Impact of Stator Core Magnetic Asymmetry on the Properties of a High Specific Power PMSM

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***Abstract*—Permanent Magnet Synchronous Machines (PMSMs) are commonly employed in applications demanding a high specific power. To achieve high specific power values, a high pole pair number PMSM with very thin yokes can be built. Such a design leads to a high operating frequency. At high operating frequencies, AC losses can more than double the DC losses if solid hairpin technology or traditional bunches of nontransposed round enameled wires are used in the stator windings of machines with a considerable power. Against this negative effect, the emerging Litz wire coil technology with prefabricated coils can be used. In this study, firstly, alternative stator slot geometries required when using prefabricated Litz wire coils are evaluated. A symmetric semi-closed slot is not suitable for inserting such prefabricated Litz wire coils into the stator slots. Instead, an asymmetric semi-closed slot can be used, and it may even offer a better performance than the symmetric open slot. After showing that the asymmetric semi-closed slot provides a better performance, it is investigated how this asymmetric stator slot geometry can be used beneficially. The findings were first studied with finite element analysis (FEA) and then experimentally verified on a high-specific-power machine.**

***Index Terms*—Asymmetric stator geometry, high-torque density, Litz wire, permanent magnet synchronous machine (PMSM).**

I. Introduction

PERMANENT magnet synchronous machines (PMSMs) are widely used in various applications owing to their advantages, such as high specific torque, high reliability, high efficiency, wide operating speed range, and high overload capability [1]. They are used, especially, in smaller size applications where the power output is important, e.g., in road vehicles and more electric aircraft. High-speed electrical machines (HSEMs) are popular in applications that require a mass and volume reduction, because their active volume is mostly related to the rated torque. For a given power, torque can be reduced by increasing the rotational speed. The low mass of a high-speed motor is a key factor in mobile applications, and therefore, a high number of pole pair numbers is favored to make the motor lightweight. Such a motor, however, needs a converter capable of providing a high output frequency [2], [3], [4], [5]. In the context of high-speed applications, the mass of the motor is considered differently in industrial drive systems and in mobile applications. In industrial drive systems, mass is not a major concern and a low number of pole pairs is favored, resulting in a heavy machine but with a moderate electrical frequency. In mobile applications, a low mass is a priority, and thus, PMSMs with increased pole pair numbers are used to make the motor lightweight. In theory, an infinite number of poles results in a yokeless machine.

To achieve a high specific power, it is crucial to not only increase the rotational speed but also attain a high specific torque. In recent years, as a result of developments in magnetic materials and the wide bandgap (WBG) power electronic switches, it is possible to run machines with a very high fundamental frequency. A high number of poles can lead to a high specific torque but, at the same time, the motor operating frequency rises, and at high operating frequencies, both the iron loss density and the Joule losses increase. The AC losses can easily more than double the DC losses if solid conductors, such as hairpin technology or a traditional bunch of nontransposed round enameled wires, are used in the stator windings of machines with a considerable power [6]. The Litz wire coil technology has been adopted to counteract this negative effect [7]. A prefabricated Litz wire coil is manufactured outside of the machine [8]. Therefore, it poses a challenge to assemble prefabricated Litz wire coils into semi-closed stator slots. Moreover, it is not possible to place such prefabricated Litz wires in traditional symmetric semi-closed stator slots. This will be shown in the following sections. Thus, there are only two practical alternatives: asymmetric semi-closed slots and symmetric open slots. In this study, firstly, a comparison of the alternative feasible stator slot geometries is discussed.

On the other hand, it should be noted that an asymmetric structure is not only applied for the sake of structural/manufacturing needs but also to improve the machine performance. Asymmetries may also result from manufacturing tolerances or variations [9], [10], [11]. The effect of asymmetry on radial and tangential stresses, torque pulsations, and unbalanced magnetic pull caused by imbalances in the air gap were analyzed analytically and by using Finite Element Analysis (FEA). These findings were further verified through experimental testing in the given studies. In addition to these studies, asymmetry has long

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been used in industry to improve the performance of certain electrical machines. Asymmetric rotor and stator designs are common in various types of electrical machines, such as universal motors and DC machines, for improved commutation [12], in single-phase brushless permanent magnet (PM) machines for an optimized torque profile [13], in squirrel-cage asynchronous motors for sensorless control [14], and in switched-reluctance machines for enhanced torque characteristics [15].

The rotor or stator geometry can be optimized through asymmetry to achieve the desired torque performance [16]. Asymmetry in a PMSM can be divided into several categories in the rotor or stator parts. The first of these is skewing or step skewing of the magnets in the rotor [17]. Skewing helps to minimize cogging torque, torque ripple, and back-EMF harmonics by suppressing harmonics with counter harmonics generated in other parts of the motor. Although skewing can reduce the harmonics of the torque ripple, cogging torque, and back-EMF, it also reduces the fundamental of the back-EMF and the average torque [18]. Another way to achieve a beneficial asymmetry is to modify the geometry of the hard [19] or soft [20] magnetic material used in the rotor. Optimization of the geometry of the magnetic material, i.e., permanent magnets or steels, suppresses the undesired air gap flux density harmonics.

Symmetric and asymmetric stator slots are compared in [21] to investigate the electromagnetic performance of a PMSM. According to the results, properly designed asymmetric stator teeth result in a higher fundamental flux density in the air gap, and therefore, a higher average torque. They also provide a lower torque ripple, a lower cogging torque, and less harmonics in the air gap flux density distribution. The rotor or stator teeth can also be modified to minimize variation in synchronous inductance under different operating conditions [22]. Modifying the magnetic core can enhance performance in high-specific-torque machines, where local saturation at nominal load results in synchronous inductance variation. Some examples of other asymmetries are unequal tooth tips [23], [24], and shifting of the slot opening [25], [26] and the permanent magnets [27], [28].

