Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 24 (2018) 159–165

Procedia
MANUFACTURING

www.elsevier.com/locate/procedia

4th International Conference on System-Integrated Intelligence

Hybrid Spindle – An approach for a milling machine tool spindle with extended working range for HSC and HPC

B. Denkena[a], B. Bergmann[a], M. Mücke[a]*, J. Königsberg[b], B. Ponick[b]

[a]*Leibniz Universität Hannover, Institute of Production Engineering and Machine Tools (IFW), An der Universität 2, 30823 Garbsen, Germany*
[b]*Leibniz Universität Hannover, Institute for Drive Systems and Power Electronics (IAL), Welfengarten 1, 30167 Hannover, Germany*

Abstract

Commercial motor-driven spindles for milling machine tools are generally developed for specific machining operations, such as HPC (High Performance Cutting) or HSC (High Speed Cutting). HPC and HSC require significantly different working ranges regarding spindle speed and torque. E.g. in HPC operations, high torque at low spindle speeds is needed. The two working ranges are covered only limited by a conventional spindle so far. However, a spindle system that can switch the working range allows cost-effective manufacturing of a wider range of materials within the same machine tool. The spindle bearings and the power electronics supply are challenges, when switching between both working ranges. HPC operation requires high bearing stiffness in order to transmit high forces occurring during the cutting process. However, the associated high bearing preload leads to high frictional losses at high speeds for HSC operations. Furthermore, the wide operating range generates contrary requirements for the motor winding. To increase the spindle speeds with a winding being assembled for high torques, the current has to be increased. For this purpose, expensive and non-standardized motor inverters are required. This paper introduces a concept to overcome these challenges. Firstly, an approach to adjust the bearing preload is presented, using a compact, electrically controlled bearing preload element, which is suitable for industrial applications. Next, an approach for a reconfigurable winding design of the spindle motor is shown. This allows electrical switching between the working ranges using conventional motor inverters. Finally, an analysis of the conditions of use of the hybrid spindles is presented.

Peer-review under responsibility of the scientific committee of the 4th International Conference on System-Integrated Intelligence.

Keywords: Machine tool; Hybride spindle; Milling

---

* Corresponding author. Tel.: +49-0511-762-18276; fax: +49-0511-762-5115.
E-mail address: muecke_m@ifw.uni-hannover.de

Peer-review under responsibility of the scientific committee of the 4th International Conference on System-Integrated Intelligence.
10.1016/j.promfg.2018.06.045

1. Introduction

Motor spindles with a wide range of rotational speed and torque have the potential to increase the productivity for manufacturing various materials within only one milling machine tool. The productivity is increased by an optimum adaptation to the efficient processes like HSC and HPC milling [1]. HSC operation is characterized by high cutting speeds, which leads to high rotational speeds. In combination with small chip volumes and high machine feeds, good surface qualities are achieved at high removal rates [2]. At HPC milling, high chip removal rates are achieved by applying high depth of cut and cutting width. This requires high torque at low rotational speeds [3]. Conventional spindles offered on the market are only limitedly suitable for the utilization within both operation, due to their limited torque working range (Fig. 1). Powerful motor spindles are optimized for the individual requirements of individual processes. The bearings and the drive are designed either for high rotational speeds for use in HSC milling or for high torques for HPC milling. Thus, the bearing arrangement and the drive are designed only for HSC or HPC milling [1]. For technical and economic reasons, an operating switchover including an adaptive bearing system has not been used frequently so far.

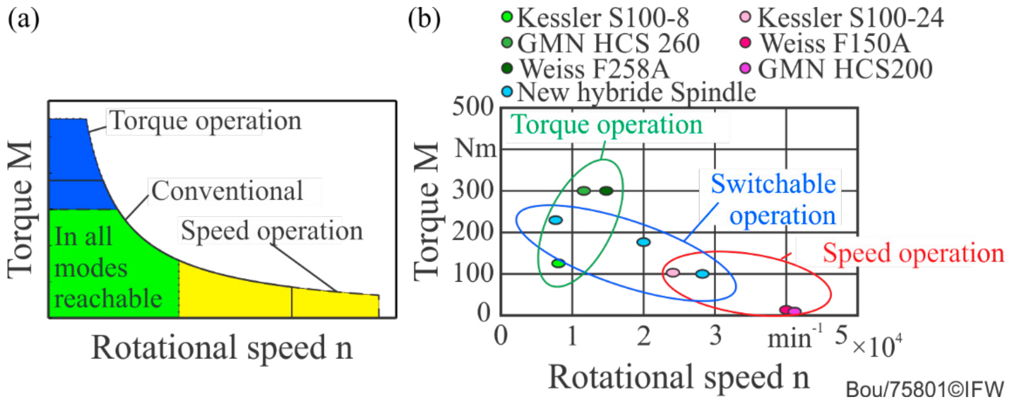


Fig. 1. (a) Spindle operating ranges and (b) the desired operating range of the switchable spindle to be developed

