On the design of a PMSM rotor with ferrite magnets to substitute a rare earth permanent magnet system

Aryanti Kusuma Putri, Martin Nell, Marco Hombitzer, David Franck and Kay Hameyer, *Senior Member, IEEE*

***Abstract*—In this paper, the design of a permanent magnet synchronous machine (PMSM) with spoke type rotor and ferrite permanent magnets (spoke-type PMSM) as a substitute to an existing PMSM is presented. The reference machine is a fractional horsepower interior PMSM with v-shaped NdFeB-magnets (VPMSM). The spoke-type PMSM is designed based on the geometrical properties of the reference machine. The characteristic of the machines in two operating points are compared; one in the base speed area and one in the field weakening range. The foci of the comparison are the electrical and mechanical properties of the machines, e.g. back-emf, torque, radial force densities and iron losses. The effect on the machine's cost by using different materials is analyzed.**

Index Terms*—*low power drives, low cost machines, ferrite, rare-earth material, permanent magnet synchronous machines, NdFeB-free motor, radial force densities, torque harmonics

I. Introduction

Due to the high power density, the permanent magnet synchronous machines (PMSM) are widely used in applications with low volume and light weight requirements. Because of the same reason, the use of high-speed machines for these applications are increased in the recent years. A PMSM with interior magnets (IPMSM) has a better performance than a PMSM with surface mounted magnets (SPMSM) in field weakening range. Therefore, IPMSM is more attractive for applications with a wide constant power range when compared to SPMSM ([1], [2]).

The IPMSM with v-shaped magnets (VPMSM) from rare earth magnet materials, such as the combination of Neodymium-Iron-Boron (NdFeB), are commonly used in various applications. The machines with this combination exhibit high synchronous and reluctance torque in the base speed area, and also have a good flux weakening capability. However, compared to another iron-based (Fe) magnets, the cost of NdFeB-magnets is high. The price ratio of NdFeB-magnets and Fe-magnets is roughly between 7 and 12 [3].

To lower the cost of the PMSM, alternative machines without rare earth material are examined ([3]–[5]). However, the stator outer diameter or the axial length of the machine, and thus the volume of the rare earth free machines, have to be increased to generate a comparable power. This approach is not suitable for applications with specific limited space requirements.

Particular PMSM with different rotor geometries and utilized magnet materials are compared in [6]. It is shown, that using spoke type PMSM with Fe-magnets (spoke-type PMSM) a similar behavior to IPMSM with NdFeB-magnets in the field weakening area can be achieved. However, the maximal torque in the base speed area in this case is lowered. This is a disadvantage for application with particular torque requirement.

A. K. Putri, M. Nell, M. Hombitzer, D. Franck and K. Hameyer are with Institute of Electrical Machines, RWTH Aachen University, Aachen, Germany (e-mail: aryanti.putri@iem.rwth-aachen.de).

TABLE I: Requirements of the reference PMSM.

Stator outer radius $r_{stator,o}$	60 mm
Minimum air gap length δ	0.7 mm
Axial length l_{Fe}	30 mm
Winding type	single-tooth winding
Maximum input voltage U_{line}	190 V
Maximum phase current I_{eff}	7.1 A
Maximum electrical frequency f_{max}	1600 Hz
Maximum speed n_{max}	20000 min^{-1}
Maximum torque T_{max}	3 Nm
Efficiency in OP 1 at 70° C	
$n_1 = 610\,\mathrm{min}^{-1}$ and $M_1 = 1.31\,\mathrm{Nm}$	66.0 %
Efficiency in OP 2 at 70° C	
$n_2 = 19520\,\mathrm{min}^{-1}$ and $M_2 = 0.26\,\mathrm{Nm}$	80.9 %

In this paper, a spoke-type PMSM is designed to substitute an existing VPMSM with NdFeB-magnets for household applications. The designed machine should have a similar torque-speed characteristic to the reference machine. Furthermore, the efficiencies of the reference machine in two working points, one in the base speed area and one in the field weakening range, have to be satisfied. The construction space is strongly limited as well. In Table I the requirements of the reference machine are listed.

In addition to the listed requirements, the quality of the alternative machine with ferrite-based permanent magnet system has to be assured. These are evaluated through the comparison of the parasitic effects in the chosen operating points of both reference and designed machine, e.g. back-emf harmonics, torque harmonics, radial force densities and iron losses.

The main advantage of the Fe-magnets to the NdFeB-magnets is the lower material costs. However, the remanence flux density of the Fe-magnets is also low, when compared to NdFeB-magnets. To compensate this drawback, the amount of other utilized materials has to be increased. To evaluate whether the costs of PMSM with Fe-magnets are lower than PMSM with NdFeB-magnets, the total costs have to be considered.

