Design Methods of Transversally Laminated Synchronous Reluctance Machines

Shun Cai, Jianxin Shen, Senior Member, IEEE, He Hao, and Mengjia Jin

Abstract—Transversally laminated synchronous reluctance machine (SynRM) are usually designed with multiple-layer flux barriers to achieve high electromagnetic performance. This paper summarizes three design methods to optimize the machine. Related implementation procedures are detailed. Besides, advantages and disadvantages of these methods are discussed. Based on these conventional techniques, a comprehensive optimization method is proposed, with which a prototype SynRM is designed. The performances of this prototype are discussed to verify the optimal design method.

Index Terms—Design method, flux barrier, synchronous reluctance machine, torque ripple.

I. INTRODUCTION

SYNCHRONOUS reluctance machine (SynRM) has attracted much attention recently, thanks to the advantages of low cost, robust structure and high torque density [1-3]. Compared with induction machines (IM), the rotor of SynRM is simpler to manufacture and produces less losses. In [4], testing with the same speed and load torque, the temperature rise of an IM is much higher than a SynRM. As for permanent magnet synchronous machine (PMSM), the cost of SynRM is much lower, and, problems such as the magnets demagnetization and the performance variation with temperature rise do not exist. In [5], a SynRM is optimized with the same volume of a ferrite PMSM, and their electromagnetic torque is similar. Besides, torque ripple of the SynRM is usually lower than that of the switched reluctance machine (SRM), therefore, producing less vibration and noise [6].

Define d-axis as the main flux path, namely the smaller reluctance direction, and q-axis as the larger reluctance direction. The SynRM is working based on the rotor saliency (the ratio of the d-axis inductance and the q-axis inductance), and the rotor design has been the main issue. Generally speaking, the SynRM has three rotor topologies, namely the physically salient pole (SP) structure, the transversally laminated anisotropy (TLA) structure, and the axially laminated anisotropy (ALA) structure [7]. The SP rotor in Fig. 1(a) has been perceived to be the simplest to manufacture. The saliency is gained by cutting q-axis magnetic lamination, but the pole arc of d-axis is shrunk meanwhile. Therefore, saliency of the SP rotor is the lowest among these three structures [8]. The saliency of the TLA rotor in Fig. 1(b) is produced by punching several layers of air flux barrier in the q-axis. To maintain rotor mechanical stress, ribs are preserved to connect the adjacent iron segments, but the ribs cause flux leakage. It is not difficult to manufacture the TLA rotor, and the electromagnetic performances are better compared with the SP rotor. The ALA rotor in Fig. 1(c) is assembled by stacking axial lamination layers and axial insulation layers alternatively [9]. The saliency is usually considered to be the highest, for example, in [10] the saliency ratio (i.e., $L_d/L_q$) of 10~20 is achieved. However, there are mainly two problems about the ALA rotor. First, the rotor structure is very complicated and the cost of manufacturing and assembling is high. Second, mechanically the rotor is not strong and can not operate at high speed [11]. Therefore, the most promising structure for mass production in industry application is the TLA rotor.

When the number of flux barrier layers for the TLA rotor is small, the thickness of the iron segments is large and flux lines in the q-axis can still pass along the iron segments. The flux barriers can not separate the q-axis flux line adequately, and thus the rotor saliency is decreased. It has been demonstrated that the performance of SynRM with the TLA rotor can be improved when adopting multiple-layer flux barriers [1, 11]. However, the parameters to be optimized become enormous and are dependent on each other, making the optimization procedure complex.

Now, finite element method (FEM) has been widely used to optimize the electrical machines for accurate calculation and accepTABLE time consumption [3]. If FEM is utilized to optimize the motor parameters one by one, the final results may be not optimal and sometimes even poor. If FEM is applied to optimize the parameters globally, the parameters form a huge matrix and the optimization time is not accepTABLE. Therefore, how to optimize the SynRM both accurately and rapidly is a key issue to investigate.

The purpose of this paper is to introduce various methods and propose a comprehensive method to design the transversally laminated SynRM. First of all, this paper summarizes the conventional methods to optimize the SynRM. Implement procedures are stated, and both the advantages and disadvantages of these method are compared. Then, a comprehensive optimization method is proposed to design the SynRM parameters preliminarily. This method is applied to optimize a 5kW prototype SynRM. The design procedure is detailed and the performances of the prototype are discussed to

Shun Cai, Jian-Xin Shen, He Hao, and Meng-Jia Jin are with the Department of Electrical Engineering, Zhejiang University, Hangzhou, China (e-mail: caishun@zju.edu.cn, J_X_Shen@zju.edu.cn, goodcrane@zju.edu.cn, M_J_Jin@zju.edu.cn).
validate this method.