There are two main challenges in designing a spindle for HSC and HPC machining. The design of the spindle bearing for high speeds and high rigidity leads to a contradiction; the bearings have to be highly rigid to transmit high cutting forces occurring in HPC milling with little deformation. Therefore, large bearings in combination with high bearing preloads are used. However, this design is not suitable for operations with high rotational speeds.. Because of centrifugal forces, the spindle bearings are subjected to high thermos-mechanical loads. Consequently, the bearings heat up, which can lead to a field of thermo-mechanical instability. As a result of the heating, the spindle bearings experience a thermal expansion which causes a preload increase, in turn leading to higher power losses in the spindle bearings. Therefore, for HSC milling spindles smaller bearing diameters and lower bearing preloads are preferred [1].

A further limiting factor for a universal spindle is the winding system in the spindle motor. The maximum speed of the spindle motor is limited by the voltage and the output frequency of the inverter. The maximum torque is limited by its maximum current. The number of turns per phase is a significant parameter for the ratio between voltage and current. However, the demands for high torque and high speed generate contrary requirements for the number of turns per phase. A HSC spindle requires a lower number of turns per phase than a HPC spindle, when the supply voltage is the same [4]. By overcoming these two main challenges, hybrid spindles can provide an economic solution to utilize the whole potential of universal machine tools.

2. State of the art

In research, various approaches to variate the bearing preload are known [1]. Especially, variations of bearing preload depending on the rotational speed were investigated. Furthermore, the effects of variable bearing preloads on spindle stiffness and spindle dynamics were analyzed. By adapting the preload and consequently, the stiffness and dynamic behavior process instabilities can be avoided. This way, the surface quality can be increased. However, due to complexity of the mechanisms to variate the preload there is no commercial relevance. The main challenges being mentioned are the structural integration, control of force actuators for adapting the bearing preload and the drive design.

In [5, 6], the variable bearing preload approach is based on piezo actuators being integrated into the spindle housing. An axially stored element including the actuator transmits the actuator forces to the outer bearing rings and thus applies the preload. In [7], a similar design is realized whereby the preload forces are generated by electromagnets. Both approaches are tested in turning operation of the spindle. The major disadvantages of these approaches are the costs. In addition, there is a large requirement for space to generate sufficient force densities and strokes that lead to an increasing spindle size. Another problem is the thermal interaction between the actuators and the bearings. This interaction affects the dynamic behavior of the actuators and in particular the force control due to unpredictable thermal expansion. This can be improved by the integration of force sensors between the piezo actuator and the bearing ring for measuring the preload force. In [8], the preload of a bearing can be varied by changing the oil pressure in a circumferential notch on the outer ring of a double-row spindle bearing. This approach does not require mechanical elements within the spindle. However, disadvantages are the sealing of the bearings and the complex hydraulic system for controlling the oil pressure. The approach in [9, 10] uses the radial deformation of a flexible element due to the acting centrifugal forces. The element is mounted on the spindle shaft. By a lever mechanism, the radial deformation of the element is converted into an axial displacement, whereby the bearings preload is reduced. The approach allows a simple generation of bearing preload forces without using additional actuators since the centrifugal force itself is speed-dependent. However, a disadvantage of this approach is the required, possibly large mass of the rotating element that additionally negatively influences the dynamic behavior of the spindle shaft. Furthermore, a control of the bearing preload force is only possible to a limited extent.