Under the assumption that the manufacturing costs of both machines are similar in the mass production, the total costs of both machines are compared based on the amount of the material used in the machine. Due to the requirements of stator outer radius and the axial length, the amount of the used

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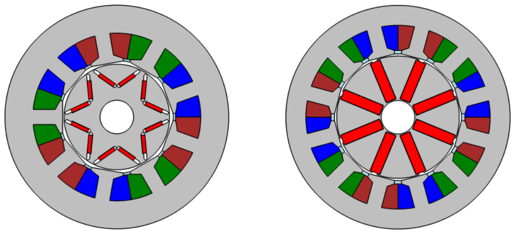


(a) VPMSM with NdFeB-magnets (b) Spoke-type PMSM with Fe-magnets

Fig. 1: The geometry of the studied machines.

electrical steels in the manufacturing process is identical. Only the amounts of used copper and magnet materials, scaled with the price ratio of Ferrite- and NdFeB-magnets, are relevant for the comparison.

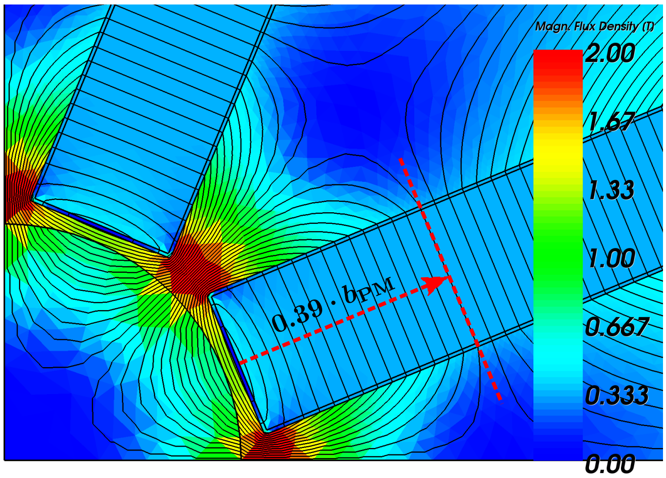
II. Design

In this section the design steps of the spoke-type PMSM are presented. First, the general measures to design the rotor and stator geometries are explained. In the next step, the procedures to minimize the stray flux of the spoke-type PMSM are presented.

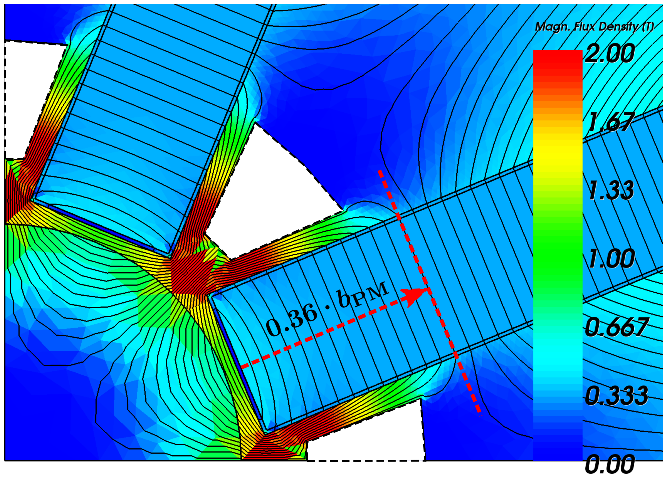
A. General Design Considerations

In Fig. 1(a) the cross section of the reference VPMSM, which is presented in [7], is illustrated. The machine has the number of pole pairs p = 3. The outer contour of the rotor is modified to form sinusoidal field poles according to [8] to reduce the harmonics of the rotor flux density, which are related to the induced parasitic effects such as iron losses and torque ripple. Due to the low remanence flux density of Fe-magnets $B_{\mathrm{r,Fe}} \approx$ 0.4 T when compared to the NdFeB-magnets $B_{\mathrm{r,NdFeB}} \approx$ 1.2 T, the required torque cannot be reached without redesigning the machine. To reach the required torque, the number of poles for a machine with Fe-magnets has to be larger than a machine with NdFeB-magnets [6]. Due to the maximum electrical frequency of the converter f_{max} = 1600 Hz at n = 20000 min^{-1}, the maximum possible pole pairs is p = 4. This defines the number of pole pairs of the designed machine.

The flux density generated by the designed machine is lower than the flux density of the reference machine. Thus, the yoke height and the tooth width of the stator can be reduced until the similar magnetic saturation level to the reference machine is obtained. Under the consideration of the minimum air gap length δ_{min} = 0.7 mm, the rotor outer radius can be increased simultaneously. The increase of the rotor outer radius is an advantage to spoke-type PMSM, since the width of the Fe-magnets can also be increased, which enhances the rotor air gap flux density. The rotor inner radius is unchanged, so the same shaft as the one of the reference machine can be used. In Fig. 1(b) the illustration of the spoke-type PMSM is shown. Similar to the reference machine, the designed machine is constructed with single-tooth stator winding. However, the number of winding turns of the designed machine has to be adjusted, so the requirements of the working point in the field weakening range can be satisfied.



