Electric Machine Design Tool for Permanent Magnet Synchronous Machines

Svenja Kalt, Jonathan Erhard, Benedikt Danquah, Markus Lienkamp,
Institute of Automotive Technology, Technical University of Munich, Germany, (kalt@ftm.mw.tum.de)

Abstract — Since various machine parameters of existing electric machines are subject to confidentiality agreements of manufacturers, machine data sheets are often incomplete, making an accurate simulation and validation of machine design tools difficult but inevitable. Therefore, an electric machine design tool for permanent magnet synchronous machines (PSM) is introduced in this paper, enabling a holistic electric machine design for existing and new machines using few input parameters. The electric machine design tool is published under an LGPL open source license.

Index Terms — Electric Machine Design Tool, Permanent Magnet Synchronous Machine

I. INTRODUCTION

Today, an increasing environmental awareness, stricter legal requirements on carbon emissions and the prospect of a scarcity of fossil resources lead to a constant development of more efficient vehicles. The electric traction machine can be identified as a control lever for the optimization of the electric powertrain with regard to efficiency, power, weight and size [1]. Therefore, accurate and realistic machine design tools for the simulative design of electric machines are becoming increasingly important.

The permanent magnet synchronous machine has significant advantages over other machine topologies due to the excitation with permanent magnets (PM). However, special characteristics must be considered. [1]. Therefore, the authors present an electric machine design tool for PSM using MATLAB® in order to enable an automated machine design. The main focus is the estimation and analysis of the geometry and boundary conditions and the resulting machine design in regard to its efficiency. This is beneficial in order to estimate the efficiency potential of a PSM in an early design phase. The tool was created in accordance to previous work at the authors institute [2][3].

Various investigations concerning the iron and copper losses as well as first validations on existing vehicles were also carried out at the authors institute.

II. STATE OF THE ART

A. Electric machine design characteristics

An electric machine is designed in regard to electromagnetic, mechanical and thermal characteristics under consideration of their interdependencies [4].

The electromagnetic characteristics determine the electrical operating behavior. This includes, for example, the magnetic and electrical circuit, the winding design and the main dimensions of the electric machine. In the mechanical design, the mechanical boundary conditions, e.g. the calculation of forces and bearings, as well as mechanical strengths are assigned. The thermal design accounts for the losses incurred during operation, the overload operation and the cooling of the machine.

Considering the interdependencies, small changes in the electromagnetic design can lead to extensive changes in the thermal and mechanical design. Conversely, changes in the mechanical or thermal design have little or no effect on the electromagnetic design [4]. Therefore, the main focus of the machine design process is the electromagnetic design.

B. Permanent magnet synchronous machines

The main difference of the PSM to other machine topologies is the design of the rotor and the associated operating characteristics [5].

A PSM mainly consists of active parts such as the stator and rotor, as well as passive parts such as a cooling system and an inverter. The stator mainly consists of a laminated core based on the slot geometry and winding design [8]. The rotor consists of a stack of laminated electrical metal sheets like the stator and contains magnets, the arrangement of which significantly influences the electrical properties and thus the characteristics of a PSM [9].

The different rotor designs for a PSM can be roughly divided into two main types. In the Surface-Mounted Permanent Magnet Synchronous Machine (SPMSM) the magnets are glued to the surface of the rotor [9]. Machines in which the magnets are buried or inserted into the rotor are called Interior Permanent Magnet Synchronous Machine (IPMSM) [9].

The SPMSM can be easily manufactured and is therefore inexpensive [9]. However, eddy currents can occur which heat up the magnets and irreversibly demagnetize them [10]. In addition, a bandaging of the surface magnets is usually required in order to prevent the magnets from becoming detached at high rotational speeds [11]. This problem does not occur with IPMSM, because the magnets are fixed within the rotor and the centrifugal force is absorbed by the laminated core. In addition, the laminated core protects the internal magnets from mechanical damage and eddy currents [12]. Fig. 1 shows examples of different rotor
configurations. Besides surface- (Rotor A) and near-surface-mounted magnets (Rotor D), embedded magnets (Rotor B), V-shaped arranged magnets (Rotor E) or radial arrangements (Rotor C) are possible.

