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Torsional Resonance Noise Reduction by Motor Torque Phase Adjustment

Masanori Arata [1], Norio Takahashi , Motoyasu Mochizuki ,
Takashi Araki [2], Takashi Hanai [2]
[1] TOSHIBA CORPORATION, 2-4, Suehiro-cho, Tsurumi-ku
Yokohama, Kanagawa, 230-0045, Japan, masanori.arata@toshiba.co.jp
[2] TOSHIBA INDUSTRIAL PRODUCTS MANUFACTURING CO

Abstract

A Hybrid Vehicle (HEV) and an Electric Vehicle (EV) are some of solutions to improve efficiency of a cruse and to reduce CO2 gas by regenerative breaking and operating the engine in optimum condition. It is requested to decrease the motor size and to increase the maximum torque for minimizing the driving units. For these purposes permanent magnet applied motors have been commonly used recently. The motor driving systems of HEV or EV must operate at variable speed ranges of up to 1:5. For this large range, Silent and smooth operations are desirable and important. Skew method is often adopted to ensure smooth start and stop and silent operation by reducing the torque ripple. But it possibly causes noise and vibration of the motor. This paper describes the mechanism of torsional resonance noise and vibrations arising from the skew method and the countermeasure to decrease them.

Keywords: AC motor, EV, HEV, noise

1 Introduction

A Hybrid Vehicle (HEV) and an Electric Vehicle (EV) are some of solutions to improve efficiency of a cruse and to reduce CO2 gas by regenerative breaking and operating the engine in optimum condition. It is requested to decrease the motor size and to increase the maximum torque for minimizing the driving units. For these purpose a permanent magnet applied motor has been commonly used recently [1].
The permanent magnet motor (PM) driving systems of EV or HEV must operate at variable speed ranges of up to 1:5. For this large range, Silent and smooth operations are desirable and important for them [2]. Skew method is often adopted to ensure smooth start and stop and silent operation of EV and HEV by reducing the torque ripple.
There are two types of skew method. One is the stator skew which changes stator slot angle by one half of slot pitch angle along with motor axial direction. Other is the rotor skew which change rotor pole angle by one half of slot pitch angle along with motor axial direction. In the rotor skew method of an implemented permanent magnet type, discontinuous pole angle change is commonly adopted because of easy manufacturing. The authors have been developing a new motor named PRM, Permanent magnet Reluctance Motor, which largely employs the reluctance torque by changing the magnet position and magnetic circuit design to satisfy specifications [8],[9],[10][11]. However, the driving system still made noise and vibration in some operating condition even after removing the noise caused by the resonance between the core

natural frequency and the sub-harmonics electromagnetic force, the noise caused by circulation current run by eccentric rotor motion.[13],[14]

2 PRM Motor

The flux weakening method for constant-power operation enlarges the operation range of various Permanent Magnet (PM) motors (Fig.1) [6],[7]. But even for an Interior Permanent magnet Motor (IPM), its operation speed range at a constant-power without voltage booster circuit about 1:3, as shown in Fig.2 [1],[2],[11]. And it results in poor efficiency by increase of the flux weakening current and iron losses in those high-speed regions [8],[9]. In addition, there is still a possibility for breakdowns of capacitors and/or power devices of an inverter due to excess voltage in case the lost of flux weakening control.