(a) Rotor without flux barrier.



(b) Rotor with flux barrier.

Fig. 2: Distribution of the flux density in rotor.

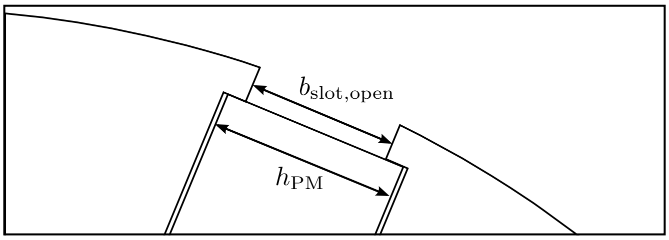
B. Optimization the Flux Density Distribution

One of the disadvantages of the spoke-type PMSM is the magnetic short circuit through the rotor shaft. In Fig. 2(a) an example of the flux density distribution in the rotor inner radius of a spoke-type PMSM is illustrated. From the isolines can be seen, that the inner side of the magnets generates only stray flux. In this case, 39 % of the flux density from the magnets, represented by the part of the magnet width b_{PM} , has no contribution to the torque build-up. This can be reduced for example using a non-magnetic shaft, which usually leads to increase of the machine cost.

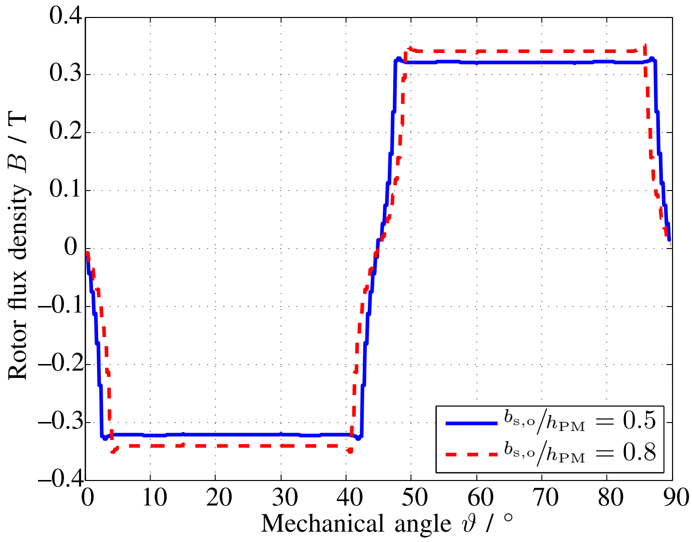
An alternative to reduce the stray flux is through saturating the bridge between the magnets. For this purpose, as example the magnet height h_{PM} can be increased. The width of the bridge will be decreased and higher saturated. However, the use of thicker magnets can be a disadvantage to the mechanical durability of the rotor due to the higher centrifugal force. The stray flux through the shaft can also be decreased through construction of flux barriers between the magnets [9]. In Fig. 2(b) the flux distribution of a spoke-type PMSM rotor with flux barriers between the magnets is shown. The flux barriers has to be designed under the consideration of the mechanical stability of the rotor. With this method, the stray flux is decreased by 3 %. Due to the decrease of the stray flux in the rotor shaft the demagnetization stability of the Fe-magnets is increased [9]. The proportions of the magnets, which contribute to the torque generation, are hereby increased.

The distribution of the rotor flux density can be influenced through the design of the rotor outer contour. In Fig. 3 the influence of the width of the rotor slot opening $b_{\mathrm{slot,open}}$ on the rotor flux density distribution is illustrated. The width of the slot opening affects the slope on zero crossing of the flux density distribution. This opening can be designed in such a way, that the slope of the flux distribution approximates a crossing of a sinusoidal function. In addition, the magnet stray flux at the rotor outer radius can be decreased through widening the slot opening. Thus, a higher flux density can be achieved with this approach. The mechanical stability of the rotor outer bridge has to be taken into account in the design of the slot opening.

A rotor contour modification can be performed to minimize the harmonics of rotor flux density. Several approaches ([8], [10]–[12]) are applied on the designed rotor and the influences on the flux density distribution are analyzed. The correlation between the used techniques and the machine behavior, such as average torque and torque ripple, are examined.



(a) Slot opening of a spoke-type PMSM rotor.



(b) Rotor flux density distributions for different ratio $b_{\mathrm{slot,open}}/h_{\mathrm{PM}}$.

Fig. 3: The influence of the slot opening on the rotor flux density distribution.