Fig. 1. Various rotor variants for permanent magnet excitation [1]

Further variants, e.g. multilayered arrangements, and optimizations of arrangement within the rotor are subject of recent research and are discussed in many scientific publications [13][14][15][16]. The relevance of this research can be seen in the BMW i3, in which a multi-layer arrangement of the magnets is implemented [17].

C. Efficiency diagram and characteristics

The speed/torque characteristic diagram resulting from the operation of the machine illustrates the characteristic behavior of an electric machine (Fig. 2).

The nominal torque $M_N$ is available from a rotational speed of 0 1/min up to the nominal speed $n_N$. This range is referred to as the constant torque region. In this range the mechanical power increases linearly with constant nominal torque and increasing rotational speed until the nominal power reaches the nominal speed and therefore the maximum voltage of the inverter $U_{max}$.

If the rotational speed is increased beyond the nominal speed, the magnetic flux $\phi$ must be reduced in order to keep the voltage constant. The reduction of the magnetic flux also reduces the torque, whereas the power remains constant. This range is called the field weakening region. Field weakening represents a certain difficulty for PSM because the field of the PM cannot be weakened directly [1]. An opposing field must be generated which weakens the field of the PM. However, this field should not exceed a specific magnitude, so that the PMs are not irreversibly demagnetized [6].

D. Losses of electric machines

The losses of the PSM can be divided into load-dependent and load-independent losses. The copper losses are assigned to the load-dependent losses and the iron and mechanical losses to the load-independent losses [18]. The additional losses are divided into load-independent and load-dependent losses [11].

In addition, losses can be differentiated according to the area of the electric machine where they occur. The stator accounts for the largest proportion of total losses because of the occurring copper losses, iron losses and additional losses. The latter two losses also occur in the rotor of a PSM. However, due to the excitation of the PM, the copper losses do not apply to the rotor. The mechanical losses are also comprised in the rotor losses [19]. The losses caused by eddy currents in the magnets can be neglected in a first approximation due to the low proportion of the total losses [20].

1) Copper losses

Copper losses $P_{cu}$ are losses in the conductors of the windings as a result of the current flow [21]. They are therefore also called winding or current heat losses [11].

For a symmetrical three-phase winding, the copper losses can be calculated with the product of the resistance $R$ and the square of the phase current $I_{Str}$ [11]:

$$P_{cu} = 3RI_{Str}^2$$

The copper losses are significantly involved in the heating of the electrical machine, which must be dissipated by the cooling system, otherwise ageing processes will occur or the insulation will be damaged [4].

2) Iron losses

In addition to copper losses, iron losses account for a significant proportion of the total losses and are composed of hysteresis losses and eddy current losses [4][9]. The reason for the occurrence of iron losses is the time-varying magnetic field in the laminated sheets [21].

Various model approaches by Steinmetz, Jordan and Bertotti have been developed for the analytic calculation of iron losses, some of which differ significantly in their accuracy and complexity of parameterization [23].
The Steinmetz equation is a general, empirical calculation method for determining iron losses [23]:

$$\varphi_{fe} = k_{fe} f^\alpha B^\beta$$  \hspace{1cm} (2)

The coefficient $k$ as well as the exponents $\alpha$ and $\beta$ are taken from experimental results using a sinusoidal flux. Due to its simplicity, this approach is sometimes not sufficient for realistic calculations [22]. Therefore, extensions and modifications of the Steinmetz equations have been developed which also take into account aspects such as non-sinusoidal excitation [24].

An approach by Jordan contemplates the separation of iron losses into static hysteresis losses $\varphi_h$ and dynamic eddy current losses $\varphi_w$ [23]:

$$\varphi_{fe} = \varphi_h + \varphi_w = k_h f B^2 + k_w f^2 B^2$$  \hspace{1cm} (3)

This enables a more precise description of the loss behaviour in soft magnetic materials [22].

