Torque Ripple Improvement for Synchronous Reluctance Motor Using an Asymmetric Flux Barrier Arrangement

Masayuki Sanada, Member, IEEE, Kenji Hiramoto, Shigeo Morimoto, Member, IEEE, and Yoji Takeda, Member, IEEE

Abstract—An interior permanent-magnet synchronous motor (IPMSM) is a highly efficient motor and operates in a wide speed range; therefore, it is used in many industrial and home appliance applications. However, the torque ripple of synchronous motors such as the IPMSM and synchronous reluctance motor is very large. The variation of magnetic resistance between the flux barriers and teeth causes the torque ripple. In this paper, flux barriers are asymmetrically designed so that the relative positions between the outer edges of the flux barriers and the teeth do not correspond. As a result, torque ripple can be reduced dramatically.

Index Terms—Asymmetric flux barrier, permanent-magnet synchronous motor, synchronous reluctance motor (SynRM).

I. INTRODUCTION

RELUCTANCE torque-assisted motors such as the synchronous reluctance motor (SynRM) and the interior permanent-magnet motor (IPMSM) have high efficiency and a wide range of operation speeds [1], [2]. These motors have been put to practical use in areas such as electric home appliances and electric vehicles. Two disadvantages are that the torque ripple and cogging torque are large. This problem is caused mainly by the discontinuity reluctance change between the rotor and stator [3]–[8]. Therefore, in this paper, the flux barrier is designed asymmetrically so that the relative position between each stator tooth and flux barrier does not correspond [9], [10]. This design improved the torque ripple. In addition, the magnet insertion part is not changed from conventional design. Therefore, this proposed arrangement is easily applied to the IPMSM.

In this paper, the arrangement of the flux barrier is described. First of all, the design method of the flux barrier is shown. Next, the effect of the decrease of the torque ripple of the proposed method is examined by the two-dimensional finite-element (FE) method. Finally, the proposed method is evaluated by an experiment with test machines. It is shown that the proposed flux barrier design is very useful for improving the torque ripple for reluctance torque-assisted motors.

II. CONVENTIONAL APPROACH FOR TORQUE-RIPPLE IMPROVEMENT

The method of giving the skew is generally known as a method to decrease the torque ripple in ac motors. The structure becomes complex, although the skew is effective in decreasing the torque ripple. Moreover, the output torque decreases, and the copper loss increases as the length of the armature winding becomes long.

In a synchronous motor which uses reluctance torque, the change of the torque pulse is related to the relative positions of the edges of the flux barriers and the stator teeth. In addition, the total torque pulse is great when the phase of the flux barrier in the entire motor is complete. The method in rotor design of moving the relative position for one pole between the flux barrier and teeth has been examined. For instance, the relative position between two flux barriers and the teeth is designed in reverse in the case shown in Fig. 1. That is, the barrier corresponds to the center of the teeth in $X$ and to the center of the slots in $Y$. However, a significant decrease of the torque ripple cannot be expected if the rotor is designed as a symmetry structure with a small number of flux barrier layers. Therefore, improvement of the torque ripple is insufficient in the SynRM and the IPMSM if the number of flux barrier layers is small.

The method of shifting the magnetic pole center of each pole is enumerated in other methods of torque-ripple decrease [6]. However, the output torque decreases as well as the skew, because moving the position of the magnetic pole center is fundamentally the same as the skew.
III. DESIGN OF ASYMMETRIC FLUX BARRIER

A decrease of the torque ripple can be expected by moving the relative position of each flux barrier between the teeth and the barrier edges. This requires finding the position of a rotor flux barrier of four poles that has a two-layer flux barrier as an example. Each flux barrier is named the \( P \) layer or the \( Q \) layer with respect to the center of the rotor. Each barrier is numbered as shown in Fig. 2. In the following, deciding the position of the left flux barrier is described. The positions of the “left” and the “right” flux barriers are named toward the rotor center. The flux barriers are designed in the line of symmetry with the magnetic pole center. Therefore, the rotor magnetic pole center does not move, and it is expected that the torque does not decrease with this design. Here, the permanent magnet replaces the air in the SynRM.