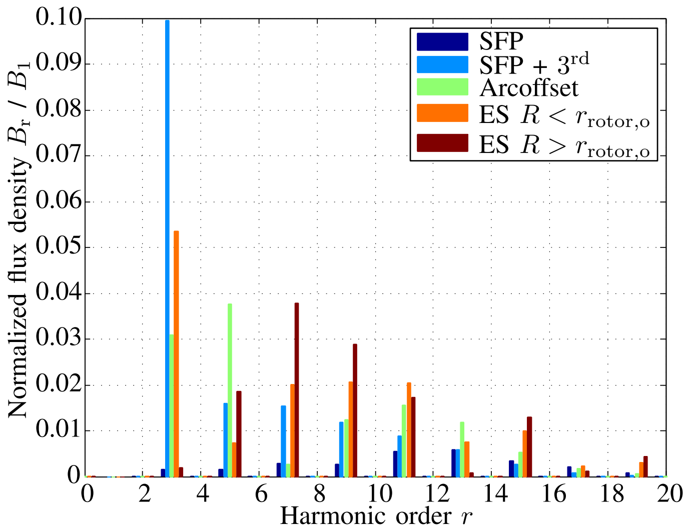


Fig. 4: The harmonics of the air gap flux density of the spoke FPMSMs' rotor normalized to the fundamental harmonics.

III. Designed Spoke-type PMSM

Several spoke-type PMSMs with a same stator are designed based on the methods explained in the previous section. A detailed analysis of the the designed machines is presented in this section. Based on the analysis, one spoke-type PMSM with the most suitable rotor is designed as an alternative to the reference machine.

The rotors of the spoke-type PMSM are designed based on the methods: sinusoidal field pole (SFP), SFP with third harmonic injection (SFP+3^{rd}), center-offset arc pole shoe (arcoffset), uniform and eccentric surfaces (ES); which are presented in [8], [10]–[12] respectively. The amplitudes of the fundamental wave of these rotors are similar with ± 1.5 % deviation from the mean value of 0.47 T. In the first step, the normalized rotor flux density harmonics of the rotors are compared. Furthermore, the cogging torque and the behavior of the machines in OP 1 and OP 2 are examined.

In Fig. 4 the normalized spatial harmonics of the rotor flux densities are shown. It can be seen, that the harmonics of the SFP-rotor are generally low, when compared to the other rotors. Through injection of the third harmonic in the rotor shape, the average torque can be enhanced [10]. However, the harmonics of the rotor flux density, particularly the 3^{rd} harmonic, are also increased when compared to the SFP-rotor. In case of the arcoffset-rotor, the amplitude of the 5^{th} harmonic is higher than the other harmonics. The 7^{th} harmonic is strongly suppressed, its amplitude is similar to that of the SFP-rotor. Two ES-rotors with smaller and larger radius of the eccentric surfaces R than the rotor outside radius $r_{\mathrm{rotor,o}}$ are designed. The rotor with $R < r_{\mathrm{rotor,o}}$ (ES 1) has a higher amplitude of 3^{rd} harmonic, but lower amplitude of 5^{th}, 7^{th} and 9^{th} harmonic than that of the rotor with $R > r_{\mathrm{rotor,o}}$ (ES 2). The amplitude of the 3^{rd} harmonic of the latter rotor is similar to that of the SFP-rotor.

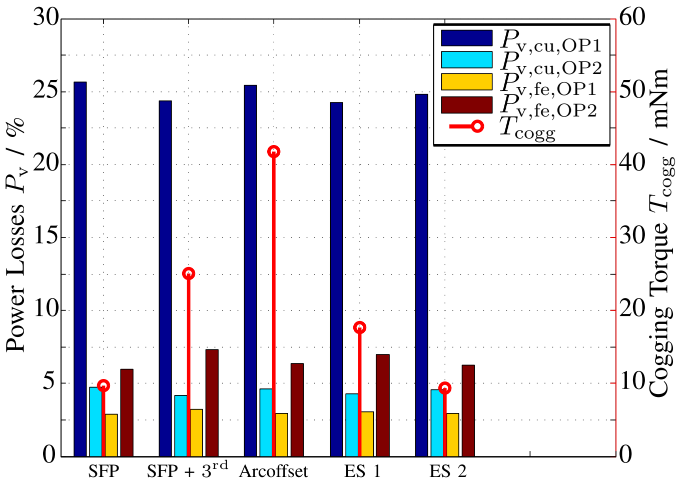


Fig. 5: The copper and the iron losses in the operating points and the cogging torque of the spoke FPMSM.

The percentage of copper and iron losses of the spoke-type PMSM with different rotors in OP 1 and OP 2 are presented in Fig. 5. Generally, the copper losses are dominant in the base speed area and the iron losses are dominant in the field weakening range. This characteristic is also reflected in the simulation results of the spoke-type PMSM. The copper losses of the machines in both operating points are similar: the maximal difference in OP 1 is $\pm 1.36\,\%$ and in OP 2 $\pm 0.54\,\%$. A same behavior can be observed for the iron losses. In this case, the maximal difference are $\pm 0.37\,\%$ and $\pm 1.31\,\%$ in OP 1 and OP 2 respectively.

