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Chapter

Design of Ultrahigh-Speed Switched Reluctance Machines

Cheng Gong and Thomas Habetler

Abstract

High-speed electric machines have been a timely topic in recent years. Switched reluctance machines (SRMs) are very competitive candidates for high-speed applications in high-temperature environments, due to the single material rotor without permanent magnets (PM). In this chapter, recent research on ultrahigh-speed SRMs (UHSSRMs) for applications from 100,000 rpm to 1,000,000 rpm is reviewed regarding the design and control. First, the proposed control methods in the literature for ultrahigh speeds over 100,000 rpm are introduced. A direct position control using low-cost nonintrusive reflective sensors is described in detail. Experiments are conducted to validate the method on a 4/2 SRM at 100,000 rpm. Next, for even higher speeds up to 1,000,000 rpm, a high-strength, high-torque-density, and high-efficiency rotor structure is introduced. Finally, the complete design of a 1,000,000 rpm SRM is proposed and prototyped using aerostatic air bearings with the help of electromagnetic finite element analysis (FEA) tools.

Keywords: finite element analysis, optical sensors, optimization, switched reluctance machine, ultrahigh speed

1. Introduction

Electric machines have been widely used in various applications such as metro systems [1, 2], electric power generation [3], etc. The size of an electric machine depends on its power level, which can vary from several 100 megawatts [4, 5] to several watts, according to the following equation [6]:

\[ S = 11K_{wt} \cdot B \cdot ac \cdot D^2 \cdot L \cdot n \]  

(1)

where \( S \) is the motor rating in watts, \( B \) is the magnetic loading in Teslas, \( ac \) is the electric loading in A/m, \( D \) is the stator bore diameter in meters, \( L \) is the machine active length in meters, \( K_{wt} \) is the winding factor of fundamental frequency, and \( n \) is the rated speed in rps.

From Eq. (1), it can be seen that for a certain power rating, since the magnetic and electric loading do not vary too much for certain materials and cooling, the machine size \((D^2L)\) scales down with the increased rotational speed [7], which saves the materials and costs, and would lead to a more compact system.

High-speed drives have become more and more interesting to researchers in both academia and industry in recent years. With the development of modern power electronics, the top speed of electric motors has increased significantly. For ultrahigh-speed drives above 100,000 rpm, there are several research conducted
for permanent magnet (PM) machines from 200,000 rpm \([8, 9]\) up to 1,000,000 rpm \([10]\). Besides PM machines, switched reluctance machines (SRMs) \([11]\) are competitive candidates due to their intrinsically simple and robust rotor geometry. They are suitable for ultrahigh-speed applications under high ambient temperatures such as turbochargers. In this chapter, the state-of-the-art ultrahigh-speed switched reluctance drives are presented in detail regarding their control and design.

2. Control of ultrahigh-speed SRMs (UHSSRMs) over 100,000 rpm

Extensive research has been conducted in the literature for high-speed SRMs up to 60,000 rpm. One of the many reasons that prevent an SRM from reaching even higher speeds is the speed sensing. One can find various rotary encoders with a maximum speed less than 60,000 rpm. However, the internal mechanical stability issues of the code disc put a limitation on the maximum rotational speed a rotary encoder can achieve. Other kinds of shaft-connected encoders, for example, resolvers, suffer from the same issue, while a custom-designed encoder is far too expensive for a practical application \([12]\). To break this mechanical speed limit, either sensor-less control or noncontact sensing control must be applied.