An extension of Jordan’s model was developed by Bertotti. In his model for the calculation of iron losses, eddy current losses are divided into classical and anomalous eddy current losses (excess losses) $\varphi_a$ [25]:

$$\varphi_{fe} = \varphi_h + \varphi_w + \varphi_a$$

$$= k_h f B^2 + k_w f^2 B^2 + k_a f^{1.5} B^{1.5}$$  \hspace{1cm} (4)

3) Mechanical losses

Mechanical losses are caused by bearings and air-friction losses [3]. They are proportional to the friction surface and the square of the circumferential speed $v$ of the rotor [8]:

$$\varphi_{mech} = k_{rb} d_a (l_{Rotor} + 0.8^3 0.6 t_p) v^2$$  \hspace{1cm} (5)

Whereas $l_{Rotor}$ represents the length of the rotor, $d_a$ the rotor outer diameter and the factor $k_{rb}$ is taken from experimental results and can be regarded as a correction factor [11].

4) Additional losses

Additional losses include losses which cannot be easily located, where the cause of which cannot simply be determined or are not directly linked to the mechanism of action [11]. The additional losses are caused by harmonics in the air-gap field, by harmonics of the feeding current and by current displacement in the windings [11]. The analytical calculation of additional losses is difficult. For the purpose of an initial rough estimate and due to the low proportion of the total losses, the additional losses can therefore be neglected [11].

III. METHODOLOGY AND CONCEPT

In this section, the implemented electric machine design tool for a PSM using MATLAB® is presented. The procedure roughly follows the classical machine design of [11]. However, the tool was extended and supplemented at various points with design refinements. The main structure of the tool is illustrated in Fig. 3.

The main function starts the design process by first initiating a pre-processing step, in which all input parameters and approximated values are inserted using a graphical user interface (GUI). Afterwards, the stopping criterions, as well as storage space reservation allocated. The next step requests the function for the machine design of the PSM, which will be further explained in the following sub-sections. Then, the request for the function of the characteristic diagrams is initiated. The parameter nomenclature is mainly in German, whereas all commentary is in English.

The primary functions are located in the .m-files Auslegung_PMSM (Machine Design PSM), Kennfeld_PMSM (Characteristic Diagram PSM) and Verluste_PMSM. The secondary functions are implemented in the folders Ergebnisse, GUI, Hilfsfunktionen and Motormodell (Fig. 4). The secondary functions, illustrate the results of the design tool and (with exception of the Ergebnisse) will not be further explained in this paper, since they are mainly comprised of auxiliary functions, e.g. plot-files.

The output variables of the model are mainly the efficiency characteristic diagram and the derived machine design parameters.

A. Input parameters and approximated values - GUI

The machine parameters are divided into primary and secondary parameters and represent the input parameters. The primary parameters consist of nominal values for the machine, e.g. the number of pole pairs, the power factor and the number of phases. For this, either the pole pair $p$ or the rated frequency $f_N$ needs to be specified. The secondary
parameters specify the design of the machine more precisely, e.g. the conductor material, the interconnection of the winding, the cooling of the stator and the magnet arrangement in the rotor.

The number of phases is set to three. For the conductor material, the most common materials for windings, i.e. copper and aluminum wires are taken into account. The interconnected winding configuration for the stator winding is set to a star configuration, since certain delta configurations form high harmonics and thus generate large additional losses [11]. For the cooling of the stator, air or water cooling is implemented. The magnet arrangement of the rotor is limited to an IPMSM (Rotor D) and a SPMSM (Rotor A) arrangement.