The cogging torque of the machines are shown as well in Fig. 5. It can be seen, that the spoke-type PMSM with SFP-rotor and ES 2-rotor have the smallest cogging torque. To choose a suitable machine construction, the torque ripple of these 2 machines are taken into account. The percentage torque ripple of the spoke-type PMSM with SFP-rotor in OP 1 and OP 2 are 1.85 % and 22.24% respectively. In case of the spoke-type PMSM with ES 2-rotor, they are 5.36 % and 7.47%. The torque ripple behavior of the spoke-type PMSM with ES 2-rotor is on average better than that of the spoke-type PMSM with SFP-rotor.

Due to the losses and the torque characteristic, the spoke-type PMSM with uniform and eccentric rotor surfaces $R > r_{\mathrm{rotor,o}}$ is found to be the most suitable alternative to the reference machine. A refinement of the designed ES 2-rotor is done to reach the required efficiencies.

IV. Comparison of the Machines

A comparison of the designed spoke-type PMSM and the existing VPMSM concerning the machine behavior is performed. Furthermore, the torque-speed characteristic of both machines are analyzed.

A. Machine cost

In Table II the relative deployed material of both machines are listed. Due to the higher number of poles and the lower magnet flux density of the spoke-type PMSM with Fe-magnets, a higher amount of copper is required, so that the requirement of the efficiency in OP 1 can be satisfied. Due to the low remanence flux density of the Fe-magnets, the amount of magnet material needed is also higher than that of the reference machine with NdFeB-magnets. However, due to the higher cost of NdFeB-magnets, the overall material cost of the designed machine is 45 % less than that of the reference machine. If the price ratio of NdFeB-magnets and Fe-magnets decreases to 3.42 instead of 7, the material cost is going to be identical.

In this paper, the particular cost for the production of the motor are not considered. These are for example the magnetizing process and the insertion of the magnets into the rotor. The magnets of the VPMSM can be magnetized after the magnets are inserted to the rotor. This can not be done in case of spoke-type PMSM, because the magnet area close to the rotor inner radius will be poorly magnetized. The different processes will lead to different production cost. In the reality these factors have to be considered.

B. No-load Simulations

In Table III the simulation results of the machines in the no-load operating point are listed. As expected, the magnet flux of the spoke-type PMSM is lower than that of the VPMSM. In this case, the ratio of the flux linkages $\psi_{\mathrm{F,spoke-typePMSM}}/\psi_{\mathrm{F,VPMSM}} = 0.66$. The difference of the inductivities of the spoke-type PMSM is also low, when compared to the VPMSM. Due to low saliency ratio of both machines, the latter factor has little influence on the torque. Considering the number of pole pairs p of the machines and the analytical equations to calculate the electrical torque $T_{\mathrm{el.}}$:

$$T_{\mathrm{el.}} = \frac{3}{2} p (\psi_{\mathrm{F}} i_{\mathrm{q}} + (L_{\mathrm{d}} - L_{\mathrm{q}}) i_{\mathrm{d}} i_{\mathrm{q}}), \quad (1)$$

it can be concluded that the maximum electrical torque of the spoke-type PMSM is 88 % of the electrical torque of the VPMSM, if the current amplitude is unchanged. This behavior can also be seen in the ratio of the back-emf amplitude. To achieve the same electrical torques, the current

TABLE II: Comparison of the Material Cost of the Machines.

Material amount / Cost (p.u.)	VPMSM with NdFeB-magnets	Spoke-type PMSM with Fe-magnets
Copper mass	1	1.42
Magnet mass	1	3
Magnet cost ratio	7	1
Material cost	1	0.55

TABLE III: The no-load simulation results.

	VPMSM	Spoke-type PMSM
PM flux linkage ψ_{F} / mVs	73.4	48.2
Inductivity L_{d} / mH	22.7	16.2
Inductivity L_{q} / mH	25.2	17.7
Inductivity difference $\lvert L_{\mathrm{d}} - L_{\mathrm{q}} \rvert$ / mH	2.5	1.5
Saliency ratio $L_{\mathrm{q}}/L_{\mathrm{d}}$	1.11	1.09
Back-emf (phase-to-line) at $n = 1000\,\mathrm{min}^{-1}$ / V	32.65	28.58
Cogging torque / mNm	25	8.5

amplitudes have to be increased around 14 %. The windings' wire diameter of the spoke-type PMSM is increased to prevent a drastic increase of the copper losses at the operating points. The diameter of the used wires lies under 1 mm. Due this value, the skin and proximity effect at the maximum frequency of 1333 Hz can be neglected.

In Fig. 6 the normalized spatial harmonics of the rotor flux densities are shown. It can be seen, that the normalized lower harmonics of the spoke-type PMSM rotor are higher than that of the VPMSM. This behavior changes starting from the 11^{th} harmonic; the flux density harmonics of the spoke-type PMSM tend to be smaller than that of the VPMSM. The presented spoke-type rotors in Fig. 6 and in Fig. 4 (ES 2 with $R > r_{\text{rotor,o}}$) are different. The deployed magnets of the rotor in Fig. 6 are thicker and the rotor surface is designed to minimize the 5^{th} and 7^{th} flux density harmonics, with a limitation of the 3^{rd} harmonics to $B_3 < 0.5B_1$. Only the radius of the eccentric surfaces are similar.

