

**REPORT ON TOYOTA/PRIUS
MOTOR DESIGN AND
MANUFACTURING ASSESSMENT**

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Engineering Science & Technology Division

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Publication Date: July 2004

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
managed by
UT-BATTELLE, LLC
for the
U.S. DEPARTMENT OF ENERGY
Under contract DE-AC05-00OR22725

In today's hybrid vehicle market the Toyota Prius drive system is currently considered the leader in electrical, mechanical, and manufacturing innovations. It is significant that in today's marketplace Toyota is able to manufacture and sell the vehicle for a profit.

This project's objective is to analyze and study the Prius drive system to understand the design and manufacturing mechanisms Toyota utilized to achieved their performance and cost goals.

During the course of this research effort ORNL has dissected both the 2003 and 2004 Toyota/Prius drive motors. This study is focused primarily on motor design considerations and an assessment of manufacturing issues.

Figure 1 shows the assembly of the Toyota/Prius hybrid THS II drive train system. The motor occupies a large portion of the drive train. Studying and analyzing the motor in detail can accomplish a through understanding of the design and manufacturing considerations of the drive system.

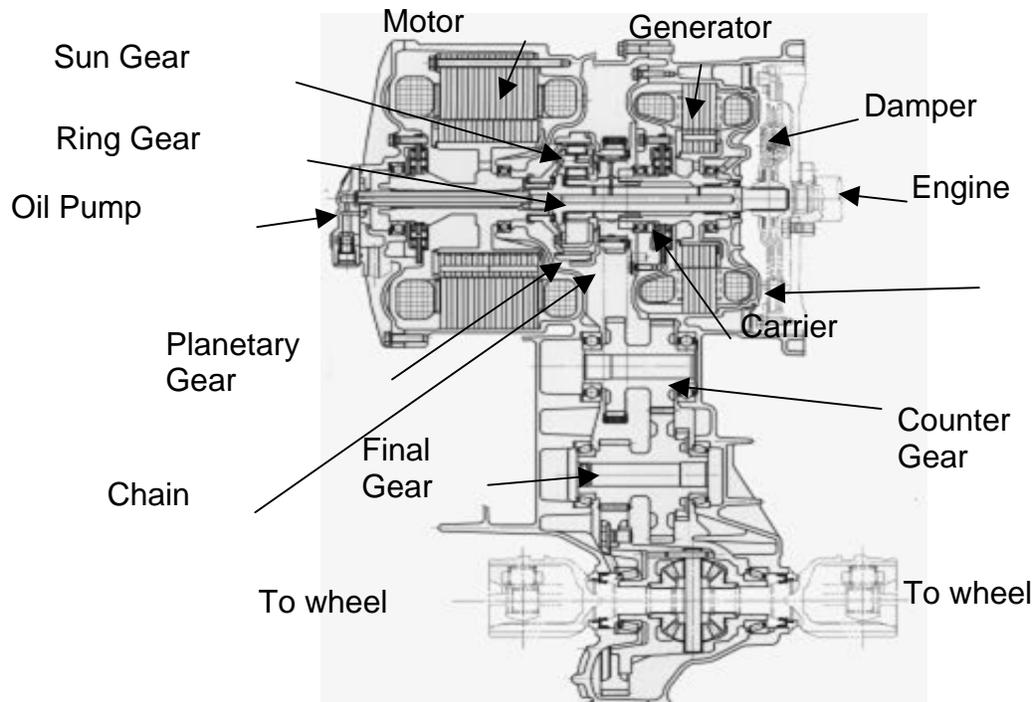


Fig. 1. Motor, generator, and engine of Toyota/Prius hybrid THS II System.

Source: *Development of Electric Motors for the TOYOTA Hybrid Vehicle "PRIUS,"* Kazuaki Shingo, Kaoru Kubo, Toshiaki Katsu, Yuji Hata, Toyota Motor Corporation.