The restrictions due to technical limits of the power electronics is another challenge for the realization of a spindle system with switchable operation mode. The reconfiguration of a winding system, to change the ratio of current and voltage, is state of the art. However, the applications and requirements are different. The star to delta conversion is used to reduce the locked rotor current of induction machines by a factor of three [11]. It can also be used to extend the speed by $\sqrt{3}$ [12], although it can be susceptible to additional losses due to circulating currents within the delta-connection. A reconfigurable winding system with the aim to extend the operating range of an inverter-powered electrical machine towards contrasting requirements for torque and speed is known for traction applications [13] but not for milling spindles. A tapped winding is most likely used in small machines, because of the induced voltage in the segregated turns and the rising currents due to a reduced number of turns. An advantage of this method is the individual number of turns that is segregated and does not contribute to the torque generation [14]. Switching between different numbers of parallel branches results in a similar behavior like a tapped winding, although the whole winding can be used for torque generation. Parallel branches halve the ratio between voltage and frequency [15]. In terms of output power, possible methods for a reconfigurable winding are a star to delta conversion and the use of parallel branches, because both methods use the whole number of turns. It can be summarized, that there is no economical way to adapt the spindle bearing preload and the motor characteristics to build a hybrid spindle for an industrial use.

3. Concept

To enable the benefits of the use of a hybrid spindle within an industrial application, a costly approach to adapt and control the bearing preload is required. Additionally, the motor characteristic has to be electrically adaptable. This allows the switching between the operation modes for HSC and HPC machining in the industrial use. Therefore, two new approaches are presented.

The new approach to adapt the bearing preload bases on an active but nevertheless cost-effective and easily implementable thermo-mechatronic system (Fig. 2 (a)). This is realized by a rotationally symmetric preload element with integrated Peltier elements, which allows a simple electrical control. Like rigid elements used today in spindles to preload the bearing, the preloading element is coaxially mounted between the spindle housing and the outer bearing ring or between a double-row spindle bearing. When the Peltier elements are supplied with current, a temperature difference between the outer and the inner lateral surface of the preload element occurs. This leads to a deformation of the element structure. The advantage of this approach is that only a small amount of heat is transferred into the spindle as power losses. The deformation of the preload element causes an axial displacement on the outer bearing ring. The range of the preload force can be adjusted over the length of the lever arm on the shown u-profile of the element. As a result, a preload force is generated at the contact points between the bearing and the spindle housing. When the current is reversed, the preload element deforms in the opposite direction, which leads to decreasing bearing preload.

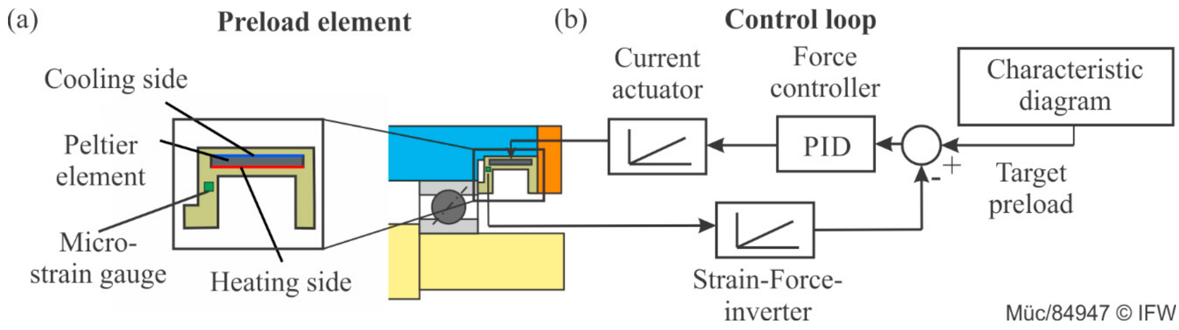


Fig. 2: (a) Concept of thermomechanical preload element with (b) control loop for the preload force control

To control the bearing preload applied by the preload element, the element is equipped with strain gauges as an input for a force control loop. With the strain gauges, the current preload force is detected. However, the force-induced strain signals are superimposed by thermally induced deformations in the preload element and due to the deformation of the whole spindle appearing as additional strain. The temperature changes are caused by the integrated Peltier elements, the bearing friction and the spindle motor. These influences can be minimized by connecting the strain gauges to a full Wheatstone bridge, similar to a measuring rosette. Alternatively, micro-Pt100 elements can be used to calculate the apparent strain from their temperature signals and compensate them. In order to be able to determine the desired states of the preload element from the sensor signals, characteristic diagrams and a control loop are used (Fig. 2 (b)).