C. Machine Operating Points

The simulation results of both machines are presented in Table IV. The efficiencies of the designed spoke-type PMSM in both operating points are higher than that of the reference machine. The differences are caused by the lower copper losses of the spoke-type PMSM when compared to the VPMSM in both operating points. Using higher amount of copper and suitable winding design, the resistance of the stator winding can be decreased and the copper losses in OP 1 minimized. Additional to the lower resistance, the required flux weakening current (or current density in stator slots, due to the different number of turns) of the spoke-type PMSM in OP 2 is lower than that of the VPMSM due to the lower remanence flux density of the Fe-magnets. Thus, the copper losses of the designed machine in this operating point are 35 % lower than that of the reference machine.

The iron losses of the spoke-type PMSM are higher than the iron losses of the VPMSM. This is caused by the higher number of poles of the spoke-type PMSM, which is related to the higher electrical frequency at the same mechanical speed. The iron losses are proportional to the electrical frequency and thus, the iron losses of a machine with higher number of poles are high.

Although the iron losses of the spoke-type PMSM are higher than those of VPMSM, the difference in the copper losses is more significant. For these reasons, the efficiencies of spoke-type PMSM are around 1.5 % higher than those of VPMSM in both operating points.

Concerning the parasitic effects, such as the torque ripples and the acoustic excitations, the reference machine shows a better performance in both operating points than the designed machine. The torque ripples of the VPMSM in OP 1 and OP 2 are lower than those of the spoke-type PMSM.

Due to the different combination of number of pole pairs and number of stator teeth, the force excitation orders of the machines are different. Furthermore, the stator yoke height of both machines are not identical, so that the acoustic behavior of the machines can not be estimated only by the radial force densities. To estimate the acoustic radiation, the surface velocities on the stator surface are calculated according to [13]. Since the sensitive hearing range of humans lies between 2-5 kHz [14], only the surface velocities around this range are taken into account. This means, that the excitations in OP 1, which lie under 1 kHz, are not relevant. The calculated surface velocities of the VPMSM in OP 2 are lower than that of the spoke-type PMSM. In worst case scenario, in which all radial force excitations between 1-6 kHz are have the same phase, the sum of the surface velocities of the VPMSM is 88 μm/s. The sum of the surface velocities of the spoke-type PMSM is 2.7 higher than this value with 237 μm/s. The acoustic behavior of the spoke-type PMSM is expected to be inferior to the VPMSM. To validate this presumption acoustic measurements need to be performed.

In compare to the reference VPMSM, the designed spoke-type PMSM has disadvantages concerning parasitic effects; the torque ripples and the acoustic excitations are high. These are related to the spectrum the rotor flux density, which is shown in Fig. 6. The lower harmonics of the flux density, in this case 3^{rd} to 9^{th} harmonics, have stronger influences on these parasitic effects in compare to the higher harmonics.

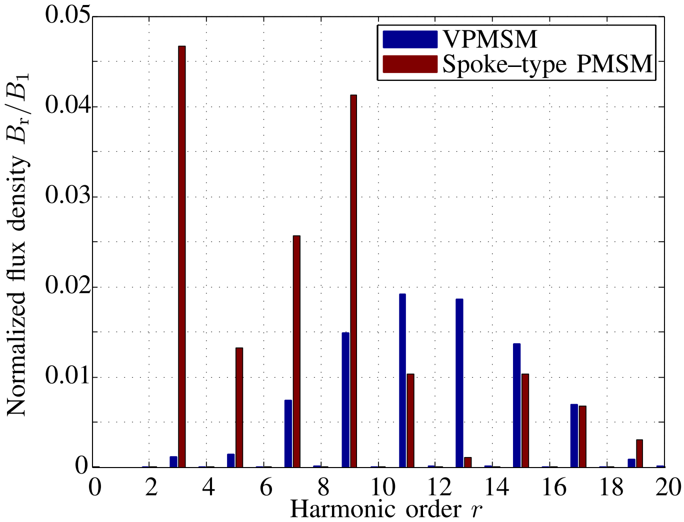


Fig. 6: The air gap flux density of the rotors normalized to the fundamental harmonics.