Table 1 gives an overview of the individual parameters with symbols, units and boundaries. The values in brackets indicate a validated sub-range.

| Parameter                              | Symbol | Unit               | Boundaries     |
|----------------------------------------|--------|--------------------|----------------|
| Rated power                            | $P_N$  | kW (20 - 100)      |                |
| Rated rotational speed                 | $n_N$  | 1/min (1500 - 4000) |                |
| Rated voltage                          | $U_N$  | V                  |                |
| Pole pair                              | $p$    |                      | 1 - 16         |
| Rated frequency                        | $f_N$  | Hz                 |                |
| Power factor                           | $\cos \phi_N$ |             | 0.8 - 1.0      |
| Number of phases                       | $m$    |                    | 3              |
| Conductor material                     | -      | Copper and aluminium |                |
| Interconnected winding configuration   | -      | Star configuration |                |
| Cooling type                           | -      | Air and water      |                |
| magnet arrangement                     | -      | SPMSM and IPMSM    |                |

The input parameters are imported using the implemented GUI (Fig. 5).

In a first step, the user must enter the desired input parameters of the PSM into the user interface. The user can then adapt the approximated values to individual requirements. A database is integrated for the approximated values, which is used to evaluate the user's entries with regard to a validity range. If a value entered is outside the validity range, it is color-coded accordingly. The validity range of the approx. values can be viewed via the "?" button and depend on the selected input parameters. The design process is initiated with the "Start" button. The overall simulation time for this step takes about 3 s.

B. Machine Design PSM

The meta-model Machine Design PSM is divided into four sections. First, the dimensions of the active parts are estimated, followed by the stator and rotor design. Finally, characteristic electromagnetic parameters are recalculated, which, in addition to the geometric parameters, is necessary for the creation of the characteristic diagrams. They are then transferred to the meta-model Characteristic Diagram PSM with the approx. parameter values.

1) Boundary and geometry calculation of active parts

The first step of the actual design process is to estimate the dimensions of the active parts using the rated values. Active parts are all components of the PSM that are involved in the energy conversion [11]. Specifically, the stator outer and inner diameter, the geometric air-gap, the rotor outer diameter and the axial length of the PSM are determined in this step. The basis for determining the main dimensions of a synchronous machine is the design equation (6), which is also valid for a PSM.

$$ P_{s,N} = C_s D_i^2 l_i n_N$$

Whereas the inner diameter of the stator $D_i$ and the ideal stator length $l_i$ are determined using the torque $M$, which is proportional to the quotient of the nominal apparent power $P_{s,N}$ and nominal rotational speed $n_N$. The utilization factor $C_s$, also referred to as the specific torque or Esson's factor, describes the electromagnetic stress of an electrical machine based on the proportionality to the product of the linear current density $A$ and the peak value of the air-gap induction $B_\delta$ [11]. The apparent power $P_{s,N}$ can be calculated using the nominal mechanical power $P_{mech,N}$:

$$ P_{s,N} = \frac{P_{mech,N}}{\eta_N} \cos \phi_N $$

The efficiency at the nominal working point $\eta_N$ must first be estimated using empirical values [11]. Concluding the calculation of the apparent power, the utilization factor and the bore volume $V_{Bohrung}$ can be determined:

$$ V_{Bohrung} = D_i^2 l_i \frac{\pi}{4} = \frac{P_{s,N} \pi}{n_N C_s \frac{1}{4}} $$
To determine the stator inner diameter and the ideal stator length, the product of $D/r_t l_t$ must be separated [11]. For this purpose, the relative length $\lambda$ is introduced, which is defined as the ratio of the ideal stator length $l_t$ to the pole pitch $\tau_p$ [11]:

$$\lambda = \frac{l_t}{\tau_p} \quad \text{with} \quad \tau_p = \frac{D_t \pi}{2p} \quad (9)$$

The pole pitch corresponds to the length between two poles measured at the stator’s circumference. For the relative length, literature values are selected according to [11]. By inserting (9) into the design equation (6), the stator inner diameter, as well as ideal length can be calculated. Then, the maximum required stator outside diameter $D_{a,max}$ can be estimated:

$$D_{a,\text{max}} = D_t + \frac{2.5 A}{S \varphi_n \left(1 - \frac{B_y}{B_{y,\text{max}}}ight)} + \frac{B_y \tau_p}{B_{r,\text{max}}} \quad (10)$$

The values for the current density, air-gap induction $B_S$, as well as induction of the teeth $B_T$ and yoke $B_r$ of the stator can be determined using literature values [11]. The groove filling factor $\varphi_n$ represents the ratio of the cross-sectional area of the conductors to the cross-sectional area of the grooves. The linear current density $A$ can be calculated using (6).