Reduced permeance, accompanied by the saturation of tooth tips, may lead to a decrease in the magnetic flux. Depending on the torque direction, the tooth tips on one side of the tooth conduct more flux than those on the other side, causing asymmetric saturation within the stator core. This change necessitates a heightened armature reaction and an increased flux linkage to maintain a constant flux linkage when the voltage remains the same. In theory, reducing the inductance when operating in a certain torque direction should increase the overload capability in that direction if the back-EMF is not affected. However, the reduction of synchronous inductance as a result of the increased magnetomotive force (MMF) often also leads to a decrease in the fundamental back-EMF, which has a negative impact on the torque as a function of applied current. Further investigation is needed to understand the impact of tooth tip saturation on the synchronous inductance and the overall torque performance. In the case under study, the use of an asymmetric structure was mostly required for manufacturing reasons. However, the impact of an asymmetric structure on electromagnetic performance is investigated in detail, and it is discussed that the possible use of asymmetric tooth tips may be preferred not only for manufacturing reasons but also in terms of electromagnetic performance.

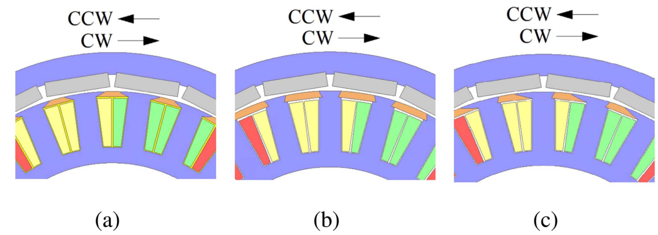


Fig. 1. Types of a possible stator slot geometry in an outer-rotor PMSM: (a) symmetric semi-closed slot, (b) symmetric open slot, (c) asymmetric semi-closed slot (clockwise (CW) and counterclockwise (CCW) are indicating torque directions).

In this study, firstly, a performance comparison between symmetric and asymmetric stator geometries is made. Following the comparison, the reasons for using asymmetric stator tooth tips are explained. The proposed asymmetric stator tooth tip geometry is analyzed in the FEA considering different torque directions. In order to validate the simulation results, a test machine is prototyped with the proposed asymmetry. The paper is organized as follows. Section II outlines the reasons that lead to local saturation in the stator core and discusses the possible stator teeth geometries in a PMSM with a tooth-coil winding. Section III describes the FEA model and discusses the FEA results. Section IV addresses the test setup and the experimental results.

II. Analysis of Local Saturation and Stator Teeth Geometry in a PMSM With a Tooth-Coil Winding

To enhance the specific torque and power of electrical machines, attention is turned to PMSMs. These motors are good candidates for high-speed and high-power applications, where efficiency and specific torque are of paramount importance.

Each image in Fig. 1 depicts the cross-section of different stator slot geometries of a 24-slot, 20-pole outer-rotor PMSM with concentrated, nonoverlapping tooth-coil windings. This machine is based on a 12/10 base machine that has two coil groups for each phase. Different colors in the slots represent different phases. Here, two pivotal factors that influence the performance of PMSMs are explored: local saturation and the role of stator teeth geometry.

A. Local Saturation

There are two contributors of flux in the air gap: the PMs and the armature reaction. The PMs provide an approximately constant source of flux in the air gap, and typically, the operating flux density harmonic (in this case the fifth) is much higher than the other harmonics. However, different values of armature reaction generate different harmonics of the air gap flux density (including high-order harmonics and subharmonics—in this case the fundamental is behaving like a subharmonic). In addition, the armature reaction can affect the value of the synchronous inductance, which, in turn, affects the flux density value generated by the PMs. Further, the interaction of the PMs flux and the armature reaction flux in some stator core areas (e.g., stator teeth and tooth tips) can have a direct impact on the machine performance, making the tooth tip geometry critical for the PMSM performance.

Flux interaction in different stator core areas (e.g., tooth tips) can result in saturation, which, in turn, reduces the torque-to-current ratio. One solution to reduce such an effect is to increase the cross-sectional area of the magnetic core, where saturation occurs. However, doing so occupies more space within the machine (reducing the space for the winding) and can also increase the leakage inductance (e.g., slot leakage inductance), which may not always be desirable, especially in high-specific-torque PMSMs. Additionally, it can lead to inefficient use of magnetic materials and higher stator Joule losses, as the winding area becomes smaller.

The flux density distribution in the teeth is nonsymmetric under load. At different loads, the distribution of flux density in the teeth changes, and the maximum flux density also changes. The interaction of the PM flux with the armature reaction flux affects the distribution of flux density in the teeth, leading to an asymmetric saturation in the symmetric tooth tip design. This has direct effects on the magnetizing inductance and the leakage inductance but also on the torque-to-current ratio. Therefore, the tooth tip design has a significant impact on the overall performance of the machine [1]. The study highlights that it is important to carefully consider the tooth tip geometry in the design of a high-specific-power PMSM.

The asymmetricity of the total flux density distribution, which results from the interaction of the armature reaction and the PMs, can significantly affect the performance of the PMSM under different loading conditions. This asymmetry in the flux density distribution is caused by variation in the armature reaction, which by interacting with the PM flux increases the total flux on one side of the teeth and reduces it on the other side, thus altering the reluctance according to the direction of the torque. This asymmetry in the flux density distribution must be carefully investigated for possible improvements in the performance of the PMSM and for optimizing the design of the stator geometry.

B. Stator Tooth Geometry

Recent studies have shown that increasing specific torque and power in electrical machines has become a priority in machine design for special applications. Various studies have been carried out and different methods have been adopted to achieve a high specific power. One of the most effective methods is to increase the current density of the stator windings. When increasing the current density, the thermal behavior of the machine should be considered because the loss density is also increasing. To avoid AC losses caused by a high fundamental frequency, a prefabricated Litz wire coil is employed. The stator windings with prefabricated Litz wire coils are manufactured before inserting them into the machine. The method is also known as prewound winding. When prefabricated coils are placed in stator slots, the slot openings have to be wide. The possible stator slot geometries are shown in Fig. 1. It is not possible to place the prewound windings in the stator slots in a symmetric semi-closed slot structure while keeping the end-winding length at the minimum. Another alternative is to use a symmetric open slot structure, but using an open slot reduces the stator tooth tip width significantly. This reduces the flux and back-EMF. However, also the synchronous inductance becomes smaller, partly compensating the effect of reduced flux in the torque production of the machine. Another alternative without reducing the stator tooth tip width is to use an asymmetric semi-closed slot. The slot opening and the stator tooth tip width remain the same as with a symmetric semi-closed slot. Therefore, in the asymmetric semi-closed slot structure, the back-EMF and torque are not reduced as much as in the case of an open slot opening design.

