for a maximum torque operation. However, the maximum rotor diameter is limited by maximum possible mechanical stress at maximum speed operation. A compromises from the mechanical safety and electromagnetic utilization is needed. For the described application a high strength electrical steel 280-30AP [19] is utilized as rotor material, for which a maximum mechanical stress of $370\,\frac{\mathrm{N}}{\mathrm{mm}^2}$ is evaluated.

Adjustment of the width of magnet bridges depending of the rotor outer diameter is necessary to avoid the damage of the rotor. A most suitable rotor diameter has to be chosen, at which a maximum torque can be achieved for the constant current. According to [16], electromagnetic torque of synchronous machine can be calculated as follows:

$$T = \sigma \cdot V_{rotor} = \frac{\xi}{\sqrt{2}} \cdot A \cdot B_g \cdot \frac{\pi}{2} \cdot {D_r}^2 \cdot l. \quad (12)$$

Here A is current layer and ξ a winding factor, depending on the winding configuration. For this application with distributed winding a winding factor is equal to $\psi = 0,96$. Current layer of electric machine can be calculated with a following equation 13:

$$A = \frac{2 \cdot m_1 \cdot w \cdot I}{\pi \cdot D_r}. \quad (13)$$

Here m_1 is number of phases ($m_1 = 3$) and w is number of turns of the winding. From equation (12) it can be concluded that increase of rotor diameter results in higher torque (active length l is kept constant). However, change of the rotor diameter influences current layer and air gap flux density. When outer stator diameter is limited, increase of rotor diameter results in decrease of current layer, according to equation (13). In addition the number of turns has to be decreased due to reduction of the stator slot area, which makes the negative influence stronger. In contrary, air gap flux density, which depends generally on the permanent magnet mass m_{PM} and remanence flux density B_r, is increased due to increase of the mass of magnet material.

$$B_g \sim B_r, m_{PM} \sim B_r, V_{PM} \sim D_r. \quad (14)$$

By this way, a most suitable combination of current layer, air gap flux density and rotor diameter can be found, so that a maximum torque at limited outer dimensions can be achieved. For the given application a most suitable rotor diameter of $92\,\mathrm{mm}$ is evaluated. Magnet thickness and placement are also adjusted under consideration of the maximum possible flux and mechanical stability. The minimum possible bridge tickness of $1,4\,\mathrm{mm}$ is considered from the machanical stress calculation. Field and torque calculation are provided by FEM simulation. In the next step, the end winding length l_{end} can be approximately evaluated as $l_{end} = 1,3 \cdot \tau_p$, according to [16]. Thus, the end winding length of $65\,\mathrm{mm}$ is assumed. A maximum possible active length of $130\,\mathrm{mm}$ can be also considered.

After dimensioning of the active part of electric machine the magnetic circuit can be designed. Tooth width b_t and yoke h_y height have to be considered with a purpose to ensure a good electromagnetic utilization and thermal loading. Very thin teeth and yoke result in larger slot area. In this case a lower current density is needed, which reduces the thermal loading. However, possible strong saturation leads to additional losses, especially at high speed operation, where iron loss are dominant. A dependence between slot area and dimensions of magnetic circuit can be explained by the formula 15:

$$A_{slot} \sim \frac{1}{b_t}, \frac{1}{h_y} \quad (15)$$

Assuming a maximum possible thermal loading for the winding isolation of $180\,^{\circ}\mathrm{C}$ at maximum torque operation, the tooth width of $5,5\,\mathrm{mm}$ and yoke height of $14\,\mathrm{mm}$ are evaluated for the presented machine. Summarizing, the designed machine presents a combination between high torque and high speed machine.

After completing of machine dimensioning the possibilities to realize the required wide speed range have to be studied. Here, different approaches to achieve the required wide speed range can be applied: increase of the base speed, adjustment of the winding configuration. when operating at higher speed (winding reconfiguration) and application of a shiftable gearbox transmission.