**Table 1** concludes different sensing methods for high-speed SRMs over 60 krpm reported in the literature, among which most of them are below the maximum speed limit of commercially available rotary encoders on the market. Only five SRMs are reported to achieve a max speed beyond 60 krpm. Bateman uses the current gradient sensor-less (CGS) method to control a 4/2 high-speed SRM up to 80 krpm, although the target was 100 krpm \([24]\). Calverley uses a Hall sensor to detect the rotor pole saliency in order to control the motor. But the Hall sensor itself must be located very close (1.5 mm) to the rotor laminations. This implies that this method is not suitable for off-the-shelf machines. Morel uses another sensor-less method and achieved 110 krpm, although the target speed was 200 krpm. The method applies the resonant characteristic of the RLC circuit to detect the rotor position, and it requires a sophisticated design of a complex external circuitry and a carefully selected resonant frequency. Kozuka reports a 6/4 high-speed SRM at 150 krpm with test results. It uses an unknown type of special sensor that generates a series of square waveform with four times the frequency and a duty cycle of 50% of the shaft mechanical speed. However, in order to implement the method, a complex

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<tbody>
<tr>
<td>30</td>
<td>Hall Sensor</td>
<td>4/2</td>
<td>[21]</td>
<td>60</td>
<td>Unknown</td>
<td>4/2</td>
<td>[22]</td>
</tr>
<tr>
<td>40</td>
<td>Unknown</td>
<td>6/6</td>
<td>[23]</td>
<td>80</td>
<td>Sensor-less</td>
<td>4/2</td>
<td>[24]</td>
</tr>
<tr>
<td>50</td>
<td>Resolver</td>
<td>6/4</td>
<td>[27]</td>
<td>110</td>
<td>Sensor-less</td>
<td>6/2</td>
<td>[28]</td>
</tr>
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</table>

**Table 1.** Different sensor types for high-speed SRMs.
drive with FPGA must be used to provide the exact rotor position, which is also far too complicated and computationally intensive for practical use.

A simple and fast control system using low-cost noncontact optical sensors for ultrahigh-speed SRMs is proposed in [31, 32] and is followed by a multi-physics acoustic analysis [33]. Figure 1(i) shows the settings of the method. The photons emitted from the LED are reflected by the surface of the shaft and are then received by the photodiode when they are detecting a white mark. A current signal is thus generated, and a trigger signal is output after an amplifier, a Schmitt trigger, and an output transistor. On the other hand, when the photons are emitted to a black mark, all of them will be absorbed and no signal will be generated. Thus, as the shaft rotates, an output square wave signal is generated to control the motor.

Figure 1(iii) describes a simple and fast direct position control for ultrahigh-speed SRMs. A SRM with four stator slots and two rotor poles is used here for illustration purpose, and other types are similar. The goal is to reduce the cycle per resolution (CPR) to the minimum value, which is equal to the number of rotor poles, and then apply single pulse control for each phase [34]. The black and white marks on the shaft determine the switching-on and switching-off angles (denoted as \( \theta_1 \) and \( \theta_2 \), respectively). Note that from this point the photodiodes are assumed to be light on mode, which means that the trigger signal is HIGH when a dark surface is detected and is LOW when a white surface is detected. As shown in Figure 1(iii) (a), when the rotor is \( \theta_1 \) degrees from the unaligned position \( \theta = 0^\circ \), which is also the aligned position for the other phase), the optical sensor detects the black mark and gives a rising edge of the output signal. As the rotor keeps rotating clockwise, the sensor keeps detecting the black mark and outputs a high voltage. When the rotor is \( \theta_2 \) degrees from the unaligned position, the black mark ends and makes the trigger signal low voltage again. The switching-on and switching-off angles can be easily modified by changing the position and span of the black mark. A logic AND is

![Figure 1](image-url)
performed between the PWM signal and the trigger signal to control the gate signals of the MOSFETs of the corresponding phase. Figure 1(iii) shows a typical waveform of the phase currents and trigger signals during one revolution.

The advantages of the proposed sensing method are as follows:

- **Versatility.** Because it uses noncontact sensors, it can be fitted to any kind of off-the-shelf SRMs without changing the shaft geometry or opening the motor. A simple painting of the shaft is enough.

- **No virtual speed limit.** Thanks to the noncontact setup, there is no mechanical speed limit to the motor. The actual speed limit is determined only by the time delay of the signal processing circuit, which can be designed to be a very small number.