TABLE I
MAIN DIMENSIONS AND PARAMETERS OF THE MACHINE

Parameter	Value
Number of poles	20
Number of slots	24
Active length of the machine (mm)	100
Rotor inner/outer diameter (mm)	288 / 316
Stator inner/outer diameter (mm)	178 / 267.6
Thickness of the permanent magnet (mm)	9
Rated/Maximum speed (rpm)	6000 / 10000
Rated/Maximum torque (Nm)	900 / 1100
Grade of the permanent magnet	N45UH
Stator material (lamination stack)	M235-35A
Rotor material (solid core)	S355

In [16] and [21] it is suggested that modifying the tooth tips can improve the magnetic flux distribution and reduce saturation, improving the PMSM performance without affecting the manufacturability of the machine, e.g., the slot opening size remaining the same as in the symmetric geometry. The goal is to evaluate the impact of asymmetry on the PMSM performance, providing insights into optimizing PMSMs with tooth-coil windings for a high frequency and a high specific power. Tooth-coil windings also enable selecting the leakage inductance level as different base machines have very different air-gap leakage inductances.

In this study, a PMSM with tooth-coil windings and an asymmetric stator tooth tip geometry is investigated. The study focuses on examining how the performance of the machine is affected by the magnetic asymmetry in the stator tooth tip, with consideration of the direction of torque. The objective is to determine how this asymmetry can be advantageously employed to enhance the machine performance. The main dimensions and parameters of the PMSM are given in Table I. The PMSM has an outer-rotor structure with rotor-inner-surface-mounted permanent magnets. The tooth-coil winding topology is preferred owing to its several advantages. The inner-armature tooth-coil winding topology allows the stator windings to be prepared as prewound windings and then placed in the stator slots, and the asymmetric tooth tip design enables the use of this prewound winding assembly method in the present machine.

The asymmetric structure in the stator tooth tips could facilitate the implementation of prewound windings. It is possible

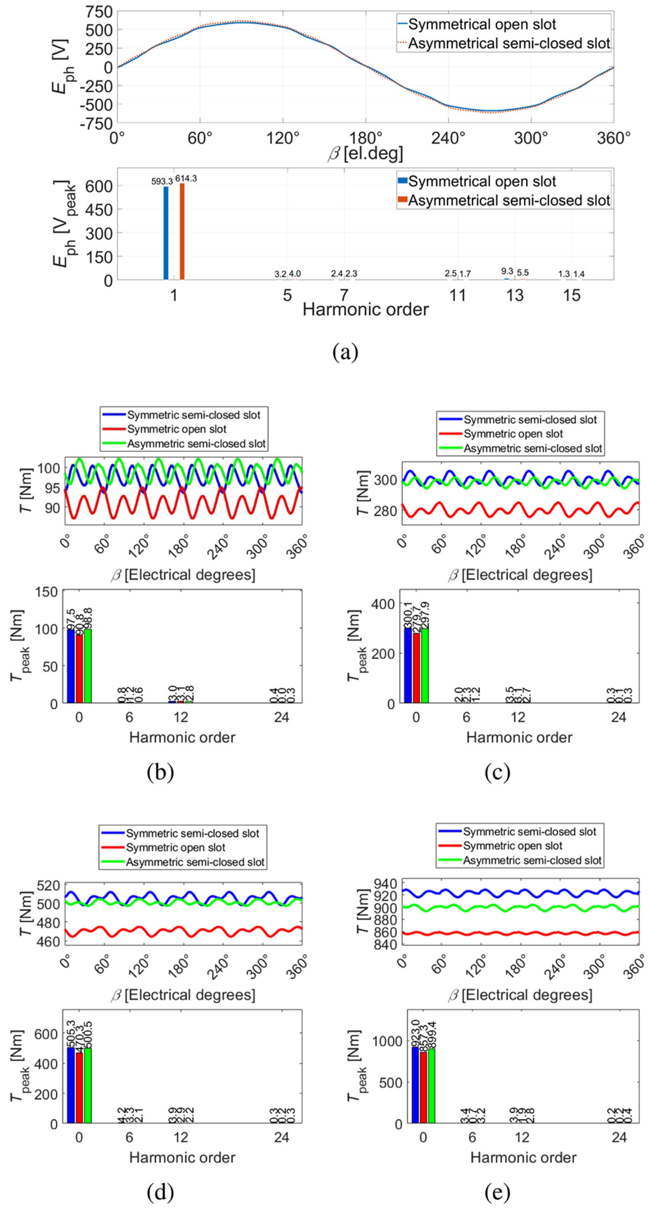


Fig. 2. Comparison of the symmetric and asymmetric geometries (in the CCW direction) in terms of (a) back-EMF, (b) $i_q = 75$ A, (c) $i_q = 225$ A, (d) $i_q = 375$ A, and (e) $i_q = 750$ A.

to place the first half of a coil turn on the tooth side with the tooth tip and then slide the second half of the coil turn on the tooth side without the tooth tip. The geometry of asymmetric semi-closed stator slot tooth tips is shown in Fig. 1(c). The figure shows that the slot opening width is about the same as in the case with the symmetric semi-closed slot tooth tips shown in Fig. 1(a). However, with the symmetric semi-closed slot tooth tips, it would not be possible to insert the prewound coils into the stator slots.

A comparison between symmetric and asymmetric geometries was made to observe the difference in the performance of the machine. The comparison is based on back-EMF and different torque levels, and the results are shown in Fig. 2. In the analyses, current values for each slot geometry were equal for the given case, and the current vector angle was controlled according to the Maximum Torque Per Ampere (MTPA) principle in all cases. Based on the results, the symmetric semi-closed slot can achieve a slightly higher torque with the same current at high loads. However, at lower loads, the asymmetric semi-closed slot provides about the same torque at the same supply current. Additionally, the torque ripple in the asymmetric semi-closed slot structure is smaller across most load levels. The main reason for applying the asymmetric semi-closed slot structure is to avoid using a completely symmetric open slot structure, which was the only alternative for proceeding with the prewound coil assembly. Therefore, in principle, there was a choice between using an open slot structure or an asymmetric structure, which provides significantly better torque characteristics.