IV. Increase of the Base Speed

Increase of base speed results in decrease of the speed ratio of electric motor. Base speed is limited by maximum DC-voltage of the power supply, which is equal to 650 V for the given application. From equation (7) it can be concluded that voltage is proportional to the flux and speed of the machine. In order to increase the base speed, flux linkage has to be reduced. This can be achieved by reduce of number of turns of the machine winding. It results in a higher required current for the maximum torque, which can be concluded from equation (1).

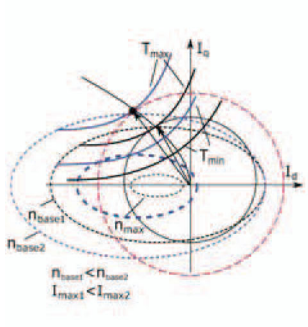


Fig. 8. Current and voltage limits for the adaptable turns number.

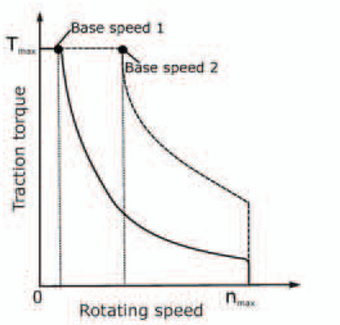


Fig. 9. Torque-speed diagram by reduced speed range.

In the figure 8 it can be seen that the reducing of the number of turns results in change of size and placement of voltage-limit ellipse. The voltage ellipse for the new base speed (n_{base2}) is located on the left to the initial base speed n_{base1} and has larger dimensions. At the same time the torque hyperbole for the equal torque (T_{max2} and T_{min2}) are located higher in comparison to initials the (T_{max1} and T_{min1}). Therefore a higher current limit (I_{max}) has to be chosen in order to achieve the required maximum torque. Now, the required torque T_{min} can be achieved at maximum speed without exceeding the voltage limits. The change of the drive cycle can be seen in figure 9. The resulted maximum power is higher than required. In this case power supply with higher current limits has to be chosen. A theoretically possible electric power will not be used by the drive unit, which means an oversizing of the machine. For this application a distributed winding without short pitching is predefined. Winding design is provided for the maximum speed operating point in order not to exceed the maximum voltage. However, the highest possible number of turns has to be considered in order to avoid large required conductor cross-section and a high number of parallel conductors, which results in a complicated winding technology, so that a winding cannot be automated in manufacturing. A number of turns equal to 30 is considered for this application. In order to reduce the number of parallel conductors the phase coils are connected parallel. The resulted efficiency map of designed electric machine is presented in figure 10.

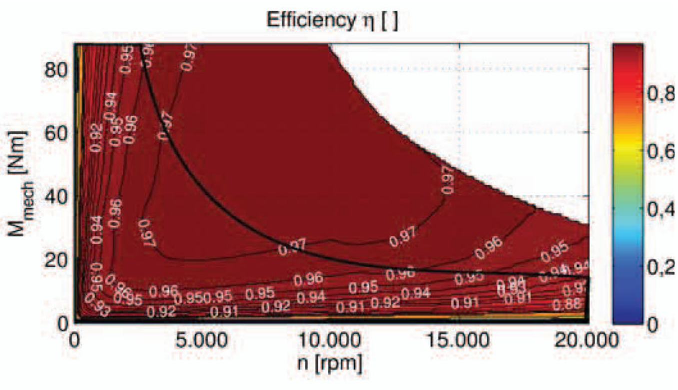


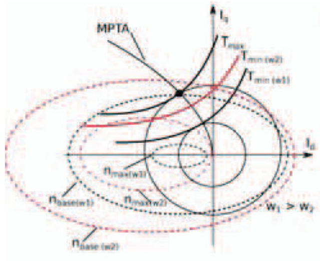
Fig. 10. Efficiency map of electric machine for wide speed range.