- **Simplicity.** The proposed method does not require speed/position transformation or an extra sampling frequency of DSP. This is because that the trigger signal is an analog type and is used to control the phases directly without and digital/analog speed/position manipulations.

- **Low cost.** Conventional rotary encoders are very expensive. A typical high-speed rotary encoder (i.e., US digital E5) costs several 100 dollars. But the proposed method only costs several dollars for very cheap components such as LEDs, photodiodes, and operational amplifiers.

Table 2 gives a comparison of the proposed method and different sensing methods proposed in the literature.

The method was validated on a high-speed 4/2 SRM at 100,000 rpm. Figure 2 shows the experimental setup. Two optical sensors were built for sensing the rotor position for each phase. The optical sensors are the light on mode, which means that the output voltage is 5 V for black and 0 V for white. The mark patterns are drawn in such a way that the two optical sensors detect the two different phases, as is shown by the black and white marks in Figure 2. The switching-on and switching-off angles are optimized to be 0° and 70° using a fast equivalent model based on finite element analysis (FEA) [32]. Figure 3 shows the block diagram of the closed loop control. A video reference can be found in [35]. Figure 4 shows a screenshot of the oscilloscope at 100,000 rpm. Channel 1 (yellow) is the voltage waveform of phase A with a DC link voltage of 140 V. Channel 2 (blue) is the optical trigger signal of phase A. Channels 3 and 4 (magenta and green) are the current profiles of phase

<table>
<thead>
<tr>
<th>Speed limit</th>
<th>Hall sensor</th>
<th>Optical encoder</th>
<th>Resolver</th>
<th>Sensor-less</th>
<th>Proposed</th>
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<tr>
<td>Nonintrusive?</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Implementation simplicity</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Direct control without signal processing?</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Accuracy</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Typical cost</td>
<td>$300</td>
<td>$200</td>
<td>$300</td>
<td>$0</td>
<td>$5</td>
</tr>
</tbody>
</table>

Table 2. Comparison of different sensing methods.
Figure 2. Picture of the 4/2 SRM and the optical sensor setup.

Figure 3. Block diagram of the closed loop control.

Figure 4. Experimental result at 100,000 rpm.
A and phase B, respectively. It can be seen that the optical sensor controls the current very well. The current sensor conversion rate is 1A/100 mV. It can be read from the oscilloscope that the frequency of the current profile of phase A (magenta curve wave) is 3.353 kHz. So the speed is \(3353/2 \times 60 \approx 100,000\) rpm. Higher speeds could have been achieved, but for the safety concerns of the bearings, the final speed was stopped at 100,000 rpm.

3. Rotor design of ultrahigh-speed SRMs over 1,000,000 rpm

For ultrahigh-speed electric machines that run at speeds over 1 million rpm, one needs to follow a totally different design procedure from “regular” or what is commonly referred to as a “high-speed” machine design. The first thing to be considered is the rotor structure, because the conventional rotor geometries are not suitable for ultrahigh-speed applications over 1 million rpm. In this section a new rotor structure for ultrahigh-speed SRMs is described in detail [36]. The rotor lamination has smooth surfaces on both sides without any shaft bore in the middle. The shaft surrounds the rotor stack on both sides with two clamping arms. Compared to the conventional design, the proposed design has many advantages, such as high strength, high torque density, high efficiency, and high reliability.

3.1 Problem of conventional rotor designs

At over 1 million rpm, the conventional rotor structures cannot be applied due to the following reasons.

3.1.1 Localized stress concentration

Figure 5 shows the finite element stress analysis of the conventional rotor structure with an outer diameter (OD) of 4 mm under the operational speed of 1.2 million rpm. It can be seen that the maximum stress is 606 MPa, which is located at the sharp corners. However, most of the lamination steels only have a yield strength less than 400 MPa. This localized stress concentration is not a big issue when at low speeds. But it would cause failure when the rotor is rotating at ultrahigh speeds.