III. FEA Model and Results

An FEA model was used to simulate and analyze the magnetic field behavior. The flux density distribution and flux line patterns are given in Fig. 3. The figure shows the magnetic flux density distribution of the PMSM with tooth-coil windings and the asymmetric semi-closed stator slot geometry in different torque directions. The direction of the torque is given in the figures. In the analysis, the machine operates always in the motoring mode. The figure highlights the asymmetric flux density distribution in the stator core and the saturation points at the tooth tips in different torque directions. The saturation points at the teeth become significant with higher load levels. The saturation points are indicated by white circles. The analysis helps to understand the impact of an asymmetric semi-closed stator geometry on the magnetic field behavior and to optimize the design of the PMSM for better performance and efficiency.

The asymmetric stator geometry leads to varying saturation levels in the teeth depending on the direction of the torque. Saturation increases the magnetic circuit magnetomotive force and thereby reduces the synchronous inductance as the load level increases. The change in inductance with both the direction of torque and the load level demonstrates the importance of considering the asymmetric stator geometry in the design of the outer-rotor PMSMs with tooth-coil windings. The asymmetry of the stator geometry affects the inductance, the value of which changes with the direction of torque and the load level. The results of the FEA analysis are used in determining the performance characteristics of the PMSM.

The motoring performance characteristics of the machine, including efficiency, power factor, phase current, and phase voltage, were evaluated and compared in different torque directions. The Maximum Efficiency Per Ampere (MEPA) control algorithm was applied to maximize the efficiency of the PMSMs by controlling the current angle command based on the total losses. This algorithm searches for all possible current vectors and selects the one that provides the highest efficiency. The maximum current supply is allowed in all scenarios.

Figs. 4–7 depict various performance characteristics of the machine in relation to the direction of torque. The torque directions are shown in Fig. 1. The CCW torque direction refers to

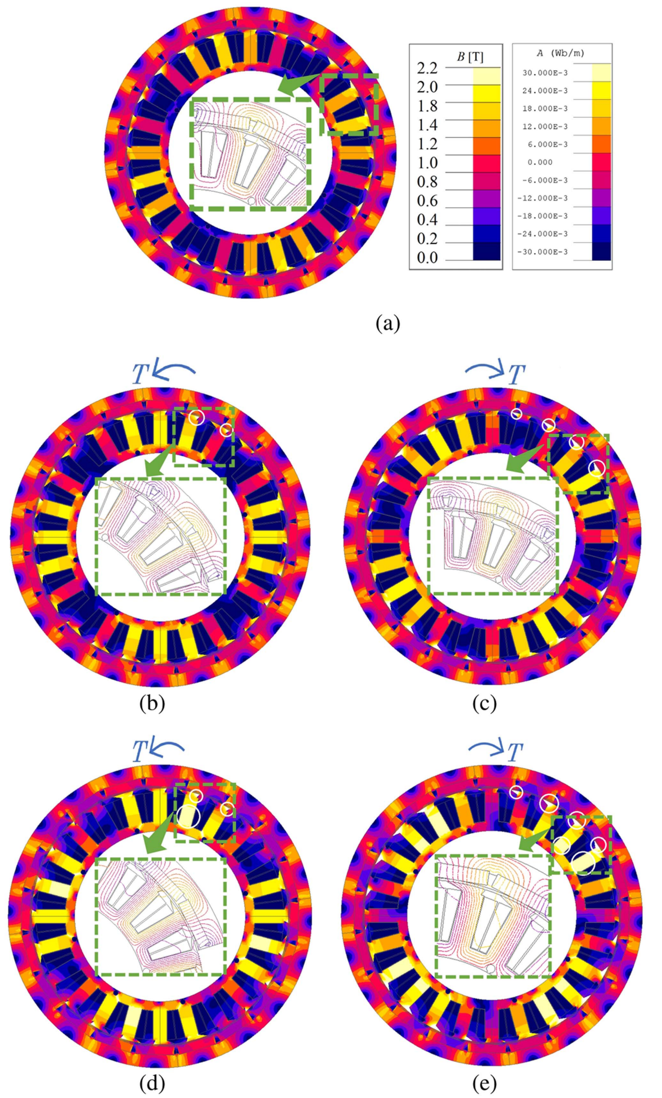


Fig. 3. Flux density and flux line distribution at (a) no-load, (b) $i_q = 500$ A (CCW direction), (c) $i_q = -500$ A (CW direction), (d) $i_q = 1000$ A (CCW direction), (e) $i_q = -1000$ A (CW direction). (The negative values of the i_q current are given to indicate the operating direction in motoring.).

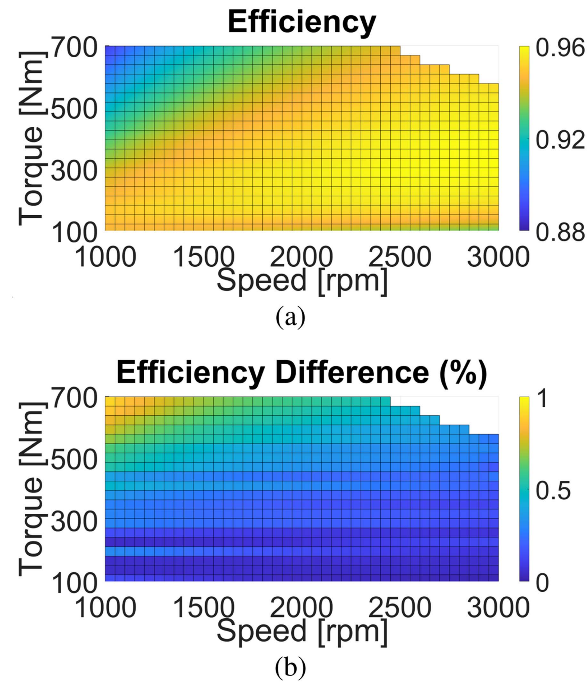


Fig. 4. Efficiency map for different operating speeds and load levels (a) for the CCW torque direction, (b) difference from the CW torque direction.