First of all, the flux barrier positions of the first layer (i.e., \( P_1-P_4 \)) are decided. As an example, the relative positions between the barriers of the \( P \) layer and the stator teeth for the symmetry arrangement is shown in Fig. 3. Each relative position of \( P_1-P_4 \) between the flux barrier and teeth is the same, and the torque ripple is fairly large.

In the proposed arrangement, the relative position between the edge of each flux barrier and stator tooth is shifted by \( \delta \), based on the position of \( P_1 \). For example, the position of \( P_2 \) shifts \( \delta \), \( P_3 \) shifts \( 2\delta \), and \( P_4 \) shifts \( 3\delta \).

\[
\delta = \frac{\tau_s}{p}
\]  \hspace{1cm} (1)

where \( \tau_s \) is the slot pitch, and \( p \) is the number of poles.

The relative position \( s \) of each barrier edge in this design method is shown in Fig. 4.

In addition, the positions of the flux barriers of the second layer (i.e., \( Q_1-Q_4 \)) are designed as follows. Each flux barrier of the \( Q \) layer is shifted by \( \lambda \) from the position of the first layer. The shifted distance \( \lambda \) is defined by the following expression:

\[
\lambda = \tau_s \times C + \frac{\delta}{2}
\]  \hspace{1cm} (2)

where \( C \) is assumed to be an integer. \( C \) is adjusted so that the distance between the flux barriers is not too small.

An example of the relative positions between the flux barriers and teeth in the second layer is shown in Fig. 5. At this time, it is assumed that \( C = 1 \) so that the flux barriers of \( P \) and \( Q \) are not partially in succession. As mentioned above, all flux barrier positions of the SynRM and the IPMSM that have the two-layer flux barrier are determined using (1) and (2). Each position between the edge of the flux barrier and the stator teeth is shown in Fig. 6.

The relationships between the flux barriers and teeth in Fig. 6 are as follows.

A  The flux barrier completely corresponds to the stator teeth.
B  The center of the flux barrier corresponds to the center between the teeth and the slots.
C  The flux barrier and the slot correspond completely.
D  The center of the flux barrier corresponds to the center between the slot and the teeth.
E  The flux barrier completely corresponds to the stator teeth (it is the same as A).

If the barrier position is decided by the proposed method, the relative positions between all the flux barriers and teeth are uniformly distributed. Therefore, it is expected that the torque ripple of the entire motor is improved.

This method can be applied to every number of poles. Moreover, it is possible to design a motor using a similar procedure.
even if the number of layers is not two. The space of the permanent magnet is limited in this proposed structure. However, because a strong permanent magnet can be used and the balance of the permanent-magnet flux and the armature flux is important in the design of an IPMSM, it is not a severe restriction.

In the asymmetrical flux barrier design, the dynamic balance of the rotor collapses, and the vibration and the noise might increase. Then, when the rotor is produced, the silicon steel plates are rotated by 90° or 180° every one piece or every several pieces and laminated, as shown in Fig. 7. Because the shape of the permanent-magnet insertion part is invariable, this technique can be applied to the IPMSM. Even if this technique is used, some rotor imbalances still remain. However, the imbalance can be completely solved by using a method such as punching the end plate. Because the perfect flux balance between one pole to the next pole is not achievable in the case of 180° rotation with the IPMSM, the winding in the stator per phase can only be connected in series. However, this problem does not occur in the case of the 90° rotation, because the four poles become magnetically equivalent. Therefore, a circulating current will not be present even if the winding is connected in parallel.

IV. CHARACTERISTICS BY FE ANALYSIS

In this section, the SynRM and the IPMSM based on the proposed design method are analyzed by the two-dimensional FE method. The effect of the torque-ripple improvement is examined.