3.1.2 Too small space for the shaft

Although the rotor size can be reduced to decrease the highest stress to be less than the yield strength of the lamination material, there is another critical problem that prevents the conventional designs from being used at ultrahigh speeds. Usually the rotor OD is limited to a maximal value of 3 to 4 mm when operating at such high speeds. This will result in the rotor shaft OD less than 1 mm (see Figure 5). Shafts with such thin OD are extremely difficult to manufacture and are obviously not strong enough at high speeds.

3.1.3 Too much windage loss

Another problem is the high windage loss at ultrahigh speeds due to the fact that the air drag loss is proportional to the third power of the rotational speed. Moreover, the traditional rotor structure is actually not well designed in the perspective of aerodynamics due to the rotor double-salient structure. But the rotor saliency, in
turn, is the source of the output torque. This implies that the intrinsic properties of the SRM rotors are contrary in terms of aerodynamics and electromagnetics.

3.2 Possible solutions in the literature

3.2.1 Using bolts rather than a shaft

To solve the shaft bore problem, a “shaft-less” rotor design (shown in Figure 6) has been proposed in [37]. However, this design still needs bolts fed through the rotor laminations, which increases the assembling difficulty and is also not possible in very tiny scales under ultrahigh-speed cases. On the other hand, the double-salient geometry will still lead to very high windage loss.

Figure 6.
High-speed rotor lamination with no shaft bore (left) and rotor assembly with end plates (right) [37].
3.2.2 Using rotor sleeves

Some efforts has been made to solve the high windage loss problem in the literature, such as using a rotor sleeve that is made from titanium or carbon fiber, just as in high-speed PM machines [28, 38]. It is not a good design in the perspective of electromagnets, although it is mechanically well designed. A typical value of the air gap of ultrahigh-speed SRMs is 0.1–0.25 mm in order to increase the torque density [26]. These nonmagnetic rotor sleeves are equivalent to an extra air gap in the flux path, which increases the equivalent air gap length by twice or more in the radial direction. This will lead to a low torque density [38]. As shown in Figure 7(i), the equivalent air gap length is 0.6 mm, which is the summation of the 0.35 mm actual air gap length and the 0.25 mm rotor sleeve thickness. This large air gap results in a low maximum flux density of 0.86 T in the stator teeth.

3.2.3 Design with “flux bridges”

Another design to solve the high windage loss problem is using “flux bridges” to connect the salient rotor poles [39, 40]. This unique design has advantages in the perspective of aerodynamics. However, it requires the flux bridge to be thin enough to be magnetically saturated. As can be seen from Figure 7(ii), such thin flux bridge is obviously not mechanically strong enough to sustain the high centrifugal forces at ultrahigh speeds. From the stress finite element analysis, it can be seen that at 1.2 million rpm the highest stress is 1055 MPa, which is located at the connection points of the flux bridge.

3.3 A novel rotor geometry for ultrahigh-speed SRMs over 1,000,000 rpm

From the analysis above, it can be concluded that a new geometry has to be proposed for UHSSRMs over 1 million rpm. It has to be mechanically strong enough to endure the high centrifugal force at ultrahigh speeds. Also it should not have any holes or rotor sleeves. In addition, it should have a good aerodynamic performance. In this subsection, a novel rotor geometry that combines all these advantages is proposed in detail [36, 41].

3.3.1 Design details

To design an SRM, the first step is to select a suitable pole/slot combination. The less poles an SRM has, the less core losses and switching losses it will have because

---

Figure 7.
(i) High-speed SRM with rotor sleeves (left). (ii) stress distribution of the rotor with “flux bridges” (right).
of the less fundamental frequency. Eq. (2) shows the relationship between the fundamental frequency and the rotor pole number.

\[
f = \frac{N_r \cdot N_{rpm}}{60}
\]  

(2)

where \(N_r\) denotes the number of rotor poles and \(N_{rpm}\) denotes the rated speed in rpm. So the rotor pole number is chosen to be two in the proposed design.