Both operating points can be achieved. Efficiency at maximum torque is 91% and at maximum speed 92%, which is smaller, than in case of machines, designed for a particular requirement. This demonstrates the compromise when designing an electric machine for contrary requirements (high torque and high speed). It can be seen that operating point, which are situated behind the constant power line, are located under the area with maximum efficiency. The area of the best efficiency is not used.

V. Winding Reconfiguration

The second possibility is winding reconfiguration. In order to achieve operating points in high speed area it is possible to use another winding, when operating speed has to be increased. This can be realized by changing the winding configuration during the machine operation, when rotational speed has to be increased. There are several possibilities to change the winding configuration: changing the number of pole pairs, switch between two different windings and change of the effective number of turns.

In general, changing of number of pole pairs is possible. Here it should be mentioned that changing of the number of pole pairs is not suitable in case of a PMSM machine without complicated operation strategy, because rotor geometry depends on the number of pole pairs and cannot be changed during the operation. This solution can be possible at the electric machine types, where the rotor pole number is adjusted depending on the stator pole number (induction machine with squirrel-cage rotor). For the second possibility there are two separate windings with different number of turns. However, slot fill factor is reduced in this case, because in the same slot the turns of both windings are located, this is crucial at high torque operation due to higher current and therefore high copper losses. Therefore, the machine design with two windings is excluded. Reconfiguration of the effective number of turns is most suitable for the given application. Here the coils of each phase are connected in series, when operating at high torque. For the high speed application the coils have to be connected parallel. This possibility is, for example, utilized in the drive, presented in [8]. The influence on the torque-speed diagram is explained in figure 12.



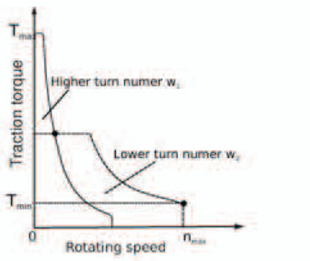


Fig. 11. Current and voltage limits for the concept with two windings.

Fig. 12. Torque-speed diagram for the concept with two windings.

As it can be seen in the figure 11, the voltage limiting ellipse gets larger and is replaced to the left, when number of turns is decreased. The hyperbole, which describes minimum torque T_{min} moves up, because, when decreasing the number of turns and therefore the flux linkage, larger current is needed in order to achieve the torque. However, the machine can be operated at minimum torque and maximum speed without exceeding the current and voltage limits. For other operating points the control operation is provided on the same way. The driving cycle of the electric motor with two different winding configurations consists of two operation areas, as it is shown in figure 12. Efficiency map of the electric motor for the given application with winding reconfiguration is shown in figure 13.

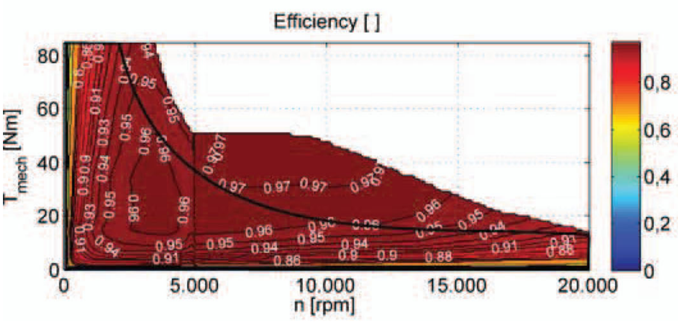


Fig. 13. Efficiency map of the electric motor with winding reconfiguration.

Now, the wide speed range can be achieved without increase of the base speed and current limits. Efficiency at maximum torque achieves 91% and at maximum speed 92%, which is the same, as in case of the machine with a higher base speed. This is because the overall flux linkage does not change. Better efficiency is therefore note expected. However, a smaller power converter can be chosen for this application. The thinner phase cables can also be chosen cause of smaller input current. This can additionally save space and reduce the weight of the vehicle.