The winding factor $\xi_p$ must be estimated initially. Here, a starting value of 0.92 is selected [11]. The induced voltage $E_i$ depends on the phase voltage $U_{\text{air}}$, the power factor $\text{cos} \varphi_n$ and the excitation of the machine. For a power factor of one, the induced voltage corresponds approximately to the phase voltage [11].

The rotor outer diameter $d_a$ results from the difference between the stator inner diameter and twice the air-gap [10].

2) Stator design

The stator design mainly consists of the selection of a suitable winding, the connection of the winding and the determination of the groove form.

The aim of the winding design is to minimize the winding factor for harmonics and subharmonics and at the same time maximize the winding factor of the fundamental wave $\xi_p(1)$ in order to obtain an air-gap wave that is as sinusoidal as possible. The determination of the winding design is based on [6][11].

The regarded winding types and an optimized concept for the winding design, connection of the conductors, as well as the determination of the slot geometry using parameter permutation is presented in previous work of the authors [27].

3) Rotor design

The main objective of the rotor design of a PSM is the dimensioning of the PM and their arrangement in or on the rotor based on the properties of the magnetic material. As already anticipated, there is a large variety of arrangements for the magnet configuration and dimensions. This in turn results in different properties and characteristics of a PSM. With a specific arrangement of the PM, for example, the losses or the field weakenability can be influenced or the achievable output can be increased using the same volume of PM [28]. The latter is of particular interest in the automotive sector because it can reduce the cost of an electric machine, which are proportional to the volume of PM material [29].

The design equations of Ionel [30] are used for the dimensioning of the PMs. They are based on empirical factors and validated against finite element calculations and experiments.

An initial estimate of the magnet width in the direction of the magnetization depends on the available space at or in the rotor. For the SPMSM, the magnet width results from the ideal pole coverage factor $a_t$ and the pole pitch $\tau_p$. The magnetic width for the IPMSM arrangement is calculated from the difference between the rotor outer and inner diameter [30].

4) Post-Processing and final calculations

The final calculation for the PSM includes the calculation of the synchronous inductances of the $d$- and $q$-axis, as well as the winding resistance. In a first step, the unsaturated main inductance $L_d$ is determined using [11], followed by the leakage inductance $L_o$ and the groove and tooth leakage induction. The winding head leakage and the conductor length in the winding head can also be calculated using [11]. The harmonic leakage depends on the chording and the number of slots and summarizes the influence of the harmonics generated by the slots. With the main inductance and the leakage inductance, the synchronous inductance $L_d$ and $L_q$ are determined [11]:

$$L_d = L_{d,h} + L_\sigma \quad L_q = L_{q,h} + L_\sigma \quad (11)$$

Then, the winding resistance is calculated using the mean winding length and the cross-sectional area of the conductors according to [11]. Afterwards, the linked flux of the PMs can be calculated, which is necessary for the determination of the torque. For a SPMSM, no reluctance torque is generated. Therefore, the nominal torque must be achieved at the nominal speed with the nominal current [11]. For an IPMSM, the optimal field weakening condition using the design comparisons from Ionel [30] is implemented. With the recalculation, the meta-model Machine Design PSM is completed and the basic features of the machine have been calculated to such an extent that characteristic diagrams can be determined.

C. Characteristic Diagram PSM

The goal of the meta-model Characteristic Diagram PSM is the creation of efficiency diagrams for the designed
electric machine. Here, a motor-model is implemented which operates the PSM within specific boundaries of the motor operation.