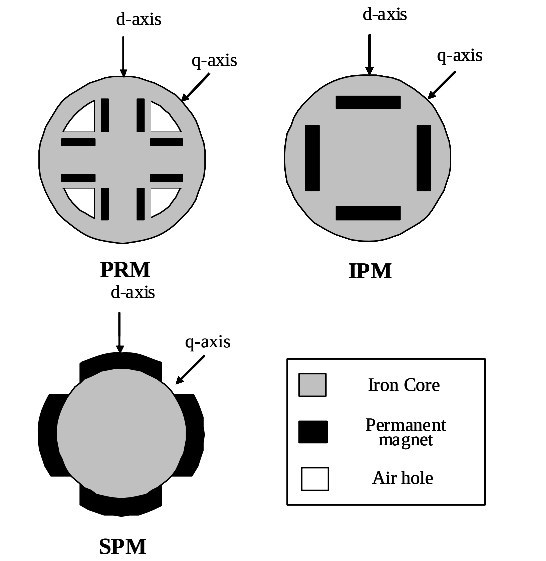


Figure 1: Rotor Configurations of PM Motors

The authors have been developing the Permanent magnet Reluctance Motor (PRM) to resolve those defects of the IPM by largely employing the reluctance torque by changing the magnet position and magnetic circuit design. Increase of reluctance torque leads to decrease of permanent magnet amounts and smaller back EMF. They allow a large variable speed range over 1:5, smaller flux weakening current and higher efficiency at high speed operating region [1],[2],[8],[11],[12].

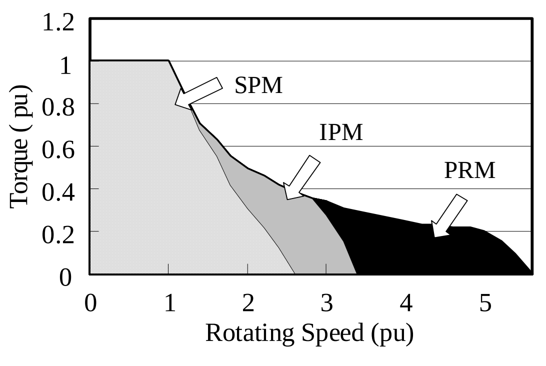
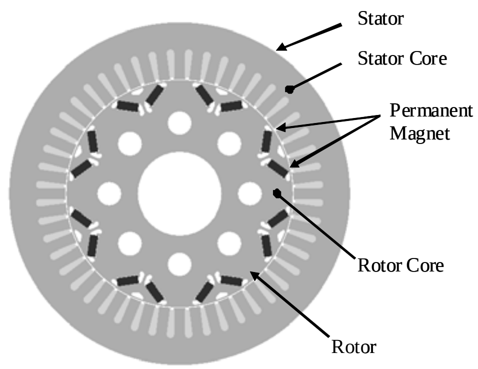
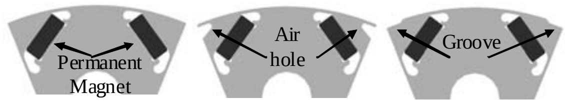


Figure 2: Performance of Motors at Variable speed

Fig.3 shows a typical cross section of the PRM and its variety. They are both possible to create magnetic flux flow controller increasing the difference d-axis and q-axis reactance by cutting an air holes inside a rotor and by setting a groove outside a rotor.



(a) An example of cross section of the PRM



(b) Rotor structure variety (pole part)

Figure 3: Structure of PRM

Fig.4 shows typical structure of PRM. After adjustment between motor performance and noise, it delivers maximum torque of 210Nm and maximum output of 65kW. It can operate until 13,500rpm at almost constant power.

Figure 4: PRM Structure for SUV

Fig.5 shows typical a torque versus rotating speed characteristic. The PRM is a powerful, compact motor and suitable to a variable speed drive.