Figure 2 compares the output power and torque versus speed of the 2003 (THS) and 2004 (THS II) model Prius motors. Both the power and the torque of the motor are significantly increased in the 2004 model.

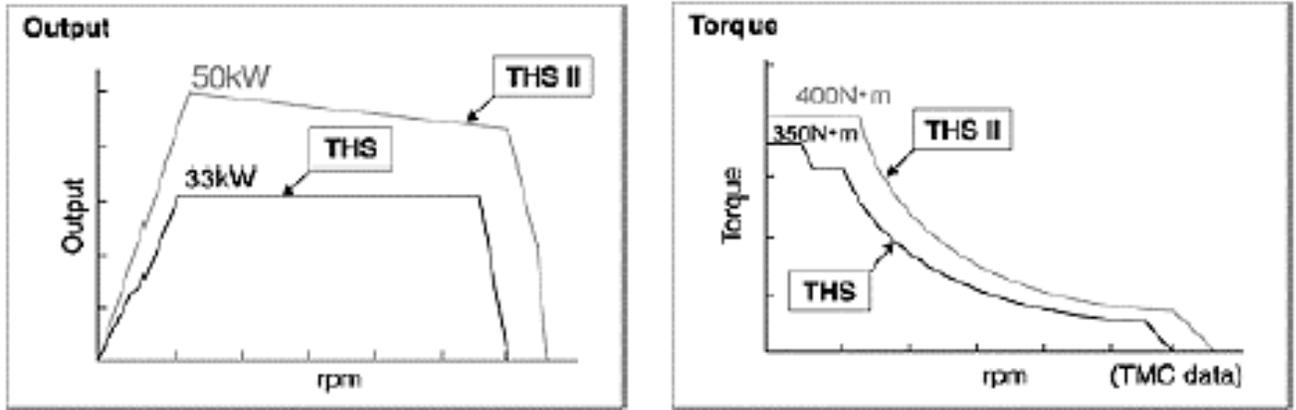


Fig. 2. Comparison of output power and torque versus speed between 2003 (THS) and 2004 (THS II) Prius motor.

The power at base speed of the 2004 model, as tabulated in Table 1, is 50 kW, which is significantly higher than the 33 kW of the older model. The 400 Nm torque of the 2004 model is also higher than the 350/305 Nm of the 2003 model.

Table 1. Power and torque of PM synchronous motor of Toyota/Prius hybrid THS II system

| | New Model (2004) | Previous Model (2003) |
|---------|----------------------------|---|
| Power: | 50 kW at base speed | 33 kW 1040–5600 rpm |
| Torque: | 400 kW up to base speed | 350 Nm–305 Nm 0–400 rpm 400–1000 rpm |

Source: *Development of Hybrid Electric Drive System Using a Boost Converter*, Masaki Okamura, Eiji Sato, Shoichi Sasaki, Toyota Motor Corporation.

How did Toyota improve the motor performance without increasing the motor size? In fact, the motor core length is even slightly shorter in the 2004 model (3.3 in. versus 3.5 in.). In dissecting the motor, ORNL researchers assessed that the windings of the 2004 and 2003 models have the same gauge wires, same number of turns per coil, same winding distribution, and the same stator punching. The only difference between the stators is that the windings are connected in series instead of in parallel in the 2004 model.

The series winding would certainly boost the torque, because for a given current, doubling the turns of the winding that interact with the fixed flux of the permanent magnets (PMs) would double the torque. On the other hand, a series winding requires twice the voltage of a parallel winding. In the low-speed region of operation, the back electromotive force (emf) is low and the 200-V bus voltage is quite sufficient to drive the motor. For high-speed operation, a boost

converter to raise the bus voltage from 200 V to 500 V is required. The following table outlines the winding comparison between the old and new Prius technologies.