In a first step, a grid of operating points is generated. Then, the currents and voltages required for controlling the operating points are calculated. Afterwards, the loss proportions in the individual operating points are determined. Finally, efficiency characteristic diagrams for the analysis of the PSM can be created using the calculated machine parameters (Fig. 6).

The efficiency diagram illustrates the type of characteristic diagram chosen by the user. The possible characteristic diagrams include a diagram for the:

- overall machine efficiency
- overall losses
- heat losses
- iron losses
- \( i_d, i_q, u_d, u_q \)

The characteristic diagram visualization

Fig. 6. Overview of the GUI for the characteristic diagrams

For the calculation of the efficiency and the creation of the efficiency characteristic diagram, the occurring losses are determined for each calculated operating point. The total losses consist of the heat losses, iron losses and mechanical losses. The additional losses are neglected as previously described. For the calculation of the iron losses, Jordan’s approach is chosen, because it represents a good compromise between accuracy and effort of parameterization [22][23].

The characteristic diagrams can be modified by the user. In the user interface, the loss components that are to be calculated for the efficiency diagram can be selected. The selection of an electrical sheet is necessary for the iron loss calculation. The variables can be adapted in order to apply an overload operation. Since the machine is not thermally evaluated, special care must be taken when adjusting the variables.

The calculation of the full-load characteristics is carried out using the Optimization_M function, which is part of the motor-model. Another part of the motor-model is the function Optimierung_i, with which the currents in the operating points are calculated. The function Elektroband provides the calculation of the loss characteristic curve for the selected electrical steel sheet. After the calculation, the diagrams can then be displayed via the user interface. The plot_map function updates the diagram area according to the desired size.

With the calculation of the efficiency for each operating point, the calculations of the meta-model Characteristic Diagram PSM is completed. The overall simulation time for this step takes approx. 7 s.

It should be noted that the meta-model Characteristic Diagram PSM is based on a linear approach to simplify the analytical calculation. Accordingly, neither saturation phenomena, cross-coupling of inductances or dynamic processes within the electric machine are considered. Furthermore, the inductances and the interlinked flow of the PM are not load- or current-dependent and therefore constant for all operating points [31].

D. Output parameters - Results

The stored results in Ergebnisse are comprised of three files – an efficiency diagram (.fig-file), an Excel-File and a .mat-file. The Excel-File includes several of the derived machine parameters. This includes a sheet with an overview of the input parameters of the GUI, as well as a sheet with the calculated output parameters of the machine design tool. In addition, the tool offers an integrable ANSYS interface, which is not included in the open source machine design tool. Therefore, the sheet with output parameters from ANSYS remains empty in this case. The sheet with the input parameters for ANSYS mainly consists of the necessary output parameter values of the design tool. The .mat-file contains all calculated parameter values of the tool and is the source for the Excel-File.

IV. SUMMARY AND OUTLOOK

The main idea of this work was the development of an electric machine design tool using MATLAB® that guides the user through the design process using a GUI and enables characteristic diagram calculations of a PSM. For this, the classic design process was adapted to the characteristics of a PSM.

The developed tool serves as a basis to which further options for additional calculations of different machine type can be integrated. For this reason, the modularity of the design and the subdivision into subcomponents was taken into consideration by the authors. Other machine variants, such as reluctance machine (GRM) or a hybrid machine
consisting of PSM and GRM, can also be integrated into this approach. The motor-model can also be extended to include the generator operating range. Another possible extension is the construction of a thermal and a mechanical model. This enables a more detailed investigation into the overload operation.

A validation was carried out on the basis of the known parameters for the BMW i3, Nissan Leaf and VW e-Golf [32][17]. The introduced machine design tool represents only a small fraction of an overall vehicle design model implemented by the authors institute [33].