![Image of rotor structures](image)

**Fig. 1.** Three different rotor structures of SynRM. (a) SP Rotor. (b) TLA Rotor. (c) ALA Rotor.

**II. CONVENTIONAL DESIGN METHODS**

Much research has been done to improve the calculation speed and achieve high performances [3], [12-29]. In this section, the conventional methods to optimize SynRM are classified as three types.

A. Combination of FEM with Optimization Algorithm

One of the solutions to solve this problem is to combine the FEM with various optimization algorithms [12-19]. By utilizing a certain algorithm to search the potentially optimal parameters according to the proceeding calculation results, the parameter matrix to be solved can be simplified and the calculation efficiency can be improved significantly.

In the first step, a parametric model is established, and the parameters to be optimized are listed. The initial parameters are given to calculate in the beginning. Take a rotor with two U-shape (2U) flux barriers [14] as an example to analyze, the rotor section is shown in Fig. 2. There are 8 parameters in the rotor, and obviously, they are dependent on each other.

In the second step, the constraint conditions of the parameters are set, including the parameter range conditions, the geometry constraint conditions, and the electromagnetic constraint conditions. The parameter range conditions include the variation range of each parameter to be calculated, and these
determine the solving time. If the variation range is too large, it may take a long time to converge. If the variation range is too small, the final result may be not optimal. So it is important to set a reasonable variation range. The geometry constraint conditions mean the possible combinations of the geometric structure. For the 2U flux barriers rotor of Fig. 2, the total thickness of the two layers of flux barriers and three layers of iron segments along the q-axis is equal to the difference between the rotor outer radius and inner radius. Therefore, the summary of $h_1$ to $h_4$ is less than the difference of rotor outer radius and inner radius. Similar constraint condition is also suitable for the $t_1$ to $t_4$. When the above conditions are satisfied, each combination of parameters can be corresponding to a rotor structure. The rotor can be optimized but the optimization time is very long. To reduce the optimization matrix, the electromagnetic constraint conditions can be attached. For the 2U flux barriers rotor of Fig. 2, the main flux lines pass through the segments along the d-axis. Although the leakage flux of the q-axis may shift the flux lines, the flux linkage of the d-axis is much larger than that of the q-axis. To distribute the flux density uniformly, the radial thickness of the second iron segment ($h_2$) should be similar to the tangential thickness ($t_2$). Similar constraint condition is also suitable for the other layers of flux barriers. By limiting the difference and the ratio, the matrix to be optimized can be reduced significantly.

In the third step, the objective functions, maximum iterations, and the minimum convergence limit are set. The conventional objective to design a machine is to ensure the torque density and power density. Since the SynRM has inherent drawbacks of poor power factor, and large torque ripple, the objective function should be set with comprehensive weights of these performances. The maximum iteration and minimum convergence limit determine the calculating time and accuracy, and ought to be coordinated properly.

In the last step, the computer calculates and outputs the optimal parameter design. Firstly, the objective function of the initial model is solved. Then the computer searches among the parameter matrix to be optimized within the constraint conditions, and calculates the objective of the new parameters corresponding prototype. The objective function is compared with the proceeding result until the maximum iteration or the
minimum convergence limit is reached. In the subsequent calculation, the computer can utilize various optimization algorithms to search potentially optimal parameters according to the results calculated before, such as the genetic algorithm [12–14], response surface methodology [15], [16], sequential unconstrained minimization technique [17], Taguchi method [18], particle swarm optimization technique [19] and so on. At present, most commercial softwares have embedded these optimization algorithms, and are capable to take multi-core parallel calculating to reduce the calculation time.

According to the analysis above, the diagram of the combination of FEM with optimization algorithms can be described in Fig. 3.

As can be seen from Fig. 3, most of the work are undertaken by the computer. The tasks for the designer are the parametric modelling, and setting the objective functions, initial parameters and constraint conditions. The professional requirements for the designers are relatively low, and the optimal design can be achieved as long as the conditions are set reasonably.