Table 2. The winding connections of the 2003 and 2004 Toyota Prius'

| 2003 | 2004 |
|---------------------|---------------------|
| Parallel | Series |
| 3.5 in. core length | 3.3 in. core length |
| (200 Vdc bus) | (200–500 Vdc bus) |

Figure 3 illustrates that because of the series winding, the motor leads of the 2004 model are substantially thinner than those of the 2003 model.

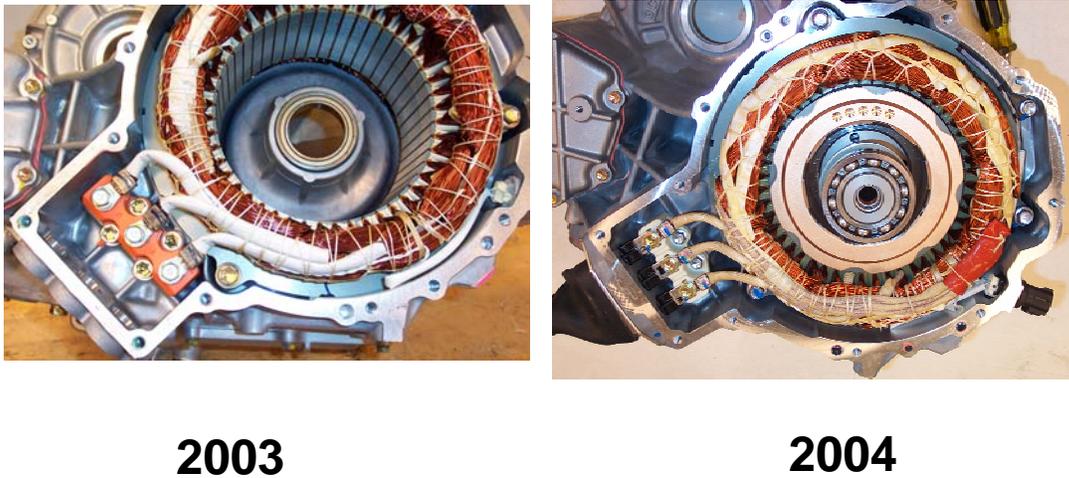
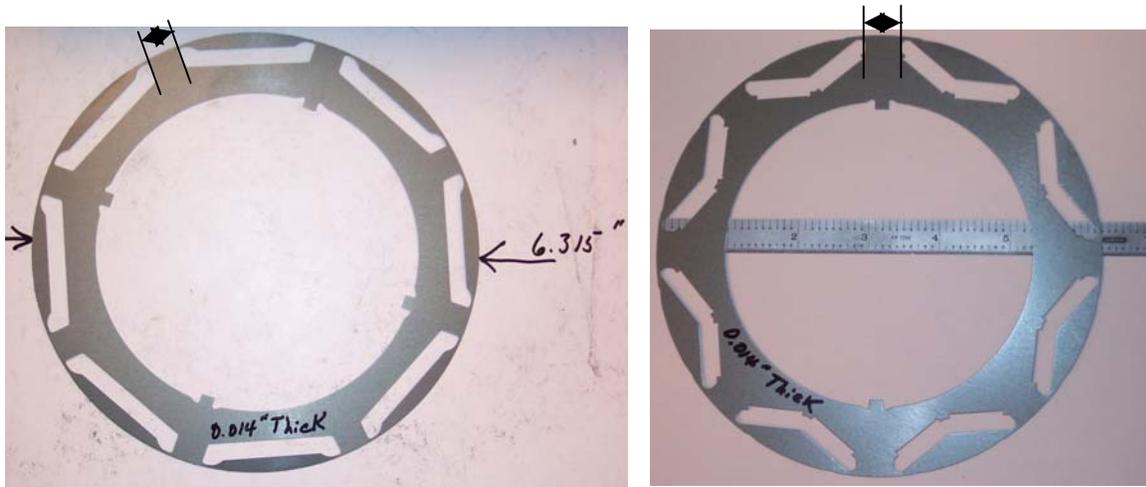


Fig. 3. Thinner motor leads after changing from two-parallel windings (2003) to series winding (2004).