A. Analytical Model

Fig. 8 shows the cross section and Table I shows the parameters of the analytical model. Fig. 8(b) shows the cross section
TABLE I  
PARAMETERS OF FE CALCULATION

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Shaft outer diameter</td>
<td>17.5 mm</td>
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<td>Stator outer diameter</td>
<td>125 mm</td>
</tr>
<tr>
<td>Rotor outer diameter</td>
<td>77.4 mm</td>
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<tr>
<td>Stack length</td>
<td>27 mm</td>
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<tr>
<td>Air gap length</td>
<td>0.3 mm</td>
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<tr>
<td>Number of turns</td>
<td>87 turn/slot</td>
</tr>
<tr>
<td>Rated current</td>
<td>1.1 A</td>
</tr>
<tr>
<td>Number of poles</td>
<td>4 poles</td>
</tr>
</tbody>
</table>

![Fig. 9. Torque versus rotor position angle. (a) Conventional structure. (b) Proposed structure.](image)

![Fig. 10. Comparison of torque ripple.](image)

![Fig. 11. Comparison of average torque.](image)

The optimally designed motor. It can be confirmed that the relative position between all the flux barriers and the teeth were distributed. The flux barriers of the rotor are in two layers. The stator has 36 slots. Moreover, the symmetry is kept for the permanent-magnet insertion.

The magnetization of the magnet of the IPMSM-A is 300 kA/m, and that of the IPMSM-B is 900 kA/m. The volume of the permanent magnet inserted in the center part of the barrier is the same as the volume in the proposed flux barrier arrangement. Moreover, the permanent-magnet part is assumed to be air for the SynRM.

B. Results of Analysis

The torque waveform at the maximum torque control in the rated current is shown in Fig. 9. The torque ripple rate is shown in Fig. 10. The electric current phase $\beta$ (i.e., the angle between the $q$ axis and the phase of the current in the $d$-$q$ coordinate) is $45^\circ$ in the SynRM, $40^\circ$ in IPMSM-A, and $35^\circ$ in IPMSM-B. As shown in Fig. 10, the asymmetrical flux barrier design greatly improves the torque ripple in each type.

The average torque at the maximum torque control in the rated current is shown in Fig. 11. The $d$- and $q$-axes inductances are shown in Fig. 12. In each rotor inductance, no big change is seen due to the asymmetrical flux barrier design. However, the inductances tend to increase slightly. Because the increase in the $d$-axis inductance $L_d$ is larger than that in the $q$-axis inductance $L_q$, the difference $L_q - L_d$ decreases. Therefore, the reluctance torque decreases slightly. However, the magnet torque increases slightly, so the permanent-magnet interlinkage magnetic flux may increase with the asymmetrical flux barrier design. As a result, the average torque is thought to show a small decrease in the SynRM, and a small increase in the IPMSM-B, as shown in Fig. 11.

The electric current phase is important in reluctance torque-assisted motors. Fig. 13 shows the torque-ripple rate versus the electric current phase in the rated current. The torque-ripple rate greatly decreases as the current phase increases. It is understood from Fig. 13 that the torque ripple can be decreased when the maximum torque control and the flux-weakening control are applied.

V. EXPERIMENTAL EVALUATION

A. Experimental Setup

SynRM and IPMSM-B experimental machines were manufactured. Table II and Fig. 14 show the specifications and photographs of the prototype motors. Fig. 15 shows the experi-
Fig. 12. Inductance: (a) $d$-axis inductance. (b) $q$-axis inductance.

Table II

<table>
<thead>
<tr>
<th>Specifications of the Prototype Motor</th>
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<tr>
<td>Shaft outer diameter</td>
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<tr>
<td>Number of turns</td>
</tr>
<tr>
<td>Rated current</td>
</tr>
<tr>
<td>Number of poles</td>
</tr>
<tr>
<td>Core material</td>
</tr>
<tr>
<td>Permanent Magnet</td>
</tr>
</tbody>
</table>

Fig. 14. Photographs of prototype motors. (a) Symmetric rotor. (b) Asymmetric rotor. (c) Stator.

Fig. 15. Experimental system.