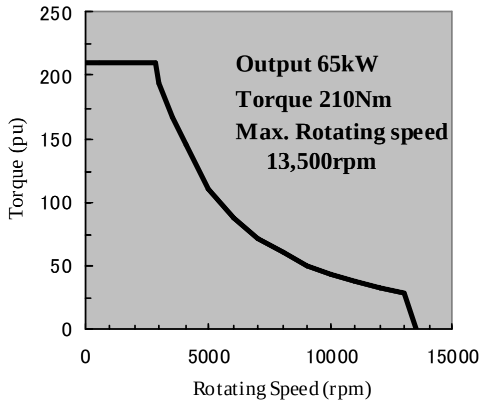


Figure 5: PRM torque characteristics For SUV

3 Motor Noise Analysis of PRM

3.1 Low speed Generating operation Noise

The PRM for Hybrid SUV use has 8 poles in the rotor and 48 slots and two star stator circuits connected in skip-pole to maximize its torque and output power considering motor efficiency, noise, producibility [13],[14]. When it delivered required torque in driving system at generating operation it made noise at low rotating speed range from 3,000rpm to 4,000rpm. That low rotating speed range noise measured and a Fast Fourie Transform (FFT) analysis was made to clarify the noise out breaking status. Fig. 6 shows the FFT analysis result in arbitrary unit at 48th order of rotating speed. At current design there are two noisy parts around 3,000rpm to 4,000rpm shown as broken circle A in Fig.6 and around 7,000rpm.

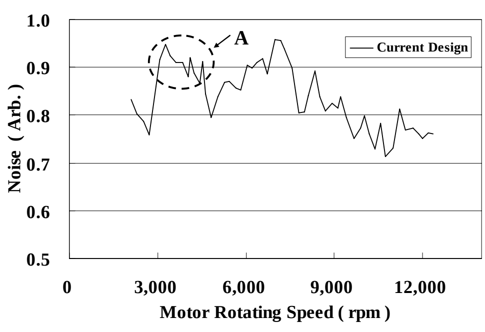


Figure 6: 48th harmonics Noise of rotating speed of original design PRM for SUV

It was expected that a noise peak would take place around 7,000rpm because of the resonance between the core natural frequency and electromagnetic force of K=0 mode. But it was unexpected such a large noise around 3,000rpm to 4,000rpm. For mass production, this noise had to be low without degrading the motor performance.

3.2 Noise and core natural frequency measurements

Noise and core natural vibration frequency were checked to identify the root cause of low speed generating operation noise around 3,000rpm to 4,000rpm.

Fig. 7 shows the core natural frequency in radial direction of PRM.

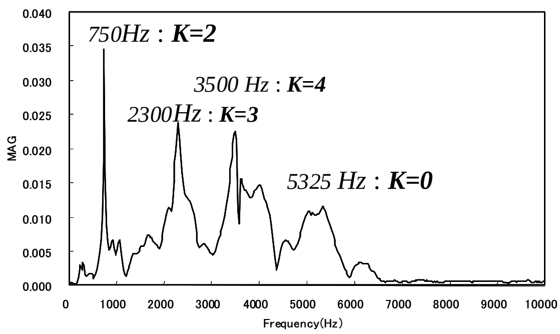


Figure 7: Stator Core natural frequency in radial direction of PRM

The frequency of the 48th noise is about 2,400Hz to 3,200Hz at rotating speed of 3,000 to 4,000rpm. The stator core has triangle like shape K=3 at around 2,300Hz. Because electromagnetic force generally doesn't have an odd number and the noise frequency slightly different from the radial core natural frequency, the root causes are something different. Authors conducted additional measurement of the core natural frequency in tangential (torsional) direction.

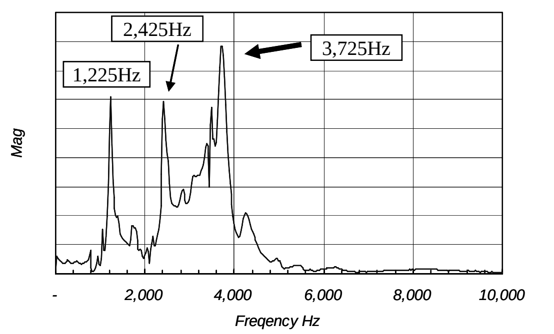


Figure 8: Stator Core natural frequency in tangential (torsional) direction of PRM

Natural frequency and its mode of the stator core were measured at support free condition. The core with stator coil sit on a rubber sheet and hammered in tangential direction by an impulse hammer.
Fig.8 and Fig. 9 show the measured the stator natural frequency and its mode.