**Figure 8(i)** shows a new rotor structure for ultrahigh-speed SRMs. There are two components to form a rotor: a rotor stack (black) and a clamping shaft (gray). The rotor stack is composed of electrical laminations that are made from magnetic materials. The clamping shaft is made from nonmagnetic materials with high mechanical strength such as carbon fiber or titanium alloy. The main idea of the design is to keep the rotor stack as integrated as possible and transfer the stress that is imposed on the rotor laminations to the shaft, which can be made from the nonmagnetic materials having much higher yield strength. Both sides of the rotor laminations are also designed to be smooth curves to avoid any localized stress concentration. Moreover, there is no shaft bore in the middle of the rotor laminations, which significantly reduces the highest stress caused by the large centrifugal force. The rotor stack is mechanically supported by the two contacting curved surfaces between the rotor stack and the two “clamping arms” (yellow shadow in Figure 8(i)), which realizes the function of the interference fit between the rotor and the shaft in regular machines or the using of bolts in [37]. It needs to be pointed out that if the rotor is manufactured to be totally symmetrical and balanced, no net force will be produced by the clamping arms when the shaft is rotating, except for the supporting force against the gravity of the rotor stack, because there is no trend of relative movement between the rotor stack and the clamping shaft. The net radial electromagnetic force exerted on the rotor stack is also zero due to the symmetrical geometry. **Figure 8(ii)** shows a prototype of the design using carbon fiber as shaft material.

### 3.3.2 Advantages

The new design has several advantages for ultrahigh-speed SRMs as follows.

- **High strength.** There is no sharp corner in the rotor laminations as in traditional rotor geometries, and the surfaces of the rotor stack are all smooth. Plus, there is no shaft bore in the center of the rotor laminations. These two features greatly reduce the highest stress in the rotor laminations. Furthermore, the OD of the shaft is the same as the rotor stack, which greatly increases the robustness of the shaft.

- **High torque density.** Unlike using rotor sleeves, which significantly increases the equivalent air gap, there is no increase of the equivalent air gap length at the two rotor pole ends in the radial direction for the new rotor structure. More specifically, when the rotor is aligned with the stator teeth, the equivalent air gap length is just the physical distance from the stator pole to the rotor pole, without adding any additional sleeve thickness. This implies that higher power density is achieved.

- **High efficiency.** Thanks to the cylindrical rotor structure, the windage loss is dramatically reduced to a minimum value.
High reliability. The new rotor structure does not need bolts or other kinds of mechanical connections between the rotor and the shaft, which implies high simplicity and reliability.

Table 3 shows a comparison of different rotor geometries in the literature regarding ultrahigh-speed applications. A detailed 3D FEA of the stress distribution of the rotor stack and the clamping shaft can be found in [36, 42]. A rotor dynamics analysis can be found in [43].

### Table 3.
Comparison of different rotor geometries.

<table>
<thead>
<tr>
<th></th>
<th>Regular Flux bridge [40]</th>
<th>Rotor sleeve [28, 38]</th>
<th>Through bolts [37]</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Practical to construct at ultrahigh speeds?</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Rotor lamination strength</td>
<td>Moderate Low Moderate</td>
<td>Moderate High</td>
<td>High High</td>
<td></td>
</tr>
<tr>
<td>Torque density</td>
<td>High Moderate Low High</td>
<td>High High</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td>Low Moderate High Low</td>
<td>Low High</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reliability</td>
<td>Low Low High Low High</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Axial length</td>
<td>Long Long Long Long Short</td>
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4. Electromagnetic design of an ultrahigh-speed SRM over 1,000,000 rpm

After the rotor is designed, the stator and windings should also be designed properly to meet the power and torque requirement. At such high speed, the stator copper loss and core loss will be significant. The former is due to the skin effect of the stator windings, while the latter is because of the high switching frequency. In addition, a proper value of the air gap length should also be determined. It should be as small as possible in order to reduce the electric loading, but it cannot be too small to be manufactured. In this section a complete design of an ultrahigh-speed SRM for
applications beyond 1 million rpm is proposed [44]. Pole pair number, dimension calculation, air gap calculation, material selection, winding selection, and windage torque calculation are included in details. The design is validated using finite element analysis. A prototype of the design is built using aerostatic bearing.