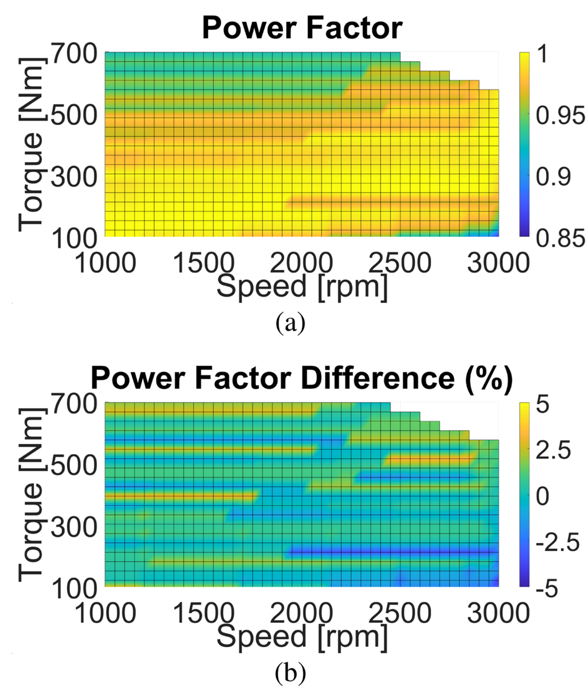


Fig. 5. Power factor variation for different operating speeds and load levels (a) for the CCW torque direction, (b) difference from the CW torque direction.

a situation where the torque direction aligns with the direction of the "hammer" tooth tip. The CW torque direction refers to a situation where the torque direction opposes the direction of the "hammer" tooth tip. The CCW torque direction was chosen as the main direction (positive q-axis current). Each graph presents the base graph first, followed by the graph showing the difference between the CCW and CW torque directions (the CW direction has been subtracted from the CCW direction). The efficiency, power factor, RMS phase current, and RMS phase voltage are presented in Figs. 4–7, respectively, based on the operating speed and load level. These figures illustrate the performance characteristics for both the CCW torque direction as the main torque direction and the difference between the CCW and CW torque directions of the machine.

The results have shown that the machine under study produces a specified torque level without a need to increase its dimensions. The high performance of the machine, which includes the prefabricated Litz wire coil in the stator windings, was confirmed by the FEA results. Additionally, there is a performance difference between the CCW and CW torque directions. However, for some motor parameters, there is only a slight difference between the

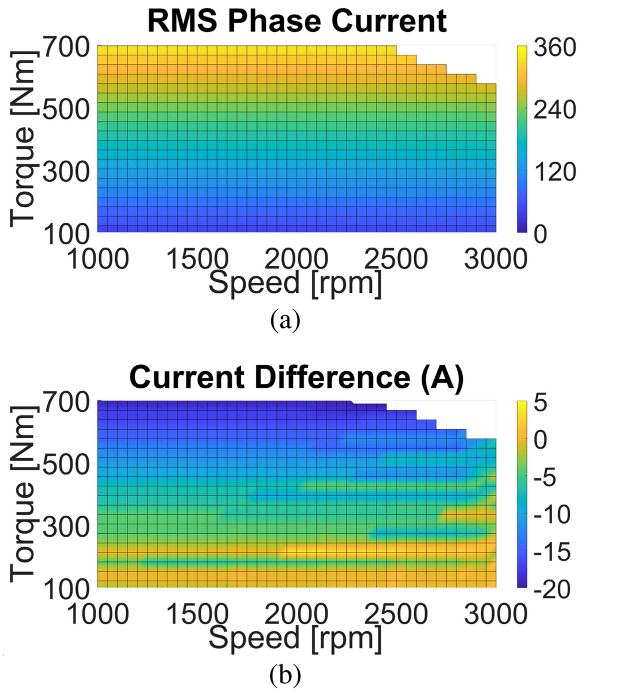


Fig. 6. RMS phase current values for different operating speeds and load levels (a) for the CCW torque direction, (b) difference from the CW torque direction.

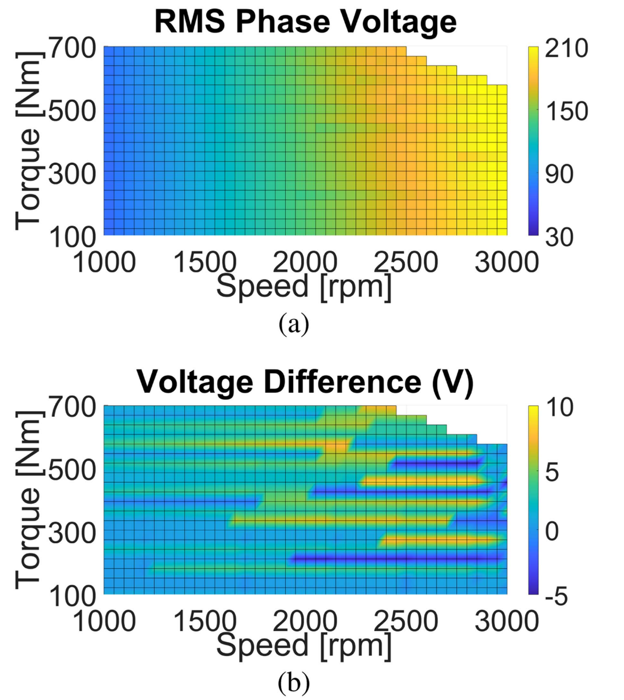


Fig. 7. RMS phase voltage values for different operating speeds and load levels (a) for the CCW torque direction, (b) difference from the CW torque direction.

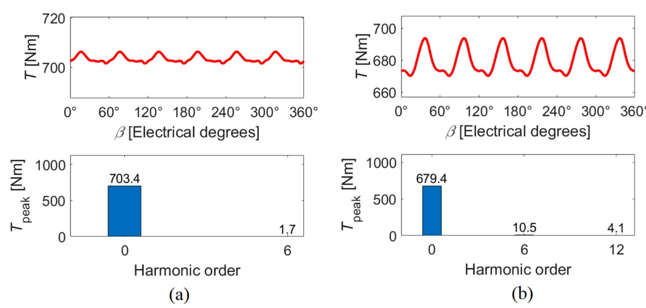


Fig. 8. Average torque and spectrum at $i_d = 0$ A for (a) CCW torque direction ($i_q = +500$ A), (b) CW torque direction ($i_q = –500$ A).

CCW and CW torque directions, e.g., for the phase voltage and the power factor. In the higher power range, the efficiency is slightly higher in the CCW torque direction, but the total losses are consistently slightly higher in the CW torque direction. Furthermore, the RMS phase current is slightly higher in the CW torque direction.