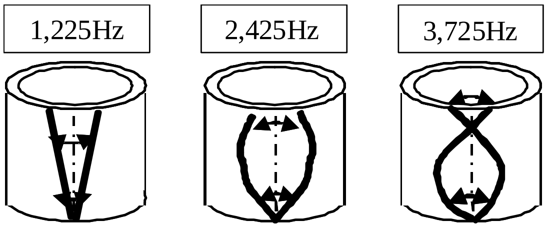


Figure 9: Stator Core natural frequency vibration mode in tangential (torsional) direction of PRM

At 1,225Hz, the Core vibrates tortuously from one end to another in same phase. Its amplitude becomes larger from one end to another. Also, it vibrates tortuously in same phase at 2,425Hz. But its amplitude is largest around the middle of its axial height. At around 3,725Hz, it vibrates in opposite phase at one end and another. If tangential force acts almost uniformly over the peripheral direction at 1,225 and/or 2,425Hz, Noise can take place resonantly. Also if torsional force acts almost uniformly over the peripheral direction at around 3,725Hz, Noise can take place resonantly.

3.3 Rotor skew and electromagnetic fore

Rotor skew is adopted in current motor design to ensure silent and smooth operation by reducing torque ripple
Original skew in current motor is a half slot skew. It is designed to depress the fundamental order of a stator slots torque ripple. Its schematic draw of one pole position is shown in Fig.10.

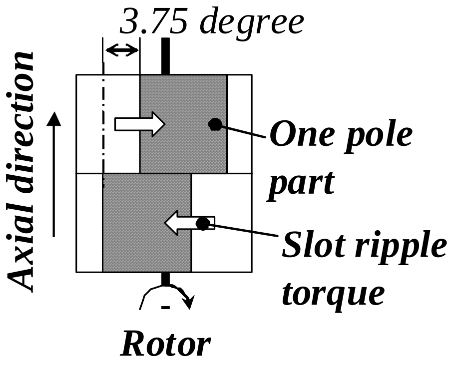


Figure 10: Schematic draw of a half slot skew

Slot ripple torque element at every stator slot in upper half of rotor is opposite to the one in lower half. Torque ripple can compensate each other on rotor axis. But their reactions on the stator are expected to be uniform over the tangential direction and opposite in upper and lower part of stator. This higher order force can excite torsional vibration around 3,725Hz.

4 Rotor skew optimization

The root cause is supposed to be the resonance between axial torsional natural frequency and electromagnetic force.
This phenomenon can be avoided if the rotor skew phase is changed and optimized.
Two skew schemes are selected keeping the torque ripple compensation and the required maximum torque of 210Nm.
One is the 4-step V skew and another is the Zig-Zag skew. These skew are shown schematically in Fig. 11.

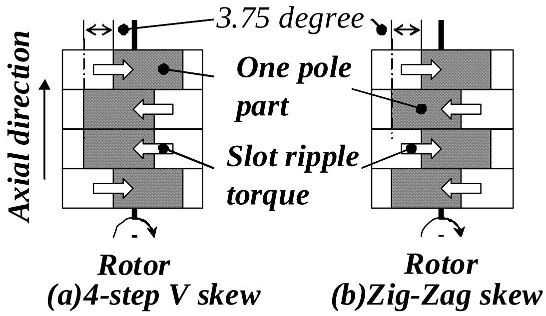


Figure 11: Schematic draws of 4-step V skew and Zig-Zag skew

The low rotating speed range noise measured and a Fast Fourie Transform (FFT) analysis was made for both skew type motors.
Fig.12 shows the FFT analysis result of the 4-step V skew motor's noise in arbitrary unit at 48th order of rotating speed.