The performance improvement is also obtained by increasing the quadrature-axis reactance X_q . This approach is well described in the literature. Figure 4 shows the 2003 and 2004 Prius motor rotor punchings. The new 2004 model punching has a wider quadrature-axis iron width than the older 2003 punching. The V-shape PM grooves in the new punching also help to increase the X_q value.



2003

2004

Fig. 4. Prius rotor punchings.

The width of bridges that contain the mechanical stresses holding the PMs against the centrifugal force has been optimized. A narrow bridge can reduce the leakage flux across the bridges and consequently can improve the motor performance.

Both the synchronous torque produced by the PM and the reluctance torque affect the final shape of the total torque. Figure 5 shows these torques components along with the resultant total torque of the 2004 motor.

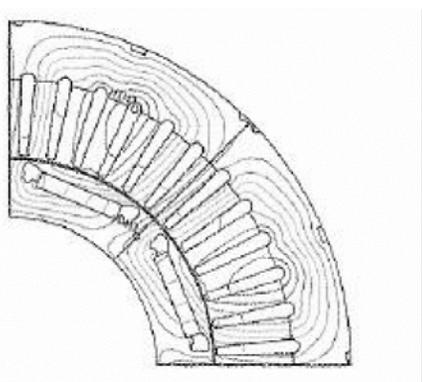


Figure 12
Torque Simulation by Electromagnetic Analysis

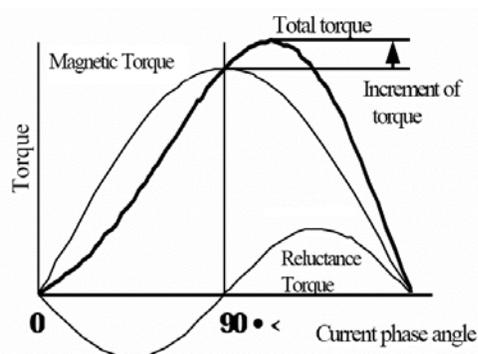


Figure 13
Torque-Current Phase Angle Characteristic

Fig. 5. Additional reluctance torque of Toyota Prius hybrid THS II motor.

Source: *Development of Electric Motors for the TOYOTA Hybrid Vehicle "PRIUS,"* Kazuaki Shingo, Kaoru Kubo, Toshiaki Katsu, Yuji Hata, Toyota Motor Corporation.

The rotor punchings are made of 0.014 in. thick processed laminations. The burr of the punching is low, less than half a mil, as shown in the side view in Fig. 6. This helps to eliminate the machining after stacking the core. Consequently, the manufacturing costs can be reduced.

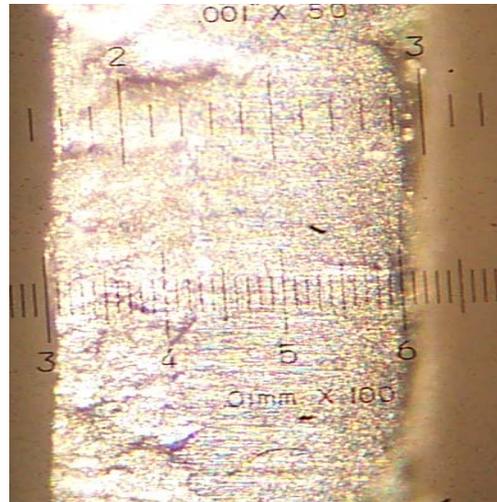


Fig. 6. Burr observation.