The power factor difference is given in Fig. 5(b); according to the figure, the power factor is higher in the high-torque–low-speed region in the CCW torque direction, while it is higher in the low-torque–high-speed region in the CW direction. However, in fact, in many operating points the difference is very small and negligible. Although the total current applied from the control algorithm, the inductance, and the PM flux linkage vary depending on the torque direction, this does not produce a significant difference in the power factor, except for some extreme operating points.

Two different scenarios were tested with $i_d = 0$ A for nominal operation and in field weakening with $i_d = –500$ A while applying $i_q = +500$ A (CCW) or $i_q = –500$ (CW). According to the results shown in Fig. 8, the average torque in the CCW torque direction is higher compared with the CW torque direction in the nominal operation. In the nominal operation ($i_d = 0$ A), the average torque in the CCW torque direction is 3.53% higher than in the CW torque direction. On the other hand, the torque spectra shown in Fig. 9 indicate that the CW torque direction has a 3.74% higher average torque in the field weakening operation. However, the torque ripple is lower in the CCW torque direction than in the CW torque direction for both nominal and field weakening operation. The higher torque can be attributed to the lower saturation level in the teeth.

IV. Experimental Results

One of the main reasons for preferring the asymmetric semi-closed stator slot structure is the opportunity to easily assemble prewound windings into the stator slots. The stator windings were prepared outside of the machine because the stator windings contain prefabricated Litz wire coils. The symmetric and asymmetric semi-closed slot structures, which are shown in Fig. 1(c), were produced with a 3D printer in order to verify the winding manufacture. The prototype symmetric semi-closed stator slot core and the prewound winding that was attempted to be placed in the stator slot are shown in Fig. 10(a).

It can be clearly seen in the figure that the prewound winding with the minimum end winding length does not fit around the tooth because of the symmetric tooth tip geometry. After making the stator tooth tips asymmetric, the prewound winding could be slid into the stator slots as shown in Fig. 10(b). It was validated

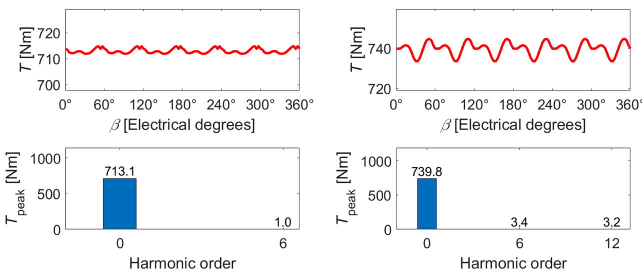
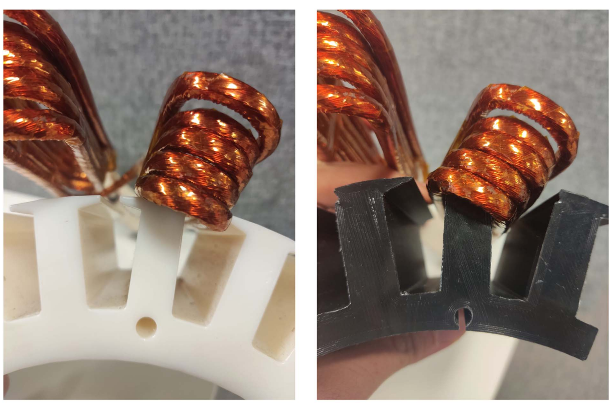


Fig. 9. Average torque and spectrum in field weakening at $i_d = -500$ A for (a) CCW torque direction ($i_q = +500$ A), (b) CW torque direction ($i_q = -500$ A).



(a) (b)

Fig. 10. Installing the prewound Litz wire coils into the stator slots with (a) symmetric tooth tips, (b) asymmetric tooth tips.

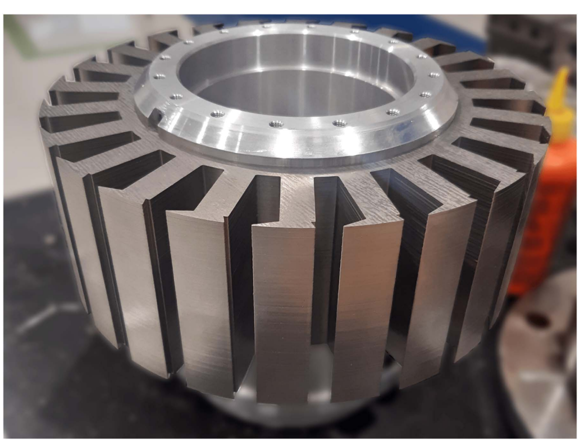


Fig. 11. Stator stack with an asymmetric stator-tooth tip geometry.

that the prewound stator windings could be inserted into the stator slots because of the asymmetric tooth tips.

The experimental setup was used to validate the performance of the machine with the proposed asymmetric semi-closed stator slots. The stator stack of the machine is shown in Fig. 11. The asymmetricity of the stator tooth tips can be clearly seen in the figure. The machine under investigation is an external rotor machine with rotor-surface magnets and a 24/20 slot-pole

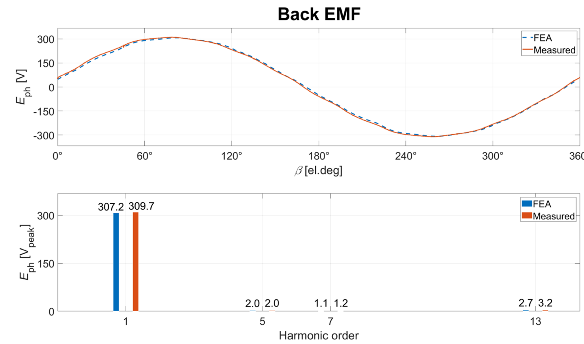


Fig. 12. FEA and experimental results of the phase voltages.