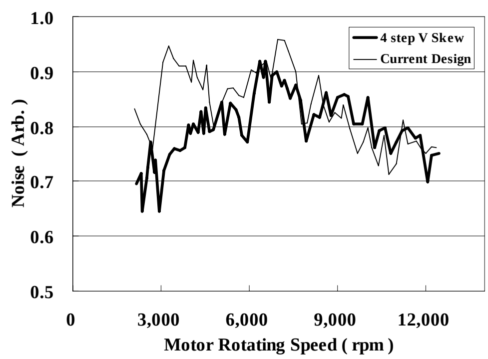


Figure 12: 48th harmonics Noise of rotating speed of the 4-step V skew PRM

The noisy part around 3,000rpm to 4,000rpm is suppressed largely as expected. It is very effective to change electromagnetic force axial distribution from axial torsional natural frequency mode.
Fig.13 shows the FFT analysis result of the Zig -Zag skew motor's noise in arbitrary unit at 48th order of rotating speed.

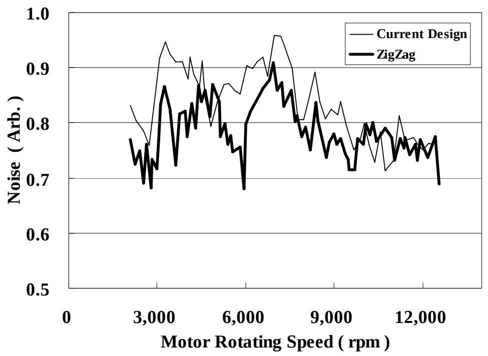


Figure 13: 48th harmonics Noise of rotating speed of the Zig-Zag skew PRM

The noisy part around 3,000rpm to 4,000rpm is suppressed significantly. And noise around 9,000rpm becomes quiet compared to current a half slot skew and the 4-step V skew. It can le to be effective for a higher axial torsional natural frequency mode. But the 4-step V skew is more effective for the noise around 3,000rpm to 4,000rpm. The 4-step V skew was adopted for the final advanced motor design.

5 CONCLUSIONS

Noise and vibration frequency and vibration mode were measured to identify the root cause of the noise at low rotating speed range from 3,000rpm to 4,000rpm in generating operation. Through this measurement and rotor skew phase optimizations, the root cause was identified to be the resonance between axial torsional natural frequency and electromagnetic force of slot ripple. Current design has conventional half slot skewed permanent magnet rotor. Rotor skew phase in the rotor was changed to 4-step V skew. After adoption of this countermeasure, the large and plateau noise .around 3,000rpm to 4,000rpm were disappeared.
This shows effectiveness of the adopted countermeasure.
This method is applied to a large electrical output and large variable speed range permanent magnet reluctance motor (PRM) for the final advanced motor design.

After large improvement in noise, the PRM are applied for a hybrid SUV, a passenger car and a hybrid truck now [2],[3].

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Authors

Masanori Arata was born in Tokyo, Japan in 1958. Since 1983, he started working for Toshiba, where he currently belongs to the Power and Industrial Systems Research & Development Center. His research interests are in the areas of a large synchronous electrical machine, a permanent-magnet applied electrical machine.

Norio Takahashi graduated the electrical engineering of the Miyagi technical high school in 1992.
He joined Toshiba Corporation in 1992 and has worked on the design and development of Vehicle use electric machines such as rotating machine based on electromagnetic field analysis.

Motoyasu Mochizuki was born in 1957. He graduated the Gifu University in 1980. He joined Toshiba Corporation in 1980 and worked on the development and mass-production of electrical power train for vehicles in Automotive Systems Division. He is currently general manager of EV division, Toshiba Industrial Products Manufacturing Co.

Takashi Araki received the B.E. and M.E. degrees in precision engineering from the University of Yamanashi, Japan, in 1988 and 1990 respectively. He joined Toshiba Corporation in 1990, and joined Toshiba Industrial Products Manufacturing Corporation in 2001. He has worked on the design and development of electric machines such as rotating machine.

Takashi Hanai was born in Aichi Prefecture, Japan, in1957. He recieved the B.S. and M.S. degrees in electrical engineering from Kyoto University,Japan, in 1979 and 1981, respectively.
He joined Toshiba Corporation in1981. He is currently senior manager of Business planning Department, EV division, Toshiba Industrial Products Manufacturing Co.