Here should be mentioned that winding reconfiguration can be provided either using an electromechanical contactor or by a special concept of the power converter, as it is presented in [20]. Here a special production of the power converter can be necessary, which means a additional challenge for drive unit design and higher costs.

VI. Application of a Shiftable Gearbox

A shiftable gearbox transmission system is widely used in the automotive application, when the required speed range of the vehicle cannot be achieved by the traction motor. A shiftable gearbox is a gearbox with variable gear ratios [21], which can be switched while the vehicle is operated. For the off-road application the vehicle has to run without shifting up, because during a field working the break of the traction force has to be avoided, according to [22]. For the transport operation the vehicle speed vary from zero up to maximum speed but with lower torque in comparison to the field working. Here it can be shifted while vehicle is moving. So, a shiftable gearbox transmission with two different speed ratios can be integrated in the drive unit. The studies, presented in [23] and [24], describe a similar application. An electric motor in combination with a shiftable transmission gear is utilized as an in-wheel drive of a tractor. These studies present the advantages of utilizing a shiftable gearbox, such as a possibility to reduce the volume of the electric machine. In the mentioned studies shiftable transmission adapts the maximum speed of the electric machine. However, adaptation of the maximum torque is also possible. In this case the requirements on the maximum torque can be reduced in dependence of the speed ratio of each shift-stage. Therefore, the electric machine can be designed smaller according to equation (12). However, it should be considered that an integration of a shiftable transmission results in additional effort and volume, because an additional shift-stage has to be installed between electric motor and gear unit. For this reason a concept, including a shiftable gearbox transmission is excluded.

VII. Results

For the presented application two possibilities to realize the wide speed range are suitable: increase of the base speed and changing of the number of turns during the operation. Now, the considered possibilities to achieve a wide speed range can be compared. The details are presented in table III.

TABLE III
Comparison of the drive units for wide speed range.

Parameter	Base speed	Winding reconfiguration
Maximum phase current	115 A	38 A
Current of IGBT module	150 A	75 A
Volume of IGBT module	$0,05\,dm^3$	$0,15\,dm^3$
Overall efficiency	94,2 %	94,2%

From the table III it can be concluded that increase of base speed and therefore current limits results in significant larger dimensions of the power converter, because a higher number of parallel connected switched elements is needed in this case. This results additionally in a larger cross-section of the phase cables, connecting the electric machine to the power supply. This has to be also considered, because the installation volume inside of the agricultural vehicle is also strong limited. The main advantage of this solution is that there are no additional components required for the control of the electric machine.

Winding reconfiguration is a possible alternative, which allows to choose a smaller power converter. In addition, the power losses on the phase cables can be reduced due to a reducing of the phase current and cross-section of the phase cable. Considering that required cross-section of the cables is proportional to the phase current, the possible reduction of the power losses can be calculated as follows:

$$\Delta P_{new} = {I_{new}}^2 \cdot R_{new} = \frac{I^2}{k^2} \cdot R \cdot k = \frac{\Delta P}{k} \qquad (16)$$

Here k is coefficient, which is proportional to the phase current reduction, when effective number of turns is changed due to winding reconfiguration. So, the losses in the phase cables can be reduced by a factor k. In dependence of the requirements on current and voltage limits and maximum available space one of the both possibilities can be suitable.

VIII. Conclusions

Design challenges of the electric machine for a particular application with required wide speed range is presented in this study. Under consideration of the strong limited installation volume the requirement on a wide speed range is crucial. When designing electric machines for the best efficiency at maximum torque or at maximum speed, the resulted machines are significantly different. Contradictory requirements influence the design of the electric machine, so that best possible efficiency cannot be achieved neither at maximum torque nor at maximum speed. Oversizing of the machine leads to higher required current limits. A larger power converter and thicker phase conductors are also be considered during the design of the complete vehicle. Application of winding reconfiguration or shiftable gearbox is a theoretically possible alternative. However, the complete required volume for the drive unit can be not sufficient, because in this case additional drive unit components are needed.

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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.

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