The Prius 2004 wound stator and its stator core are shown in Fig. 7. A very narrow stator slot is used to keep the flux density low to obtain the maximum air-gap flux produced by the PMs. The slot fill factor, calculated from the ratio of the total squares of insulated wires and the net available slot area, is 0.84. A master winder with Southern Armature, a well respected motor winding company in Knoxville, Tennessee can only produce a fill factor of 0.81 by hand winding. Normally the hand winding gets a higher fill factor than the machine winding. The end winding extensions per side is approximately 1.5 in. The slots and the stator core do not show any sign of machining or filing after the core is stacked, pressed, and welded.

The slot insulation in the new model has been changed from a Nomex to a Mylar-type material. It is speculated that the Mylar-type material has superior mechanical holding property inside the stator housing filled with oil droplets.

Figure 8 shows the shapes of the slot and phase insulations. Because the voltage rating of the 2004 model has been increased, two additional ties that hold the two ends of the phase insulation together have been added.



Fig. 7. Prius 2004 wound stator and its stator core.

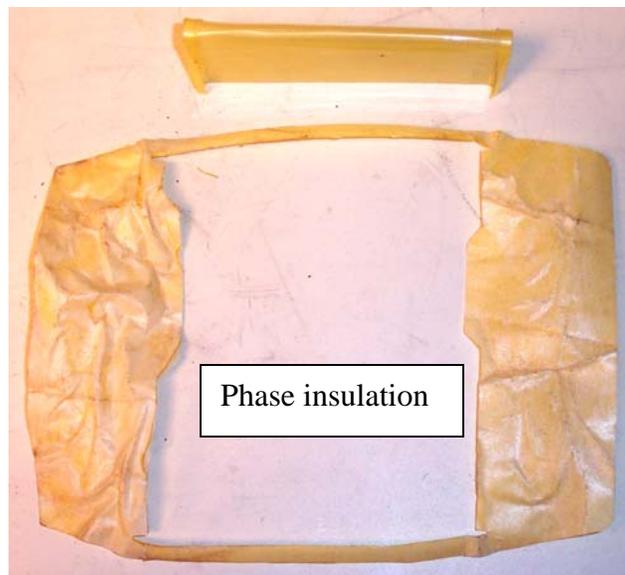


Fig. 8. Slot insulation and phase insulation of 2004 Prius motor.

Figure 9 shows the Prius 2004 rotor. The periphery of the end piece is not perfectly round. It has eight semi-round grooves that are used to sling the oil to produce oil droplets inside the motor housing for cooling the motor windings and cores.

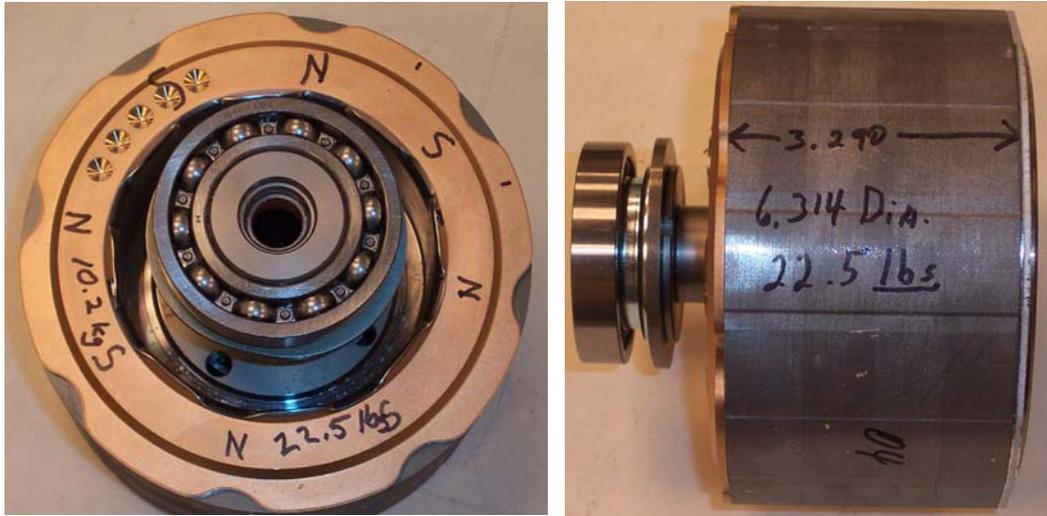


Fig. 9. Prius 2004 rotor.