4.1 Air gap design

Choosing the right air gap length is of great importance in the design of ultrahigh-speed electric machines. Various types of electric machines require different air gap length. Usually SRMs need smaller air gaps than permanent magnet machines due to the lack of magnets in the rotor. For instance, the high-speed PM motor in [45] has a physical air gap of 0.5 mm. Nevertheless, the equivalent air gap length is larger due to the use of the retaining sleeve. The typical value of the length of the air gap in high-speed SRMs is in the range of 0.1–0.25 mm according to [26]. For example, the SRM proposed in [26] has an air gap of 0.2 mm. The designed value of the air gap in [46] was 0.3 mm and had to be changed to 0.5 mm due to manufacturing limitations. The air gap length of the SRM in [38] is 0.35 mm, plus an additional 0.25 mm of the sleeve thickness, resulting in an overall equivalent air gap of 0.6 mm. This large equivalent air gap leads to a low flux density in the stator and rotor core.

Considering the tiny size, ultrahigh-speed target, as well as the manufacturing limitations, the final air gap length is determined to be 0.3 mm. This value is comparatively large for such a tiny scale motor. But it can give better mechanical robustness when the machine is passing through the natural frequencies before reaching the rated speed of 1 million rpm, which is very important. The trade-off is that the electric loading will be higher to achieve the same torque density.

4.2 Stator winding design

Due to the high fundamental frequency of 33.3 kHz, the skin effect of the stator windings is significant at such high frequency. So Litz wire is used in the stator windings [47]. Different types of Litz wires are recommended for different operational frequencies. Selecting the most suitable type of Litz wire requires a trade-off among different aspects such as the switching frequency, the winding area, the maximum allowed current, and so on. For the fundamental frequency of 33.3 kHz of the proposed design, it can be assumed that the switching frequency of the power switches is about 10 times this frequency. Thus, the Litz wire of strand gauge of 42 is chosen to be used here [48].

Among all different types of Litz wires with the strand gauge of 42, those who have a strand number of 66, 105, and 165 are of particular interest considering the maximum allowed current. The rated RMS current is finally chosen to be 3.5A based on [38, 47, 49], which is a compromise between high current value and low winding area. This choice of maximum current will be verified in the next section.

After choosing the Litz wire, the winding cross section area can be determined. Because of the large air gap, the AC loading or the number of turns per phase has to be greater than usual. In order to produce enough flux to overcome the air gap to generate enough torque, the number of turns per coil is chosen to be 50 by an iterative design procedure. This is also a compromise between high-torque and small winding area. Assuming a filling factor of 0.25, the slot area is finally calculated to be 40 mm$^2$.

4.3 Stator design

Because of the ultrahigh speeds, laminations that are suitable for high switching frequency have to be applied. Metglas 2605SA1 (an iron-based amorphous metal) is
reported to have less than 10th of the losses of the thinnest standard iron laminations \[50, 51\] at high switching frequencies \[52\]. However, amorphous alloys are well known to be extremely difficult to work with, not only due to their necessary thickness but also because of their inherently extreme brittleness. Only very limited shapes are available because it's almost impossible to be stamped and laser cutting has its own problems as well \[53\]. For this reason, 0.006” Hiperco 50 laminations, which are also used in the rotor stack, will be applied to make the stator stack in order to reduce the manufacturing cost. Another benefit of using Hiperco 50 is to increase the torque density of the motor thanks to the high saturation flux density of the material.

The stator dimension is determined based on \[18\], particularly the stator and rotor pole arcs. The final OD is calculated to be 30 mm so as to provide enough winding area of 42 mm². A CAD model is shown in Figure 9 to verify that the designed stator has enough space to contain 50 turns of Litz wire inside.