TABLE IV: Operating Points of the Machines

	OP 1		OP 2	
Speed / rpm	610		19520	
Torque / Nm	1.31		0.26	
Output power / W	83.68		531.47	
	VPMSM	Spoke-type PMSM	VPMSM	Spoke-type PMSM
Copper losses / W	38.87	34.67	52.97	34.21
Iron losses / W	3.20	3.72	33.66	45.03
Efficiency / %	66.01	67.98	80.88	81.81
Torque ripple / Nm	0.04	0.09	0.02	0.04
Surface velocity orders (temporal, spatial) / μm/s				
1952 Hz (6, -3)			58	-
2603 Hz (8, -4)			-	149
3904 Hz (12, 3)			29	-
5205 Hz (16, 4)			-	88
5856 Hz (18, 0)			1	-

D. Overall Operating Area

In Fig. 7 the torque-speed characteristic of both machines and the difference of the machine efficiencies $\Delta\eta = \eta_{\text{Spoke-PMSM}} - \eta_{\text{VPMSM}}$ in the entire operating area are presented. It can be seen, that the characteristics of the machines are similar to each other. In the base speed area with high load, the spoke-type PMSM shows advantages over the VPMSM. Generally, due to the low magnet flux densities the spoke-type PMSM requires higher current than VPMSM to produce the same torque in this area. Through proper design of the stator winding, the resistance of the spoke-type PMSM is lower than that of the VPMSM. It leads to lower copper losses and higher efficiencies in this area. In field weakening range, the copper losses of the spoke-type PMSM are also lower than those of the VPMSM due to the low current required to weaken the magnet flux. Therefore, the efficiencies are higher. In the transition area between the base speed and field weakening area with low torque, the efficiencies of the VPMSM are up to 4 % higher than that of the spoke-type PMSM.

The distribution of the losses in the whole operating area is examined. Due to the same construction of the mechanical parts, the friction losses are not presented in the losses comparison. In Fig. 8 the differences of the losses of the machines are presented. As can be seen in Fig. 8(a), the copper losses of the spoke-type PMSM in the entire operating area are lower than those of the VPMSM. In the base speed area, the copper losses of the spoke-type PMSM are up to 35 W lower than that of the VPMSM. At the rated operating point, the losses difference is around 4.6 % of the mechanical power. The difference of the copper losses in the field weakening area is up to 25 W. At the maximal speed with maximal load, this value represents 3.4 % of the mechanical power.

The iron losses of the spoke-type PMSM are higher than the iron losses of the VPMSM, which is caused by the higher number of pole pairs and thus the electrical frequency. This behavior can be seen in Fig. 8(b). The iron losses of the spoke-type PMSM in the base speed area are up to 11 W higher than that of the VPMSM, which means 1.4 % of the mechanical power at rated operating point. In the field weakening area, the difference of the iron losses reaches 13 W. This represents 1.7 % of the mechanical power at the maximal speed with maximal load.

From the losses analysis can be concluded, that the increase of the iron losses can be compensated through minimizing the copper losses. This can be achieved through increase of copper deployment and suitable design of the stator winding. The sums of the losses at rated operating point, maximum speed with maximum load, OP 1 and OP 2 of the spoke-type PMSM are lower than those of the VPMSM.

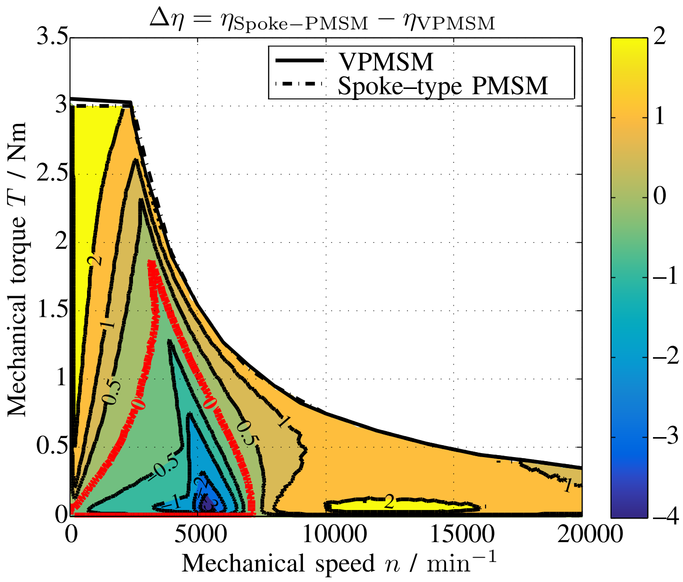
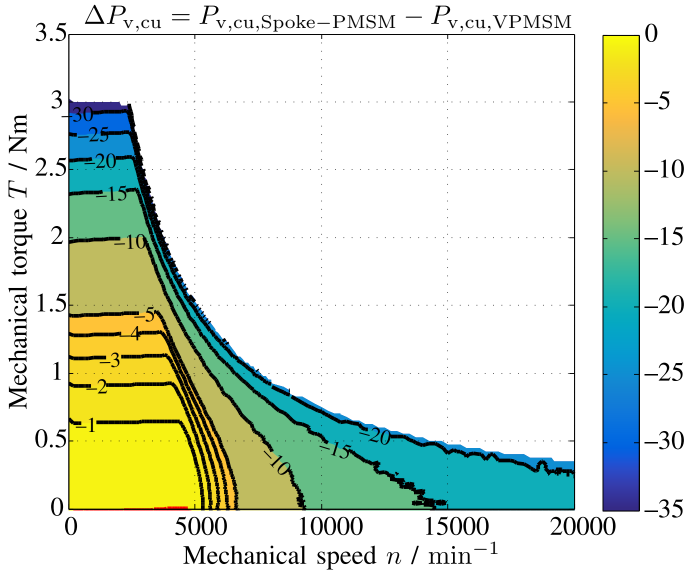
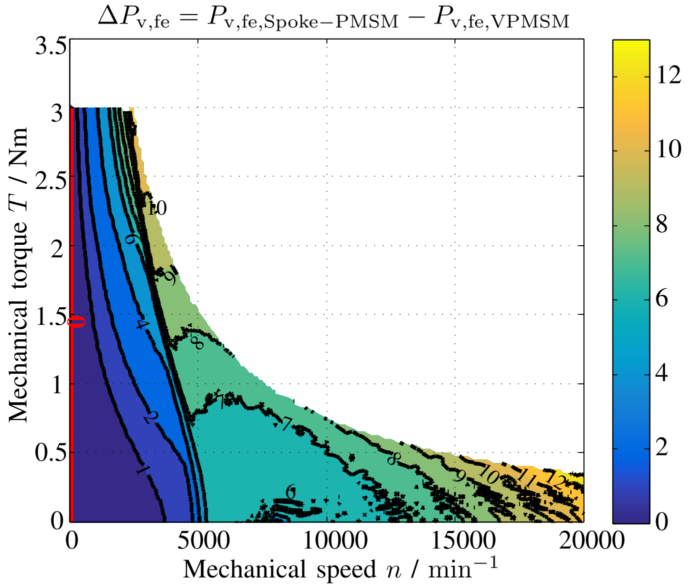