OPEN SOURCE
https://github.com/TUMFTM/Electric_Machine_Design

CONTRIBUTION

As first author, Svenja Kalt initiated the idea of the presented design method and drew up the overall concept. Jonathan Erhard supported as part of his Master’s thesis with the implementation. All authors discussed and commented on the article at all stages. Markus Lienkamp made an essential contribution to the conception of the research project. He revised the paper critically for important intellectual content. Markus Lienkamp gave final approval of the version to be published and agrees to all aspects of the work. As a guarantor, he accepts responsibility for the overall integrity of the paper. The tool was created in accordance to previous work of Wacker [2] and Horlbeck [3].

ACKNOWLEDGMENT

This work was supported by the organization Bayern Innovativ and the Bavarian Ministry of Economic Affairs, Regional Development and Energy within the research project DeTailED - Design of Tailored Electrical Drivetrains.

REFERENCES

[1] A. Kampker, D. Vallee and A. Schnettler, “Elektromobilität: Grundlagen einer Zukunftstechnologie”, Springer-Verlag, 2013.
[2] P. Wacker, “Effizienzsteigerung im Antriebsstrang von Elektrofahrzeugen mittels aktiver Batteriepackverschaltung”, Dissertation, Technical University of Munich, 2018.
[3] L. Horlbeck, “Auslegung elektrischer Maschinen für automobile Antriebsstränge unter Berücksichtigung des Überlastpotentials”, Dissertation, Technical University of Munich, 2018.
[4] W. Meyer, “Technologie elektrischer Maschinen”, Munich, 2018.
[5] A. Farschtschi, “Elektromaschinen in Theorie und Praxis: Aufbau, Wirkungsweisen, Anwendungen, Auswahl- und Auslegungskriterien”, 2nd Ed., Berlin: VDE-Verlag, 2007.
[6] A. Binder, “Elektrische Maschinen und Antriebe: Grundlagen, Betriebsverhalten”, Berlin: Springer-Verlag, 2012.
[7] P. Hofmann, “Hybridfahrzeuge”, Wien: Springer-Verlag, 2014.
[8] R. Fischer, “Elektrotechnik für Maschinenbauer”, 15th Edition, Wiesbaden: Springer Vieweg, 2016.
[9] J. Teigelkötter, “Energieeffiziente elektrische Antriebe: Grundlagen, Leistungsdektronik, Betriebsverhalten und Regelung von Drehstrommotoren”, Wiesbaden: Vieweg+Teubner Verlag, 2013.
[10] J. Pyhonen, T. Jokinen and V. Harbovocova, “Design of rotating electrical machines”, Chichester: Wiley, 2014.
[11] G. Müller and B. Ponick, “Grundlagen elektrischer Maschinen” and “Berechnung elektrischer Maschinen”, 10th Edition, Weinheim: Wiley-VCH, 2014.
[12] A. Kampker, “Elektromobilproduktion” , Berlin: Springer-Verlag, 2014.
[13] Z. Yang et al., “Design and Comparison of Interior Permanent Magnet Motor Topologies of Tractive Applications”, IEEE Trans. Transp. Electrific., Edition 3, 2017.
[14] T. Gundugud and G. Komurgoz, “Design of permanent magnet machines with different rotor types”, International Journal of Electrical and Computer Engineering, Ed. 46, No.10, 2010.
[15] K. T. Chau, C. C. Chan and C. Liu, “Overview of Permanent-Magnet Brushless Drives for Electric and Hybrid Electric Vehicles”, IEEE Trans. Ind. Electron, Edition 55, 2008.
[16] S. Yoshioka, S. Morimoto, M. Sanada and Y. Inoue, “Influence of magnet arrangement on the performance of IPMSMs for automotive applications”, IEEE Energy Conversion Congress and Exposition (ECCE): IEEE, 2014.