The yoke thickness has a significant effect on the noise, vibration, and harshness (NVH) behavior of the stator. Motors with thicker yokes tend to have higher natural frequencies \[54\], which are beneficial for high-speed operations. Thus, the yoke thickness is designed to be 2 mm although that 1 mm yoke is thick enough to keep away from saturation. The teeth can be modeled as cantilevers that are attached to the stator back iron in \[55\]. So an uneven wedge-shaped tooth that is thicker at the connecting point and thinner in the tip is designed to increase the mechanical stability of the stator. Figure 9 shows the CAD model of the stator.

4.4 Windage torque estimation

At ultrahigh speeds, air friction losses might be very significant due to the fact that the windage losses are proportional to the third power of the angular speed. This phenomenon is particularly prominent for double-salient motors such as SRMs. However, thanks to the cylindrical design of the new rotor geometry, the windage losses are significantly reduced. The ultimate goal is to drive the rotor to as high speed as possible to achieve beyond 1 million rpm. So the motor will be tested at no external load at the first stage, which means the only load for the motor to overcome is the air friction.

The general equation for windage losses of a cylinder is \[52\]:

\[
P_{f,\text{air}} = c_f \pi \rho_{\text{air}} \omega^3 r^4 l
\]

(3)

Figure 9. CAD model of the machine with 50 turns of Litz wire.
where \( \rho_{\text{air}} \) is the air density, \( \omega \) is the angular frequency, \( r \) is the radius, and \( l \) is the length of the cylinder. The proposed question can be simplified to be one cylinder encased in another cylinder, despite the fact that the inner surfaces of the stator tooth tips are actually separated with each other rather than forming a cylinder. This two-cylinder model itself is a very complicated research topic in aerodynamics. Many different methods can be used to calculate the losses. According to the method in [52], the air flow in the air gap can be categorized into three different situations: laminar Couette flow, laminar flow with Taylor vortices, and turbulent flow, which depends on the rotational speed and the Taylor number \( Ta \) (\( Ta < 41.3 \), \( 41.3 < Ta < 400 \), and \( Ta > 400 \) for the three situations, respectively). The Taylor number \( Ta \) is defined as follows [52]:

\[
Ta = \frac{r \omega \delta}{\nu} \sqrt{\frac{\delta}{r}} \tag{4}
\]

where \( \nu \) is the kinematic viscosity of the air and \( \delta \) is the air gap length.

For laminar Couette flow, the friction coefficient \( c_f \) can be calculated using [52]:

\[
c_f = \frac{1.8 (\frac{\delta}{r})^{-0.25}}{Re} \left( \frac{(r + \delta)^2}{(r + \delta)^2 - r^2} \right) \tag{5}
\]

where \( Re \) is the Reynolds number and can be defined as follows:

\[
Re = \frac{r^2 \omega}{\nu} \tag{6}
\]

According to a different model in [38], the \( c_f \) can be calculated using:

\[
c_f = \begin{cases} 
0.515 \left( \frac{\delta}{r} \right)^{0.3} \frac{1}{Re^{0.5}}, & 500 < Re < 10^4 \\
0.0325 \left( \frac{\delta}{r} \right)^{0.3} \frac{1}{Re^{0.2}}, & Re > 10^4 
\end{cases} \tag{7}
\]

Using the above equations, the corresponding \( Ta \) is calculated to be 1315 at 1 million rpm. This indicates that the machine has already been in the turbulent flow region, where the windage loss increases dramatically. Normally it is extremely difficult to calculate the windage loss in the turbulent flow area from analytical equations. In order to ensure that the machine has the torque capability to overcome the air drag at such high speeds, the windage loss is estimated assuming the same relationship of the friction coefficient \( c_f \) as described in [52]. The final friction loss is estimated to be 38w at 1 million rpm and 64w at 1.2 million rpm, which corresponds to a friction torques of 0.36 and 0.51 mN\( \cdot \)m, respectively. Assuming a safety factor of two, the machine should be designed to output a maximum torque of 0.7 mN\( \cdot \)m and 1 mN\( \cdot \)m at 1 million and 1.2 million rpm, respectively. Although this assumption may not necessarily be true, it still gives a good estimation of the windage losses of the proposed machine in the turbulent flow area, especially in the design stage.