FEM simulations were carried out to evaluate the potential of the thermo-elastic preload element. The simulation results are shown in Fig. 3. The Peltier element introduces a temperature difference of up to 45 K into the preload element. Through this, preload forces of up to 3 kN can be generated. Commonly applied preload forces on spindle bearings vary between 250 N for low preloads and up to 1,5 kN for high preload. The achieved preload forces are sufficient to change the operating mode between two machining steps. The switching of the operating mode can be done simultaneously to tool changes. Thus, switching does not cause any additional non-productive time.

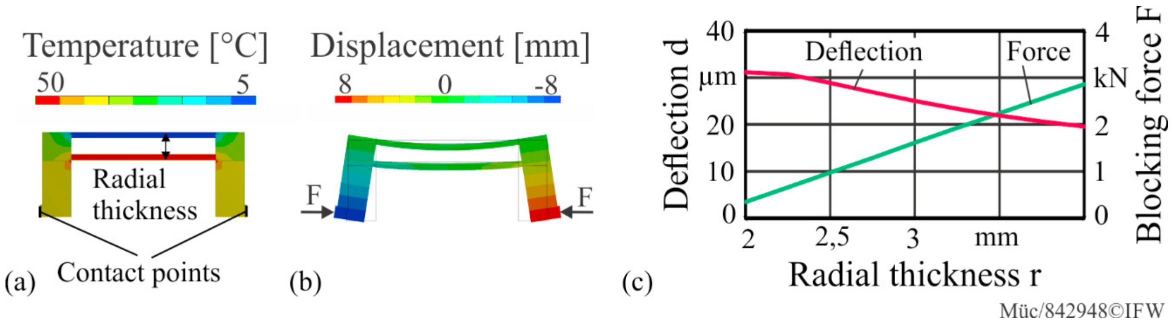
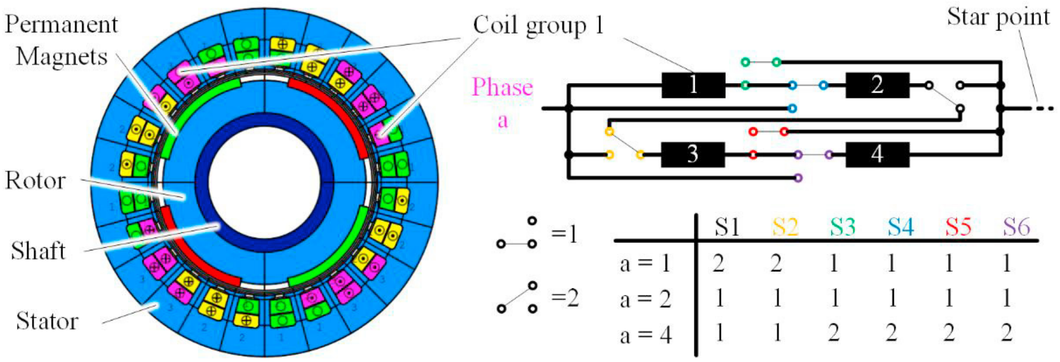


Fig. 3: (a) Temperature distribution in the preload element, (b) thermal displacement of the preload element, (c) force-displacement characteristic curve of the preload element

HPC and HSC spindle motors may have the same outer dimensions, while differing mainly in their winding design. The number of turns per phase is a significant parameter for the maximal achievable rotational speed, which is defined during the design process of the spindle motor. Usually, it cannot be changed after the machine has been manufactured. To enable the cost-efficient use of standard frequency inverters for HPC and HSC processes, the new spindle motor is designed with a reconfigurable winding system. A switchable number of parallel branches, exemplary shown for phase a of a star winding configuration in Fig. 4 (b), allows the change of the motor characteristics and enables a transition from HPC to HSC behavior by reducing the number of turns per phase. Assuming a constant line current, the maximum rotational speed is doubled and the maximum torque is halved, when the motor is switched to the next higher number of parallel branches.



	S1	S2	S3	S4	S5	S6
a = 1	2	2	1	1	1	1
a = 2	1	1	1	1	1	1
a = 4	1	1	2	2	2	2

Fig. 4: Concept of a reconfigurable four-pole permanent magnet spindle motor with switchable number of parallel branches

Requirements for a reconfigurable winding are power electronic or mechanical switches and a controlling logic, which prevents short circuits and initiates the switching process. Challenges exists in the trade-off between torque and speed requirements and the reconfiguration of the winding system during operation. The spindle motor can be designed with a conventional winding.