The drawbacks of this method are the huge calculation task for the computer and the long solving time. For the 2U flux barriers rotor of Fig. 2, the number of parameters to be optimized increases by 4 when the flux barrier increases by one layer. At the same time, the dimension of the parameter matrix increases, and the calculation time boosts. Therefore, with the increases of flux barrier layers, the calculation efficiency significantly drops, and it becomes much harder to achieve the optimal design.

B. Analytical Method

Since the FEM is time-consuming, much research has been done to seek for the replacement of FEM. In [24] and [30], an analytical method is proposed based on the magnetic circuit model to evaluate the SynRM with single- and double-layer flux barriers, respectively. In [23], an analytical model is raised based on the synthesis of d-axis and q-axis MMF effect. In [29], a detailed model is discussed to solve the SynRM with asymmetric flux barriers. The analytical calculation is much faster compared with FEM. In [20], a saturating lumped parameter model is presented to take the saturation into account. In [21], a nonlinear reluctance network model is established to evaluate the SynRM with a complex rotor structure. FEM is applied in the beginning to divide the reluctance network properly. Then the machine can be calculated and optimized with the fast reluctance network method. Since the saturation and iron losses are considered, the results can be satisfactory even with high load [22].

In this part, an analytical method based on the magnetic circuit model is introduced to evaluate the SynRM with multiple-layer flux barriers. The calculation speed is very advantageous, and the result coincide with the FEM when the saturation is not severe [28].

The rotor topology discussed in this part is shown in Fig. 4. Each flux barrier has an even thickness and so is with the iron segments, in order to keep the flux density uniformly distributed and to avoid local saturation. The number of flux barrier layers is \( n_b \), the thickness of the \( k \)th layer flux barrier is \( t_{fb} \), the circumferential length of the \( k \)th layer flux barrier is \( l_{fb} \), and the position of the \( k \)th layer flux barrier end is \( \theta_{fb} \). The flux barrier from the outermost to the shaft is called as the 1st layer flux barrier, the 2nd layer flux barrier, ..., and the \( n_b \)th layer flux barrier.

![Diagram of combination of FEM with optimization algorithm](image)

Fig. 3. Diagram of combination of FEM with optimization algorithm.

If the saturation in both the stator core and rotor core is neglected, the magnetic circuit of one pole can be presented as in Fig. 5, where \( R_{fb} \) is the reluctance of the \( k \)th flux barrier, \( R_{gk} \) is the reluctance of the air-gap adjacent to the \( k \)th layer iron segment, \( \phi_{fb} \) is the flux through the \( k \)th flux barrier, \( \phi_{gk} \) is the flux going through the \( k \)th layer flux barrier, \( \phi_{gk} \) is the flux going through the \( k \)th layer iron segment, \( f_{fb} \) is the average MMF of the stator adjacent to the \( k \)th layer iron segment, and \( f_{gk} \) is the MMF of the \( k \)th rotor iron segment.

Take the \( k \)th layer flux barrier as an example, the flux conservation can be expressed as

\[
\phi_{fb} = \phi_{gk} + \phi_{fb}
\]

(1)

where \( \phi_{fb} \) and \( \phi_{gk} \) can be expressed as

\[
\phi_{gk} = \frac{f_{gk} - f_{fb}}{R_{gk}}
\]

(2)

\[
\phi_{fb} = \frac{f_{fb} - f_{gk+1}}{R_{fb}}
\]

(3)

Define the angle between two flux barrier ends as

\[
\Delta \theta_{e} = \theta_{k} - \theta_{k+1}
\]

(4)

Then \( R_{fb} \) and \( R_{gk} \) can be expressed as

\[
R_{fb} = \frac{t_{fb}}{\mu_0 l_{ef}}
\]

(5)

\[
R_{gk} = \frac{\Delta \theta_{e}}{2 \cdot \mu_0 \cdot D_e \cdot l_{ef}}
\]

(6)

where \( \mu_0 \) is the permeability of vacuum, \( \delta_{ef} \) is the effective air-gap length, \( l_{ef} \) is the effective axial length and \( D_e \) is the diameter of air gap (the average of the rotor outer diameter and stator inner diameter).