[17] D. Staton and Goss James, “Open Source Electric Motor Models for Commercial EV & Hybrid Traction Motors”, [Online] Available: https://iiss.co/oolwishingexpo/benln/_media/pages/Tutorial-1-D-Staton-&-J-Goss-MDL.PDF, Accessed: 05.02.2019.
[18] A. Krems, “Elektrische Maschinen und Antriebe: Grundlagen, Motoren und Anwendungen”, 2nd Edition, Wiesbaden: Vieweg+Teubner Verlag, 2004.
[19] U. Vollmer, “Entwurf, Auslegung und Realisierung eines verlustoptimierten elektrischen Antriebs für Hybridfahrzeuge”, Dissertation, Brandenburgische Techn. Universität Cottbus, 2007.
[20] J. F. Gieras, “Permanent magnet motor technology: Design and applications”, 3rd Edition, Boca Raton: CRC Press, 2010.
[21] D. Schröder, “Elektrische Antriebe – Grundlagen: Mit durchgerechneten Übungs- und Prüfungsaufgaben”, 6th Edition, Berlin: Springer-Verlag, 2017.
[22] Z. Neuschl, “Rechnerunterstützte experimentelle Verfahren zur Bestimmung der lastunabhängigen Eisenverluste in permanentmagnetisch erregten elektrischen Maschinen mit additioanalem Axialfluss”, Dissertation, Brandenburgische Technische Universität Cottbus, 2007.
[23] A. Krings and J. Soulard, “Overview and Comparison of Iron Loss Models for Electrical Machines”, Journal of Electrical Engineering, 10th Edition, 2010.
[24] D. Lin, P. Zhou, W. N. Fu, Z. Vadic and Z.J. Cendes, “A Dynamic Core Loss Modell for Soft Ferromagnetic and Power Ferrite Materials in Transient Finite Element Analysis”, IEEE Trans. Magn., 40th Edition, 2004.
[25] G. Bertotti, “General properties of power losses in soft ferromagnetic materials”, IEEE Trans. Magn., 24th Edition, 1988.
[26] E. Spring, “Elektrische Maschinen: Eine Einführung”, Berlin: Springer-Verlag, 2009.
[27] S. Kalt, Jonathan Erhard and Markus Lienkamp, “Optimized Stator Design Method using Machine Parameter Permutation”, Journal Forschung im Ingenieurwesen, CoFAT, Fürstenfeldbruck, 2019.
[28] K. Yamazaki, Y. Kato, T. Ikemi and S. Oliki, “Reduction of rotor losses in multi layer interior permanent magnet synchronous motors by introducing novel topology of rotor flux barriers”, IEEE Energy Conversion Congress and Exposition, 2013.
[29] S. Yang et al., “Cost reduction of a permanent magnet in-wheel electric vehicle traction motor”, International Conference on Electrical Machines (ICEM), IEEE, 2014.
[30] D. M. Ionel et al., “Design considerations for permanent magnet synchronous motors for flux weakening applications”, IEEE Trans. Ind. Electron, Edition 55, 2008.
[31] K. T. Chau, C. C. Chan and C. Liu, “Overview of Permanent-Magnet Brushless Drives for Electric and Hybrid Electric Vehicles”, IEEE Trans. Ind. Electron, Edition 55, 2008.
[32] A. Kampker, “Elektromobilproduktion”, Berlin: Springer-Verlag, 2014.
[33] H. Jelden, P. Lück, G. Kruse and J. Tousen, “Der elektrische Antriebsstrang unter Berücksichtigung des Überlastpotentials”, IEE Proc, Electrical Machines (ICEM), IEEE, 2014.
[34] D. M. Ionel et al., “Design considerations for permanent magnet synchronous motors for flux weakening applications”, IEEE Trans. Ind. Electron, Edition 55, 2008.
[35] K. T. Chau, C. C. Chan and C. Liu, “Overview of Permanent-Magnet Brushless Drives for Electric and Hybrid Electric Vehicles”, IEEE Trans. Ind. Electron, Edition 55, 2008.
[36] S. Yoshioka, S. Morimoto, M. Sanada and Y. Inoue, “Influence of magnet arrangement on the performance of IPMSMs for automotive applications”, IEEE Energy Conversion Congress and Exposition (ECCE): IEEE, 2014.