4. Determination of the requirements for the use in HSC operations

To design the hybrid spindle, occurring process forces and cutting powers along the operation range of HPC and HSC milling has to be identified. Typical industrial processes were defined in order to determine the respective process forces, cutting power and spindle torque.

To consider the different industrial relevant machining operations, the process load was detected while cutting typical materials, presented in table 1. In aerospace industry, titanium (TiAl6V4) and aluminum alloys (EN AW-7075) are commonly machined. Whereas in mold and tool making super steels alloys (AISI H13) are used. Other relevant sectors are the automotive industry and subcontractors with a wide range of aluminum alloys (N AW-6082) and steals (AISI 1045). The raised materials cover the typical range of tensile strengths up to 1.300 MPa. The change in tensile strength leads to different mechanical loads on the spindle. To carry out experimental investigations, the HSK 63 A tool interface was chosen as this is a commonly used interface for industrial applications. The maximum rotational speed of the tool holder is 25,000 rpm.

Tab. 1: Referenced industrial use cases and frequently used materials for HPC and HSC

Process	**High Performance Cutting (HPC)**		**High Speed Cutting (HSC)**		
Industrial use case	Aerospace	Subcontractors	Aviation	Automotive	Mold making
Material	Titanium TiAl6V4	Low alloyed steel - C45	Aluminum EN AW-7075	Aluminum EN AW-6082	Tempered steel X40CrMoV5-1
Rotational speed range	1,000 – 10,000 1/min		10,000 – 25,000 1/min		

In a first step, the determination of the electrical requirements based on HSC cutting processes was done. Primer quantities are the required electrical and mechanical power and the range of the rotational speed. The highest cutting speeds and so rotational speeds are used for aluminum alloys. Respecting this speed range, the maximum rotational speed of the tool holder and a common maximum inverter output frequency of $f_{\mathrm{out,max}} = 800$ Hz, the required number of pole pairs yields to $p = \frac{f_{\mathrm{out,max}}}{n_{\mathrm{max}}} = 1$ or $p = 2$. Considering the available space inside a milling spindle and the torque requirements for typical HPC processes with up to $M_{\mathrm{shaft}} = 300$ Nm, $p = 2$ is chosen. Standard tools for HSC operations are solid carbide end mills. For the experimental investigations, a HSC-tool (Seco JS534160D1B.04Z-NXT) with a diameter of 16 mm was used. The process parameters were specified according to tool manufacturer's specifications in order to avoid decreased tool lifetime. The cutting power measurements during cutting the aluminum alloys are presented in Fig. 4. The electrical power was measured with a ZES Zimmer LMG 500. The theoretical inner torque without losses is calculated based on the power equation (1).

$$M = \frac{P_{\mathrm{el}}}{2 \cdot \pi \cdot n} \quad (1)$$

With a terminal voltage of 360 V, the spindle exhibits a maximum power of 80 kW. This performance is sufficient according to the cutting power measurement results, shown in Fig. 5.