The three phase winding MMF in the stator frame can be expressed as
\[ f_s(\theta) = \frac{3N_p I_m}{\pi p} \sum_{v=-h+1}^{h} n_m \cos(v p \theta - \omega t - \alpha) \quad (7) \]

\[ \lambda_k = \frac{v m_p \pi}{2} + (v-1)\omega t - \alpha \quad (9) \]

\[ \rho_k = \sum_{j=1}^{n} (m_{k,j} - m_{k,j+1}) \sin(v p \theta_0) + m_{k,j} \sin(v p \theta_{m_k}) \quad (10) \]

\[ b_{i,j} = \left\{ \begin{array}{cl} b_{i,j} + \sum_{q=1}^{n_k} \left( \prod_{l=1}^{q-1} a_{l} \right) b_{i,q,j} & \text{if } i \geq j \\ \sum_{q=1}^{n_k} \left( \prod_{l=1}^{q-1} a_{l} \right) b_{i,j} & \text{if } i < j \end{array} \right. \quad (11) \]

\[ a_i = \frac{1}{1 + \frac{D_x}{\delta_{df}} \frac{t_k}{l_i} \sum_{j=1}^{n_k} \left( \prod_{l=1}^{j-1} a_{l} \Delta \theta_j \right)} \quad (12) \]

\[ b_{i,j} = \frac{D_x}{2\delta_{df}} \frac{t_k}{l_i} \prod_{k=j}^{i-1} a_{k} \quad i \geq j \quad (13) \]

Since the stator MMF and rotor MMF have been expressed in (7) and (8), the output torque can be calculated according to [31], and expressed as (14).

\[ T = \frac{\mu_0 p D_r I_{ref}^{2\delta_{df}}}{2} \int_{0}^{2\pi} f_s(\theta) \frac{df_s(\theta)}{d\theta} d\theta \quad (14) \]

The advantages of analytical method are the fast speed. The dimension of the coefficient matrix of (9)–(11) is \( n_k \times n_k \), which is much smaller compared with the huge node matrix number of the FEM. So the analytical method can be used to set the initial parameters and make preparation for the later FEM precise calculation.

However, the iron core saturation and stator slot opening effect are neglected in the analytical model. Since the saturation may reduce the inductance and induce the d-q axis inductance variation with rotor position, the average torque and torque ripple are deteriorated under saturation. The SynRM performance is strongly sensitive to the saturation, therefore, the analytical method cannot provide very accurate result.

C. Combination of FEM with Optimization Algorithm

As has been stated, the method to combine the FEM with optimization algorithm is very time-consuming whereas the analytical method can not guarantee the accuracy. So some researches have been focused on a compromised method to achieve high performance with high optimization speed. Some constraint conditions are attached to reduce the number of parameters to be optimized, decouple the parameters, and optimize them either one by one or globally [13].

One widely used constraint method is to regard the rotor flux barriers as uniform slots on the rotor, and therefore the angles between every two adjacent flux barrier ends are the same [32], as shown in Fig. 6. The parameters to be optimized become independent on each other and it is much easier to illustrate the effect individually. There are generally two types of constraint conditions as following.

One type is to propose a parameter called as the number of pseudo barrier ends [31-33], as shown in Fig. 6(a). The number of flux barrier layer is defined as \( n_{c} \), the angle of adjacent flux barrier ends is \( \Delta \theta \) in electrical rad. Then the pseudo flux barrier ends in one pole-pair \( n_c \) can be expressed as (15). Note that, although there is no real flux barrier end beside the q-axis, the rotor is still divided as several pseudo uniformly distributed ends. Therefore, \( n_c > 2 \times (2n_p - 1) \). The pole arc angle of the first real flux barrier \( \theta_0 \) can be expressed as (16). The consequence in Fig. 6(a) is \( n_p = 3 \), \( n_c = 18 \), otherwise the relationship is not fixed as \( \theta_0 = 2 \Delta \theta \).

\[ n_c = \frac{2\pi}{p \Delta \theta} \quad (15) \]

\[ \theta_0 = \left( \frac{n_c}{4} - n_c + \frac{1}{2} \right) \times \Delta \theta \quad (16) \]

The other refinement technique is to define by the angles between the adjacent flux barrier ends [27], as shown in Fig. 6(b). The angle between adjacent flux barrier ends is \( \alpha_{m} \), the controlled angle of the first pseudo flux barrier is \( \beta \), and the
parameters satisfy the equation (17).
\[
(n_s + \frac{1}{2})\alpha_m + \beta = \frac{\pi}{2p}
\]  (17)

\[
\frac{D_k}{2\delta_{ef}} >> \frac{l_{k}}{i_{nk}}
\]  (19)

Since only the fundamental of the stator MMF rotates at the same speed as the rotor and produces steady MMF drop on the rotor flux barriers, only the fundamental of stator MMF is considered hereafter when analyzing the rotor sTABLE MMF. For the constraint conditions in Fig. 6(a), the rotor MMF and the fundamental of stator MMF are shown in Fig. 7, where \( \alpha \) is the angle between the stator current vector and the d-axis. Note that the consequence in Fig. 7 is when the current vector aligns with the q-axis. Otherwise the fundamental of stator MMF may shift whereas the rotor MMF is always symmetric along the d-axis and q-axis.