4.5 Finite element analysis

The complete design parameters are shown in Table 4. Figures 10 and 11 show the torque and current profiles of the finite element analysis at 1 million rpm and 1.2 million rpm, respectively. The estimated average
torques are around 0.7 mN\(\cdot\)m and 1 mN\(\cdot\)m, respectively, which satisfies the design target well. The RMS currents are 3.5 and 4 A, respectively, which is a little higher than the maximum value at 1.2 million rpm. So additional cooling may be needed to keep the motor running for a long operation time.

### 4.6 Prototype

A prototype of the motor is built based on the electromagnetic design. To fix the stator and reduce the deformation due to resonance, four outer tabs with a hole of 4 mm in diameter each are added at the position of the four teeth. Fifty turns of Litz wire are then wound manually layer by layer around each stator tooth, as shown in

![Figure 10. Current (left) and torque (right) profile at 1 million rpm.](image)

![Figure 11. Current (left) and torque (right) profile at 1.2 million rpm.](image)
Figure 12(i). Two aerostatic bearings are used in the prototype as shown in Figure 12(ii).

In order to integrate the stator with the rest of the motor, two aluminum cases have been designed [56]. The cases also act as spacers to prevent the windings from contacting the air bearings. The final assembly of the complete motor is shown in Figure 13. The air compression system for the air bearings is shown in Figure 14(i). The compressed air passes through two air filters and an air regulator to function the two bearings. The working air pressure is about 90 psi. Finally, the completed prototype of the motor is shown in Figure 14(ii).

4.7 Experimental result

Experiments are conducted to verify the FEA models. A video can be found in [57]. First, $L_d$ and $L_q$ are measured using Keysight E4990A impedance analyzer. Due to the significant end effects of the unusually large number of turns of each phase windings, a 3D FEA model is built in addition to the 2D model as shown in Figure 15(i). The inductances of both phases A and B are measured at 0° (unaligned position), 30°, 60°, and 90° (aligned position). Figure 15(ii) shows the comparison of the inductance of 2D model, 3D model, and experimental results. It can be seen that, because of the fringing flux from the 3D end effect, the estimated inductance of 3D FEA is larger than 2D FEA. The measurement result is somewhere between the 2D and 3D model. Nevertheless, the slopes of the inductance profile from unaligned position (0°) to aligned position (90°), which determine the output torque, are similar among the three.

![Figure 12: Stator prototype with windings (left), aerostatic bearings used in the prototype (right).](image)

![Figure 13: Final assembly of the proposed ultrahigh-speed SRM.](image)
5. Conclusion

In this chapter, the state-of-the-art research of ultrahigh-speed switched reluctance machines is introduced and reviewed regarding the design and control. First, different control methods are compared with an emphasis on the introduction of a noncontact direct position control. This technique uses low-cost, noncontact optical sensors to detect the relative rotor positions with respect to each stator pole and achieves one pulse control for each strike, which is validated on a 100,000 rpm 4/2 SRM. Next, different rotor geometries of high-speed SRMs have been compared, and the problems that prevent them from being applied at ultrahigh speeds over 1,000,000 rpm have been analyzed. A novel high-strength, high-power-density, and high-efficiency rotor design for ultrahigh-speed SRMs has been introduced. Then, a detailed electromagnetic design of a 4/2 ultrahigh-speed SRM for applications over 1,000,000 rpm is proposed using finite element analysis. Finally, for the first time in the literature, the proposed design is integrated, prototyped, and tested with aerostatic bearings.
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