Figure 10 shows the PMs for the 2004 and 2003 models. Figure 11 shows that the magnets are molded with a polymer that enables the final sizing of the PMs to be inexpensively honed to the correct dimensions and shapes for the final assembly.

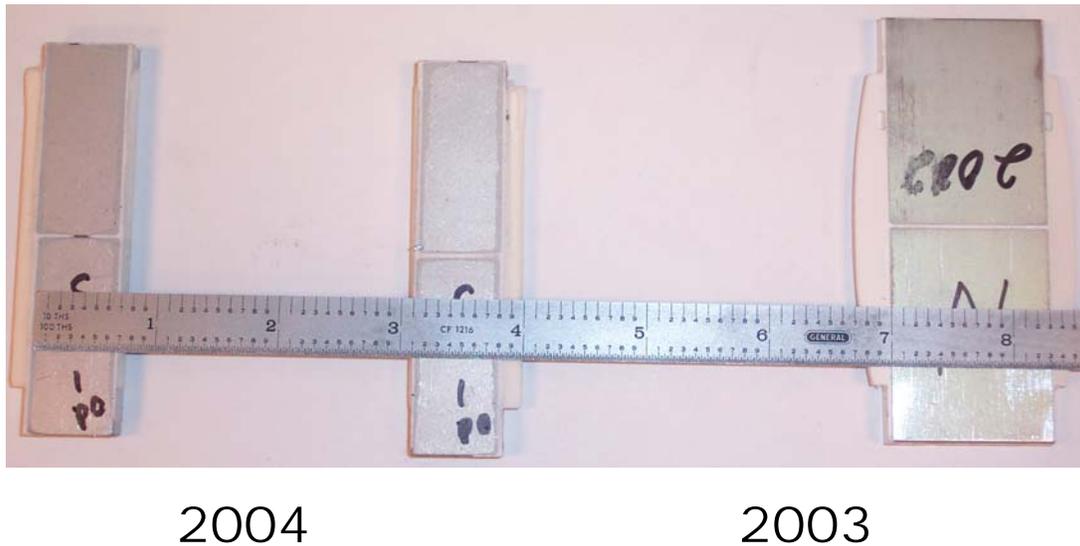


Fig. 10. Prius PMs.



2003

Fig. 11. Molded polymer is used to ensure the final dimensions of the PM.

The left side of Figure 12 shows the rotor core that has been assembled onto the rotor hub. The PMs with the polymer coating are inserted into the slots of the rotor core. The right side of Figure 12 illustrates the four keys on the rotor inner surface, which will be engaged with the key ways (not shown) on the rotor hub.

After inserting the PMs, the top-clamping piece is then inserted on the rotor core. This is followed by compressing the core and securing the location of the clamping piece.