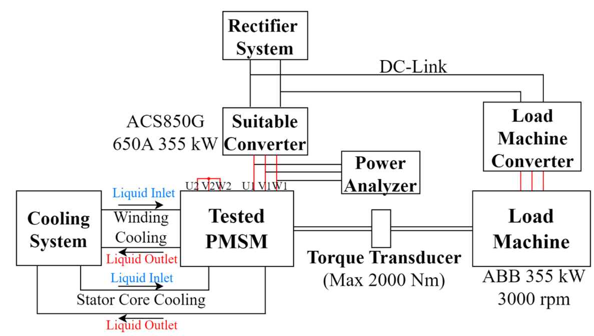


Fig. 13. Schematic of the test bench.

combination (two times the 12/10 base machine). The tooth-coil winding arrangement was selected because it provides an easier coil assembly and short end windings for the PMSM. The back-EMF of one phase is measured and compared with the FEA results to verify the experimental results of the prototype machine. The FEA and experimental measured voltage waveforms and harmonic spectra for the same phase are given in Fig. 12. There is no significant difference between the FEA and the experimental results. The mechanical shaft of the tested machine was coupled to a 355 kW induction machine (IM). The torque was measured by a torque sensor with a measuring range of 2000 Nm. Currents and voltages were measured by a power analyzer (Yokogawa PX8000). The tested machine and the load machine were controlled with a suitable commercial converter, the ABB ACS850G1 series, with different power rates. The supply of the power converter is a passive rectifier. A schematic view of the complete experimental test setup is illustrated in Fig. 13, and the experimental setup components are shown in Fig. 14.

The experimental results are presented in Figs. 15–18. The efficiency for CCW torque direction is given in Fig. 15(a), and the difference from the CW torque direction is presented in Fig. 15(b). According to the results, the efficiency is about 2% higher around the nominal operating point in the CCW torque direction. However, in some points, the difference could reach up to 9%. When the results are compared with the simulation results given in Fig. 4, it can be seen that there is a good agreement between the simulation and measurement results. There are slight differences between the simulated and measured results because of the mechanical, friction, and windage losses. Another

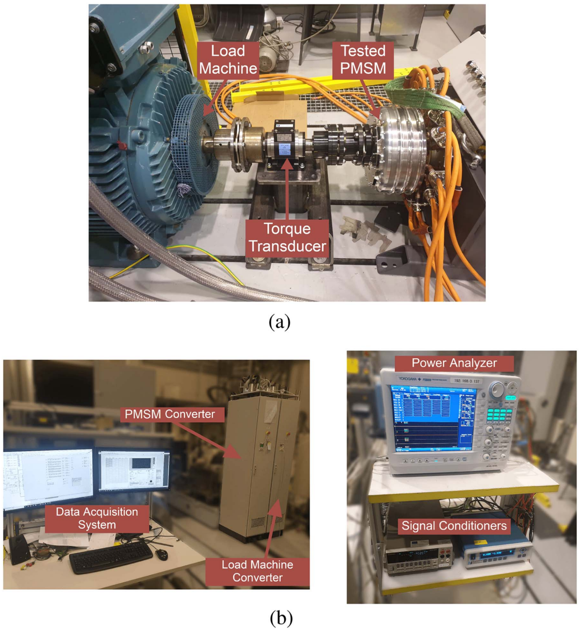


Fig. 14. Experimental test setup (a) machines, (b) converters.

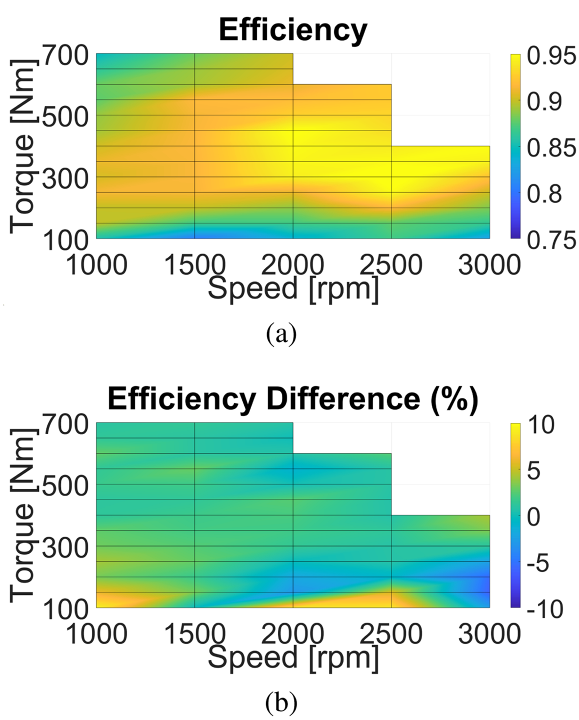


Fig. 15. Experimental results of the efficiency map for different operating speeds and load levels (a) for the CCW torque direction, (b) difference from the CW torque direction.

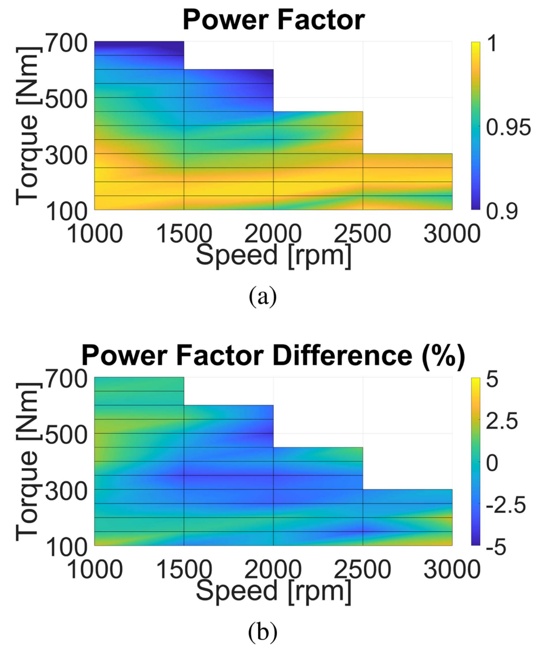


Fig. 16. Experimental results of power factor variation for different operating speeds and load levels (a) for the CCW torque direction, (b) difference from the CW torque direction.