The rotor stair MMF can be obtained from the fundamental stator MMF, and the electromagnetic torque can be calculated in (14). The average torque is shown in (20), where \( k_e \) is only dependent on the rotor parameter and called as rotor coefficient, as shown in (21).

\[
T_{ave} = \frac{9 \mu_0 D_s l_{ef}}{p \delta_{ef}} \left( \frac{N_p I_{m \alpha}}{\pi} \right)^2 \sin(2\alpha)k_e
\]  (20)

As can be seen from above analysis, the parameters of the original SynRM model are dependent on each other and the matrix to be optimized is huge. With the constraint conditions, the number of parameters to be optimized decreases significantly. It becomes much simpler to investigate the effect of each parameter and more efficient to design the SynRM.

Nevertheless, the theoretical constraint conditions cannot take the nonlinear problem into consideration. Therefore, the optimized prototype with this method may be not optimal. Besides, with the increase of constraint conditions, the calculation speed can be improved at the sacrifice of comprehensive performance.

III. A COMPREHENSIVE OPTIMIZATION METHOD

On the basis of the three conventional design methods, this section proposes a comprehensive optimization method. This method can help predict the performance rapidly, and set the initial value of the parameters. The influences of each parameter is illustrated to achieve fast design procedure.

When the air-gap length is relatively small and the diameter of air-gap (namely the average of the stator inner diameter and the rotor outer diameter), (19) is satisfied and the MMF drop on the air-gap can be neglected compared with that on the rotor flux barriers.
To reduce the vibration in accordance with Fig. 8 to gain high rotor n\(\neq f\) slots and poles (14). So when the rating time is large. And the selection of the initial model of the SynRM can be established, and the winding configuration, number of flux barrier layers, and flux barriers layer should not be too large. However, the optimization result relies on professional knowledge of the designer and require abundant experience. Besides, since the constraint conditions are proposed based on the ideal model, the final prototype may be not optimal.

As can be seen from (20), the ideal average torque is proportional to \(1/p\). However, when the number of pole-pairs is small, the yoke thickness is large, thus the slot area to contain the stator windings is reduced. Besides, a small number of pole-pairs means relatively long end-winding, and both the volume and weight are increased. So the number of pole-pairs for the SynRM is usually selected as 2 or 3.

Define split ratio as the ratio of the stator inner diameter to the outer diameter. As can be seen from (20), the average torque is proportional to the square of the current Ampere-turns. Therefore, the SynRM needs to have sufficient slot space to contain the stator winding, thus the split ratio is usually smaller than that of the PMSM [39]. However, if the split ratio is too small, the rotor can not produce sufficient saliency. Besides, the split ratio is also determined by the number of pole-pairs. Generally speaking, a small number of pole-pairs means a thicker yoke and a smaller split ratio [36].

As for the winding configuration, the average torque is proportional to the square of fundamental winding coefficient, as shown in (20), therefore, the winding configuration ought to exhibit high fundamental coefficient. Besides, the electromagnetic torque originates from the interaction of the stator MMF and rotor MMF, as shown in (14). So when the harmonic order of the stator MMF coincides with the rotor MMF, certain harmonic torque ripple is produced. As can be seen from Fig. 7, when the rotor flux barrier is symmetric, all the harmonic orders of the rotor MMF are odd. So, the low odd harmonics in the stator MMF should be avoided.

The main harmonic order for the stator MMF in Fig. 7 is \(k_1 \times n_1\), where \(n_1\) is the odd number that is nearest to \(n_s\), and \(k_1\) is an integer. The main odd harmonic order for the stator MMF is \(k_2 \times N_s/p\pm 1\), where \(N_s\) is the number of stator slots and \(k_2\) is the integer that ensures the harmonic order is odd. When the winding configuration is chosen, selection of \(n_1\) should avoid the main harmonic order of stator MMF to achieve low torque ripple.