The experimental setup. It is a field-oriented control system with sinusoidal current. The load is used as an eddy-current brake exciting induction machine in direct current. The torque detector is the SS-050 produced by ONO SOKKI Company Ltd., Yokohama, Japan. In the torque-ripple measurement, the speed regulator is not used, and the constant current commands $i_d^*$ and $i_q^*$ are directly input into the current regulator. In addition, to keep the rotational speed as constant as possible, the flywheel is installed on the load side. The torque ripple cannot be measured with high accuracy with respect to the frequency of the torque detector, when the rotational speed of the motor is high. Therefore, the torque ripple was measured at low speed.
B. Experimental Results

The torque waveform at the rated current 1.1 A and rotational speed 6.5 min⁻¹ is shown in Fig. 16. The electric current phase \( \beta \) is 45° in the SynRM and 30° in the IPMSM-B. It is understood that both the SynRM and the IPMSM-B torque ripples are obviously improved by the proposed asymmetrical flux barrier design.

Fig. 17 shows the torque-ripple rate versus the current phase. The torque ripple of the asymmetrical structure is improved compared with the symmetric structure. It is thought that the error in the calculated value of the symmetric structure is caused by the frequency of the torque detector and the influence of the motor inertia.

Fig. 18 shows the efficiency in the rated current. Because the flywheel is installed in the motor axis, the measurement rotational speed is limited to 800 min⁻¹ for safety. Therefore, efficiency is low. However, it is understood from Fig. 18 that the efficiency does not change in the asymmetrical flux barrier design.

VI. Conclusion

In reluctance torque-assisted motors, the torque pulses with the change in the relative positions of the flux barriers of the rotor and stator teeth. In addition, the total torque pulse is great when the phase of the flux barrier in the entire motor is complete.

In this paper, the asymmetrical flux barrier design was proposed as a method to decrease torque ripple for reluctance torque-assisted motors. The relative positions between each flux barrier and the stator teeth do not correspond in the asymmetrical design. In this design, the torque ripple can be greatly decreased without sacrificing the average torque. The torque ripple at a low speed was measured with experimental machines. As a result, the effect of the torque-ripple decrease could be confirmed without decreasing efficiency. The validity of the proposed asymmetrical design was shown. The utility of the method to decrease torque ripple using the asymmetrical flux barrier design was shown.

REFERENCES


Masayuki Sanada (M’94) was born in Japan in 1966. He received the B.E., M.E., and Ph.D. degrees from Osaka Prefecture University, Sakai, Japan, in 1989, 1991, and 1994, respectively.

Since 1994, he has been with the Department of Electrical and Electronic Systems, Osaka Prefecture University, where he is currently an Assistant Professor. His main areas of research interest are linear motors for direct-drive applications, their control systems, and magnetic field analysis.

Dr. Sanada is a Member of the Institute of Electrical Engineers of Japan, Japan Institute of Power Electronics, and Japan Society of Applied Electromagnetics and Mechanics.

Kenji Hiramoto was born in Japan in 1978. He received the B.E. and M.E. degrees from Osaka Prefecture University, Sakai, Japan, in 2001 and 2003, respectively.

Since 2003, he has been with Toyota Central R&D Laboratories, Inc., Aichi, Japan. His main research interest is torque-ripple improvement of reluctance torque-assisted motors.

Shigeo Morimoto (M’93) was born in Japan in 1959. He received the B.E., M.E., and Ph.D. degrees from Osaka Prefecture University, Sakai, Japan, in 1982, 1984, and 1990, respectively.

He joined Mitsubishi Electric Corporation, Tokyo, Japan, in 1984. Since 1988, he has been with the Department of Electrical and Electronic Systems, Osaka Prefecture University, where he is currently an Associate Professor. He has been engaged in research on ac drive systems and motion control.

Dr. Morimoto is a Member of the Institute of Electrical Engineers of Japan, Society of Instrumental and Control Engineers of Japan, Institute of Systems, Control and Information Engineers, and Japan Institute of Power Electronics.

Yoji Takeda (M’93) was born in Osaka, Japan, in 1943. He received the B.E., M.E., and Ph.D. degrees from Osaka Prefecture University, Sakai, Japan, in 1966, 1968, and 1977, respectively.

Since 1968, he has been with the Department of Electrical and Electronic Systems, Osaka Prefecture University, where he is currently a Professor. His main areas of research interest are permanent-magnet synchronous motors, linear motors, and their control systems.

Dr. Takeda is a Member of the Institute of Electrical Engineers of Japan, Institute of Systems, Control and Information Engineers, and Japan Institute of Power Electronics.
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