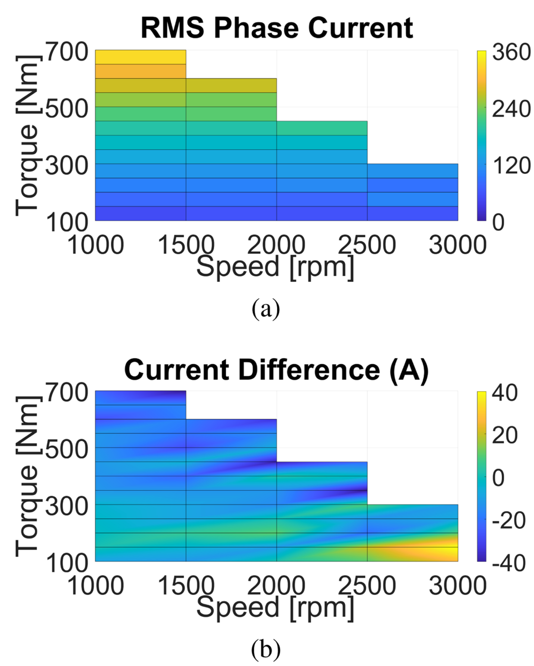


Fig. 17. Experimental results of RMS phase current values for different operating speeds and load levels (a) for the CCW torque direction, (b) difference from the CW torque direction.

reason for not perfectly matching the measured and simulated results can be due to the different control methodologies used in the simulations and the measurements. In the simulation, MEPA was used, while in ABB converters, the Maximum Torque Per Ampere (MTPA) control logic is typically used. There is an integrated fan at the end of the tested machine, and it was not modeled in the electromagnetic simulations. However, this difference is less than 1% for most of the operating points. The efficiency decreases at a higher torque as a result of the increasing Joule losses when a higher current is flowing in the stator windings. The highest efficiency of 96% reached in the motoring mode takes place at 300 Nm, 2500 rpm for the CCW torque direction in the experimental measurements.

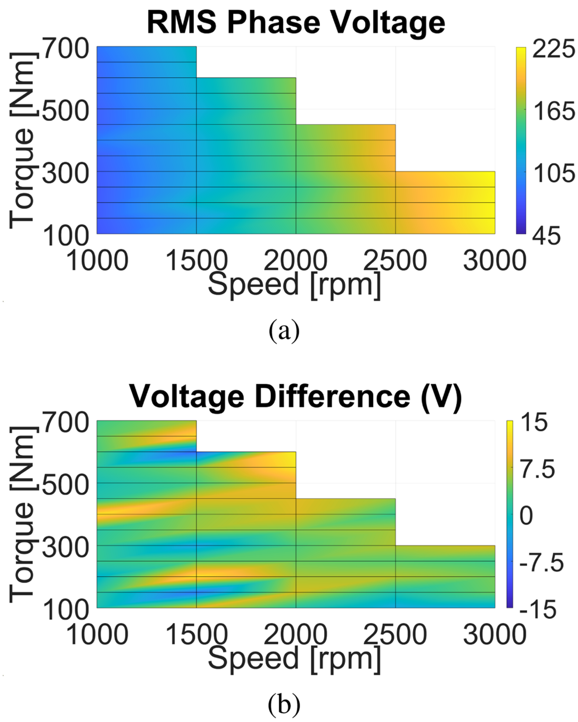


Fig. 18. Experimental results of RMS phase voltage values for different operating speeds and load levels (a) for the CCW torque direction, (b) difference from the CW torque direction.

The experimentally measured power factors for the CCW torque direction and the difference from the CW torque direction are given in Fig. 16. It can be seen that the results match quite well with the simulation results given in Fig. 5. Based on the results, high power factors in a wide operating range are obtained. While the power factor is the same in a wide range, the difference reaches up to 5% in some operating points. But around the nominal operating point of the machine, the difference is approximately 2%. The power factor is slightly higher in the CW torque direction because of the saturation phenomena in the stator tooth tips that are more prevalent in the CW torque direction.

The phase currents and phase voltages from the experimental measurements are shown in Figs. 17 and 18, respectively. In the figures, currents and voltages are given in RMS values. The results match with the simulation results given in Figs. 6 and 7 for both directions. According to the figures, the RMS phase current increases with an increasing load power level, and the RMS phase voltage increases with an increasing operating speed as expected. The applied current is slightly higher in the CW torque direction than in the CCW torque direction for the same operating point. However, the voltage in the CCW torque direction is slightly higher than in the CW torque direction for the same operating points.

V. Conclusion

A PMSM with tooth-coil windings and an asymmetric stator tooth tip geometry was investigated. The stator winding coils must, in practice, be manufactured outside of the machine and then placed in the stator slots. Asymmetric teeth enable this. A higher current density leads to local saturation, which is difficult to avoid in the stator tooth tips that are closest to the air gap; therefore, the reasons for local saturation in a PMSM with tooth-coil windings were described. This is a result of the interaction between the flux of the permanent magnet and the armature reaction. Considering these saturation effects, a comparison among the possible stator slot geometries was conducted.

It was shown that in a stator with asymmetric tooth tips, the stator windings with prefabricated Litz wire coils cannot be placed in the stator slots while keeping the end winding length at the minimum. Therefore, there are two alternatives, a symmetric open slot and an asymmetric semi-closed slot. The performances of the alternatives were analyzed by FEA, and it was found that the machine with asymmetric stator tooth tips gave a better performance than the open slot structure. After finding that the asymmetric semi-closed slot provides a better performance, it was investigated how this asymmetric stator slot geometry can be used beneficially. It was noticed that the performance of the asymmetry at the tooth tip of the stator varied depending on the torque directions of the motor. The saturation level, which changes with the torque direction, changes the inductance of the machine according to the torque direction even in a rotor-surface-magnet PMSM. Therefore, a machine with asymmetric tooth tips can have different performance characteristics depending on the torque direction.

In this study, this performance difference was examined; further, it was emphasized how this difference resulting from the torque direction can be utilized. The findings were first simulated with FEA and then experimentally verified on the machine. According to the results, the tested machine exhibited an improved efficiency in the CCW torque direction, while the power factor was slightly higher in the CW torque direction as a result of the stator tooth tip saturation phenomena, which were more prominent in the CW torque direction. Additionally, the applied current was higher in the CW torque direction, while the voltage was higher in the CCW torque direction. Based on these findings, if the machine is to be operated more in one direction, e.g., in electric vehicles, the direction of torque should be selected according to the specific requirements of the application. For example, if a high efficiency is a priority, the CCW torque direction might be preferred. However, if a higher power factor is more important, the CW torque direction might be chosen despite the slightly lower efficiency. The decision depends on the specific needs and constraints of the application.

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