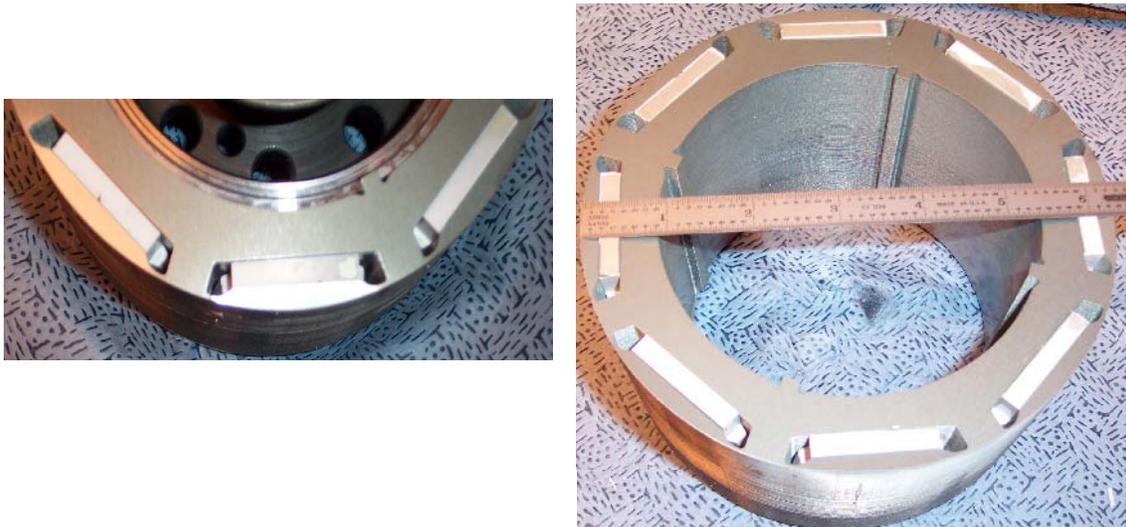


Fig. 12. Magnets were inserted into the slots of the rotor core.

The rotor assembly is now ready for magnetization of the permanent magnets.

Figure 13 shows the comparison of the measured air-gap flux densities in Gauss of the 2003 and 2004 motors. The 2004 model has a narrower but higher flux density distribution. This is accounted for by the use of the different rotor punchings between the two models shown in Fig. 4.

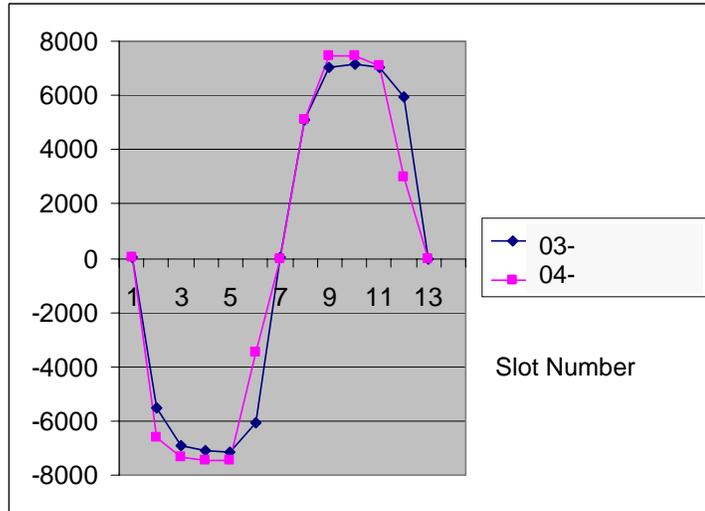


Fig. 13. Prius 2003 and 2004 no-load air-gap flux density comparison.

The PMs used were tested and compared with other types of magnets. This comparison is shown in Fig. 14. The Toyota Prius PMs are high-strength magnets. It appears that they are sintered.