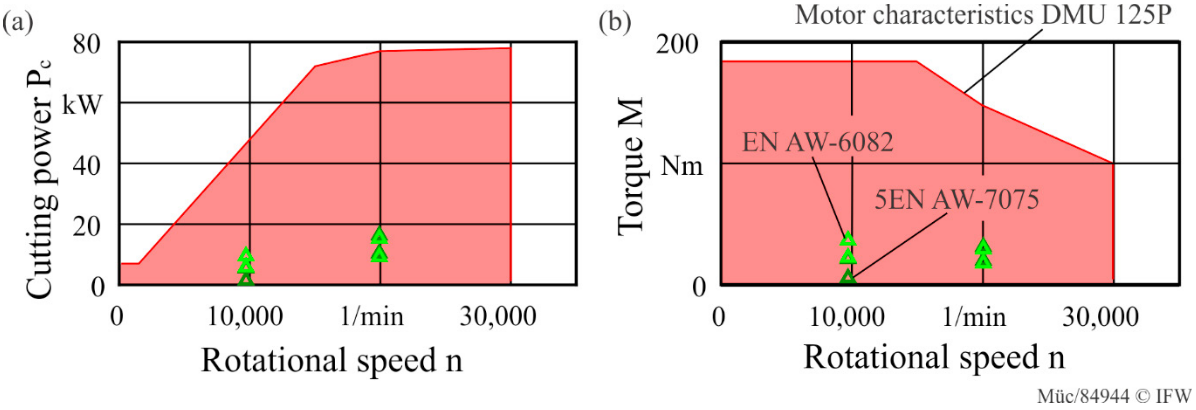


Fig. 5: (a) Cutting power and (b) Torque in HSC cutting processes

5. Conclusion and outlook

Spindles with a switchable operation mode extending the working range of the rotational speed for HPC and HSC milling have a high potential to increase the economy of universal machine tools. To overcome technical and economic problems in the design phase of suitable machine tool spindles, this paper presents two new approaches. The presented thermomechanical preload element with a simple electrical control loop represents a promising way to adapt the bearing preload with lower cost and smaller installation space. The reconfiguration of the motor winding is an approach to extend the maximum speed, without the need for an inverter upgrade. The configuration of the switches will be analyzed in future work. The definition of industrial use cases for the hybrid spindle allows designing the spindle according to industrial requirements. In future work, the HPC operations will be investigated to determine the maximum cutting forces and the required maximum torque of the spindle motor. In the next step, the bearing of the spindle can be designed considering the maximum forces. Considering the motor design, the integration of the switching element needs further development.

Acknowledgements

The authors thanks for funding the project “Hybride Spindel”. The project has been funded by the AiF within the programme for sponsorship by Industrial Joint Research (IGF) of the German Federal Ministry of Economic Affairs and Energy based on an enactment of the German Parliament.

References

[1] E. Abele, Y. Altintas, C. Brecher, Machine tool spindle units, CIRP Annals, 59:2 (2010) 781–802.

[2] R. Ben Amor, Thermomechanische Wirkmechanismen und Spanbildung bei der Hochgeschwindigkeitszerspanung, Dr.-Ing Dissertation, Universität Hannover (2003)

[3] M. Groppe,: Prozessauslegung für die Hochleistungsfräsbearbeitung von Aluminium-Strukturbauteilen, Dr.-Ing Dissertation, Universität Hannover (2005)

[4] L. Hao, C. Namuduri, High Speed Performance of PM Machine with Reconfigurable Winding, IEEE-ECCE Conf. Rec. (2015)

[5] M. Metzele, Piezoaktoren regeln die Lagervorspannung - Aktive Piezo-Stellelemente zum Anpassen schnell drehender Spindellager an die Betriebssituation, wt-online, 7/8 (2004) 344–349.

[6] H. Tönshoff, B. Denkena, T. Götz, Piezoelectric Actuator Based Preload Control Unit for Machine Tool Spindles, Production Engineering, 9 (1) (2002) 117-122

[7] Y.-K. Hwang, I.-H. Park, K.-S. Paik, C.-M. Lee, Development of a variable preload spindle by using an electromagnetic actuator, International Journal of Precision Engineering and Manufacturing, 15:2 (2014) 201–207.

[8] Universal-Kugellager-Fabrik GmbH, Vorrichtung zum Verändern der Vorspannung eines Spindellagers, Gebrauchsmusterschrift-Nr.: DE 20 2013 100 940 U1, (2013).

[9] M. Weck, B. Vites, Spreizbuchsenartiger Zentrifugalregler zur Vorspannung von Spindellagern. Teil II: Pruefung der Funktionsfaehigkeit des Reglers, ANTRIEBSTECHNIK, 37:10 (1998) 63–66.

[10] Y. K. Hwang, C. M. Lee, Development of automatic variable preload device for spindle bearing by using centrifugal force, International Journal of Machine Tools and Manufacture, 49:10 (2009) 781–787.

[11] W. S. Wood, Theory of Electrical Machines, Butterworths Scientific Publications (1958)

[12] M. M. Swamy, T. J. Kume, A. Maemura, S. Morimoto, Extended High Speed Operation via Electronic Winding Change Method for AC Motors, IEEE-IAS Annu. Meeting Conf. Rec. (2004)

[13] E. Nipp, ALTERNATIVE TO FIELD- WEAKENING OF SURFACE-MOUNTED PERMANENT-MAGNET MOTORS FOR VARIABLE-SPEED DRIVES, IEEE-IAS Annu. Meeting Conf. Rec. (1995)

[14] H. D. Stölting, A. Beisse, Elektrische Kleinmaschinen, B. G. Teubner Stuttgart (1987)

[15] G. Müller, K. Vogt, B. Ponick, Berechnung elektrischer Maschinen, Wiley-VCH-Verlag (2007)