Relationship of the rotor coefficient \(k_r\) with \(n_b\) and \(n_s\) is shown in Fig. 8 according to (21). With the increase of flux barrier layer number, the rotor coefficient boosts. But when the number of flux barriers is \(n_b>4\), the rotor coefficient hardly increases with the number of flux barriers. Considered the manufacturing and processing technique, the number of flux barriers layer should not be too large. And the selection of \(n_b\) should also be combined with that of the \(n_s\) to achieve a large \(k_r\).

With the above analysis, the number of pole-pairs, split ratio, winding configuration, number of flux barrier layers, and flux barrier distribution can all be determined preliminarily. Then, the initial model of the SynRM can be established, and the parameters can be further optimized with FEM.

The comprehensive optimization procedures are described in Fig. 9. The preliminary design is largely based on the designer's experience. The computer calculation includes the optimization of stator core and rotor flux barriers, and the calculating time can be reduced significantly. The computation can make up for the limitation of the designer's experience.

The advantage lays on the high efficiency to design the SynRM. The parameters are decoupled and can be optimized one by one. The optimization procedures do not take long time, and, generally high performance of the SynRM can be achieved.

However, the optimization result relies on professional knowledge of the designer and require abundant experience. Besides, since the constraint conditions are proposed based on the ideal model, the final prototype may be not optimal.

IV. DESIGN EXAMPLE

In this section, a prototype is optimized with the comprehensive method proposed above. The design procedures are detailed according to the diagram shown in Fig. 9. The performances of this machine are discussed to verify this design method.

A. Motor Specification

The specification and design requirements of the prototype SynRM are listed in TABLE I. To satisfy the power density, the average torque should be maximized. To reduce the vibration and noise during operation, the torque ripple should be minimized.

B. Design Procedure

To improve the rotor saliency and reduce the end-winding length, the number of pole-pairs is selected as 3. Besides, the split ratio of SynRM is smaller than that of PMSM, and the split ratio is selected as 0.55 preliminarily when the number of pole-pairs is 3.

Since the number of pole-pairs is small, modular concentrated winding of which the numbers of slots and poles satisfying \(N_s=2p\pm 1\) or \(N_s=2p\pm 2\) do not exist. To improve the fundamental winding coefficient, the conventional concentrated winding of which the numbers of slots and poles satisfying \(N_s/2p=3/2\) is not considered. Therefore, distributed winding is rather common for the SynRM. For integer-slot distributed winding, the order of the main harmonic \(k_2 \times N_s/p\pm 1\) is odd when \(k_2\) is an integer. For fractional-slot distributed winding, the main odd harmonic order is generally larger. For example, for the \(N_s/2p=9/2\) configuration, the main harmonic \(k_2 \times N_s/p\pm 1\) is odd only when \(k_2\) is an even number. Therefore, 6-poles 27-slots configuration is selected for the prototype.

The main odd harmonic order in the stator MMF is 18\(k\pm 1\), where \(k\) is an integer. So the selection of \(n_s\) should avoid the multiplier of 18. In accordance with Fig. 8 to gain high rotor coefficient, the rotor main parameters are selected as \(n_{r_i}=5\), \(n_{r_f}=29\).
After the basic design, the initial model of the prototype SynRM is established. The other parameters such as the stator tooth thickness, stator yoke thickness and rotor barrier thickness can be optimized with FEM. Besides, the mechanical strength should be enhanced to guarantee the tensile strength at the maximum speed. The optimized prototype is shown in Fig. 10.

Fig. 10. Cross section of optimized prototype.

The maximum flux density in the stator tooth, stator yoke, and rotor iron segment is about 1.6T, close to the knee point of the lamination BH-Curve. It can help ensure the material utilization but meanwhile avoid saturation. The radial flux density in the stator yoke is nearly zero, whereas the tangential flux density almost only contains the fundamental. The tangential flux density in stator tooth is nearly zero while the radial flux density almost only contains the fundamental. The tangential flux density outweighs the radial flux density in both the rotor iron segment and rotor bridge, besides, the tangential flux density contains abundant 9th order harmonic.

The excitation field of SynRM is established by the stator armature current. When the rotor iron segment is aligned with the stator tooth, the reluctance is small and the flux lines pass through that layer of iron segment. When the rotor iron segment is aligned with the stator slot, the reluctance increases and the flux lines pass through the adjacent layer of iron segment. Therefore, the stator slots influence the flux density distribution in the rotor and presents the tooth harmonic in the iron segment. The numbers of pole-pairs and stator slots are 3 and 27. So the main harmonic order in the rotor iron segment is 27/3=9th.