Fig. 7: The torque-speed characteristic and the efficiency difference in percentage point.



(a) The difference of the copper losses.



(b) The difference of the iron losses.

Fig. 8: The absolute losses difference of the VPMSM and the spoke-type PMSM in whole operating area.

V. CONCLUSIONS

Due to the price of rare earth materials a PMSM with rare earth free magnets, such as iron-based (Fe) magnets, becomes an attractive option. The major disadvantage of this magnet material is the low remanence flux density, when compared to the magnet with rare earth materials. To reach a similar machine characteristic with the PMSM with rare earth (NdFeB) magnets, the machine with Fe-magnets has to be redesigned.

In this paper is shown, that a spoke type PMSM with Fe-magnets (spoke-type PMSM) can be a suitable alternative to an interior PMSM with v-shaped NdFeB-magnets (VPMSM). To compensate the low rotor flux density, the spoke-type PMSM is designed with a higher number of poles than that of the VPMSM. Due to the higher electrical frequency, the iron losses of the machine with a larger number of pole pairs are usually high. The increase of the iron losses can be meet through minimizing the copper losses. This can be achieved by deploying higher amount of copper and redesigning the stator winding. To reduce the parasitic effects which correlate to the rotor flux density harmonics, an alteration of the rotor outer contour is performed. Several approaches are examined and based on the cogging torque and the machine performance in OP 1 and OP 2, the most satisfactory approach for a spoke-type PMSM is chosen.

Considering these design steps, a NdFeB free spoke-type PMSM is designed as an alternative to an existing VPMSM. The torque-speed characteristic of the designed spoke-type PMSM is similar to the reference machine. Furthermore, higher efficiencies can be achieved in several operating points. The disadvantages of the designed machines are the higher developed parasitic effects, such as torque ripples and radial force excitations, which can lead to inferior acoustic behavior. Another critical point is the demagnetization stability of Fe-magnets, which is inferior to NdFeB-magnets. The demagnetization behavior of both machines is analyzed and will be presented in the future works.

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VI. BIOGRAPHIES

Aryanti Kusuma Putri received the M.Sc. degree in electrical engineering from RWTH Aachen University, Germany, in 2013. She worked as a research associate at the Institute of Electrical Machines between 2013 and 2018. Her research interests include parasitic effects in electrical machines, simulation and design of electrical machines.

Martin Nell received the M.Sc. degree in electrical engineering from RWTH Aachen University, Germany, in 2017. He has been working as a research associate at IEM Since May 2017. His research interests include simulation and design of electrical machines.

Marco Hombitzer received the Dipl.-Ing. degree in electrical engineering from RWTH Aachen University, Germany, in 2010. After that he became a research associate at the Institute of Electrical Machines. Between 2016 and 2018 he worked as chief engineer of the Institute of Electrical Machines. His research fields include the simulation, the design and performance improvement of electrical machines.

Dr. David Franck received the Dipl.-Ing. degree in electrical engineering from RWTH Aachen University, Germany, in 2008. After that he became a research associate at the Institute of Electrical Machines. Between 2011 and 2017 he worked as chief engineer of the Institute of Electrical Machines. His main field of research is the acoustic behavior of the electrical machines.

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