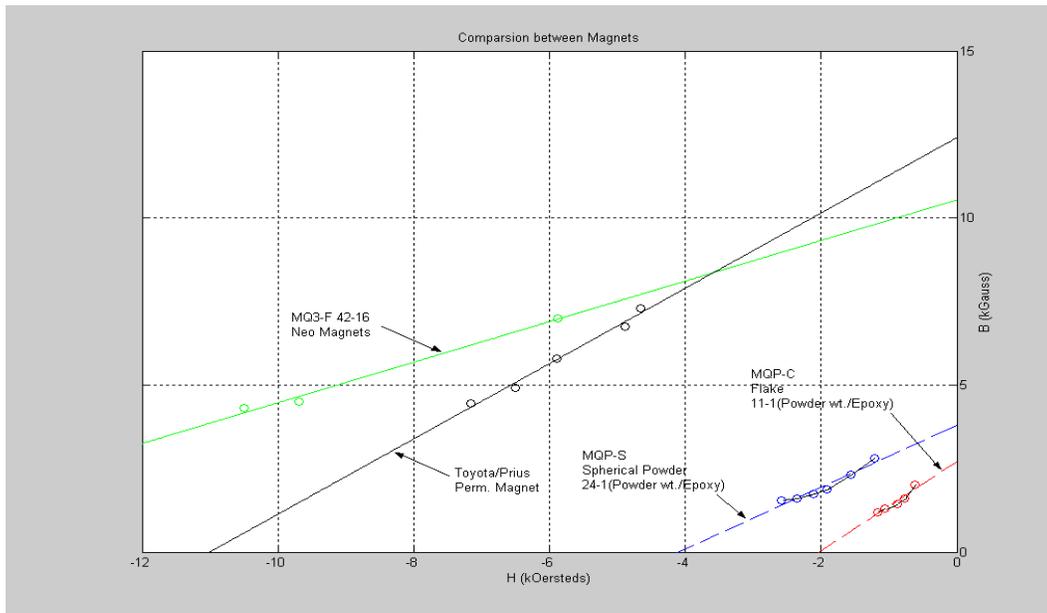


Fig. 14. Comparison of Prius PM with others.

The die cast of the Prius aluminum housing is precise, which minimizes machining operations. No shrink-fit is needed between the stator wound core and the frame. This approach helps to cut the manufacturing costs. The oil level line when the rotor is at standstill is shown in Fig. 15.

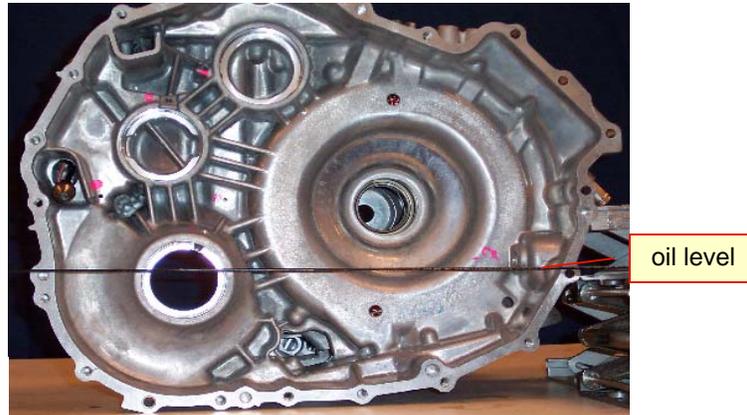


Fig.15. Oil level in Prius motor housing.

Conclusions

1. Changing the winding connections from the parallel winding of the older (2003) model to a series connection in the 2004 model increases the torque and power in the low-speed region.
2. The rotor punching design has been changed to increase the X_q value for a higher-reluctance torque component.
3. The punching quality is good. The burr is insignificant. No additional machining, grinding, and filing of the core assembly are required. This results in a reduction in manufacturing costs.
4. No shrink-fit is needed between the stator wound core and the frame.
5. Molded polymer is used to shape the PMs into their final dimensions. This results in a reduction in manufacturing costs.
6. The slot fill factor of the stator winding is very high. This increases the power density of the motor.
7. The phase insulation has been modified to add ties for meeting the higher voltage requirement.
8. The insulation has been changed from Nomex-type to Mylar-type to better withstand the oil-droplet environment inside the motor housing.

9. High-strength PMs are used.
10. The bridges that hold the PMs against the centrifugal force have been optimized for mechanical stress considerations. A narrow bridge reduces the leakage flux of the PMs and improves the motor performance.
11. Precision die casting is used to cut down machining requirements.
12. Utilizing cooling with oil droplets as well as a small water-to-water heat exchanger cast in the motor housing helps to cut the cost of motor cooling.

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