The SynRM has its rotor flux bridges saturated in order to reduce the inductance of q-axis and produce the rotor saliency. But the saturation point in the rotor flux bridge is not fixed. The saturation point may shift because of the stator slots, and thus, the 9th order harmonic in the flux bridge increases.

The d-axis inductance and q-axis inductance variations with the d-axis current and q-axis current are shown in Fig. 13, where the current is normalized by the rated current. The q-axis magnetic circuit is saturated to reduce the q-axis linkage flux. When the current amplitude is small, the rotor flux bridge is not saturated and the q-axis inductance is relatively large. With the increase of current, the rotor flux bridges become saturated.
The q-axis inductance is then reduced and hardly varies with the current. Comparatively, the d-axis magnetic circuit is less saturated and the inductance varies with the current amplitude. The saturation decreases the d-axis inductance as well as the rotor saliency. Under the rated operation condition, the d-axis inductance and q-axis inductance are 19.5mH and 6.2mH, respectively, hence, the rotor saliency is 3.1.

The torque waveform with the maximum torque per ampere (MTPA) control is shown in Fig. 14. The average torque and torque ripple are listed in TABLE II, where the torque ripple is defined as the peak-to-peak value of the electromagnetic torque. The ratio of torque ripple to average torque at rated working point is about 2%. The fluctuating torque is thus small, and the prototype can operate steadily.

V. CONCLUSION

SynRM has been attractive alternative in some traditional
AC drive applications. Especially the TLA rotor structure, with the combination of excellent electromagnetic performance as well as simple manufacturing process, is perceived to be the most promising in mass industrial production. The electromagnetic performance of the TLA SynRM is high under the condition that the rotor has multiple-layer flux barriers. However, the parameters to be optimized become enormous and are dependent on each other when the number of flux barriers is large, making the optimization procedure rather complex.

This paper summarized three conventional methods to optimize the SynRM. The first method is to combine FEM with the optimization algorithm. This method can achieve optimal design on the sacrifice of large calculating time. The second method is to utilize the fast analytical method to replace the precise FEM. This method can improve the calculating speed significantly, whereas the calculation result is not accurate with the core saturation. The last method is to attach constraint conditions to refine the parameter relationship. The constraint condition can help reduce the number of parameters and save the calculation time. However, the final prototype may be not optimal under these constraint conditions.

Based on the conventional techniques, this paper proposed a comprehensive optimization method to design the SynRM. The initial parameters are selected according to the ideal model. Then FEM is applied to make precise calculation and optimization. Since the parameters are decoupled and preliminarily optimized, it is easy and fast to obtain high performance of the motor.

A prototype is designed with this comprehensive method for the high torque density and low torque ripple. The implementation procedures are detailed to demonstrate the method. Finally, the machine performances are discussed to ensure that the prototype can operate steadily.

REFERENCES


Jian-Xin Shen received the B.S. and M.S. degrees from the Xi’an Jiaotong University, China in 1991 and 1994, respectively, and the PhD degree from the Zhejiang University, China in 1997. He was with the Nanyang Technological University, Singapore (1997-1999), the University of Sheffield, UK (1999-2002), and IMRA Europe SAS, UK Research Centre, UK (2002-2004). Since 2004 he has been a Professor of Electrical Engineering at the Zhejiang University. He has published more than 220 technical papers, including 5 prize papers, and he holds over 30 patents. He is an IET Fellow and an IEEE Senior Member. His main research interests include design, control and applications of electrical machines and drives, and renewable energies.

He Hao received the B.S. and PhD degrees from the Zhejiang University, China in 2008 and in 2013, respectively. He was an Electrical Engineer at Hangzhou Wahaha Group Co., Ltd (2013-2014). Since 2014 he has been a Post-doctor at the Zhejiang University. His main research interests include design, control and applications of electrical machines and drives.

Mengjia Jin received the B.S. and PhD degree from Zhejiang University, China, in 2001 and 2006 respectively. Now he is working with Electrical Engineering Department of Zhejiang University as an associate professor. His works focus on electrical machine design and drives.

Shun Cai received the B.S. and M.S. degree in electrical engineering from Zhejiang University, China in 2014 and 2017, respectively. He is currently pursuing the PHD degree at the University of Sheffield, UK. His research interests include synchronous machine topologies and optimization.