SAE INTERNATIONAL

Development of an Electric Motor for a Newly Developed Electric Vehicle

2014-01-1879
Published 04/01/2014

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CITATION: Nakada, T., Ishikawa, S., and Oki, S., "Development of an Electric Motor for a Newly Developed Electric Vehicle," SAE Technical Paper 2014-01-1879, 2014, doi:10.4271/2014-01-1879.

Abstract

This paper describes the development of the drive motor adopted on the newly developed 2013 Model Year (MY) electric vehicle (EV). Based on the 2011MY EV that was specifically designed and engineered for mass-production, the 2013MY powertrain integrates the electric motor, inverter and charging system into one unit in order to achieve downsizing and weight saving, unlike previous 2011 model which had these components segregated.

In general, integration of all components into one unit causes deterioration of the noise and vibration performance of vehicles due to an increase in weight and the number of resonance parts. In order to overcome such problems associated with this integration, each component in the 2013 model has been optimized to reduce noise and vibration resulting in high degree of vehicle quietness.

Since the electric motor is trigger for the noise and vibration in the vehicle, the electromagnetic field circuit of the electric motor has been reformed and redesigned thoroughly. As a result, the noise and vibration performance of the electric motor has been significantly improved.

Furthermore, by optimizing the shape of the electric motor and adopting the new permanent magnet, both improvement of the motor torque performance and downsizing and weight saving of the motor were implemented. This new magnet not only improves the motor torque performance but also significantly reduces the Heavy rare earth (Dysprosium) usage in the electric motor by 40% or more.

1. Introduction

NISSAN LEAF is the zero-emission car designed for the mass market. Since December 2010, Nissan sold total of 80,000 Leafs worldwide (as of September 2013), and Nissan has contributed to become widespread to zero emission vehicle.

The NISSAN LEAF 11MY was included on Ward's ‘10 Best Engines’ list for 2011, even though the NISSAN LEAF has no engine. It was first electric powertrain (e-PT) winner in award's history. This e-PT has been improved in accordance with the updated and improved version of NISSAN LEAF 13 MY.

This document describes mainly about improvement of the 13MY motor, including weight reduction, noise and vibration reduction, and technology adopted to reduce the amount of Heavy rare earth used in motor.

2. Electric Power Train Overview

In the NISSAN LEAF 13MY, the vehicle weight is reduced, and the torque performance and a reducer are optimized. The driving distance of the improved version of NISSAN LEAF has been increased compare to the NISSAN LEAF 11MY without sacrificing the acceleration performance (Refer to Table.1 below).

Table 1. Evolution from 11MY to 13MY

Specifications	11MY	13MY
Motor Max. Power	80 kW	80 kW
Motor Max. Torque	280 Nm	254 Nm
Reduction Gear Ratio	7.938	8.194
Changes of Vehicle Mass	-	-80 kg
Acceleration 0-60mph*	11.9 sec	11.5 sec
Driving Range* [LA4]	105 mile	122 mile

*Nissan Internal testing value

The e-PT component of the NISSAN LEAF 13MY, such as the electric motor, inverter, and the charging system, are all integrated into one unit as shown in Figure 1, and achieves great weight reduction. The Power Delivery Module (PDM) in Figure 1 is the combined unit and consists of the charger, DC/DC Converter, and the Junction Box.

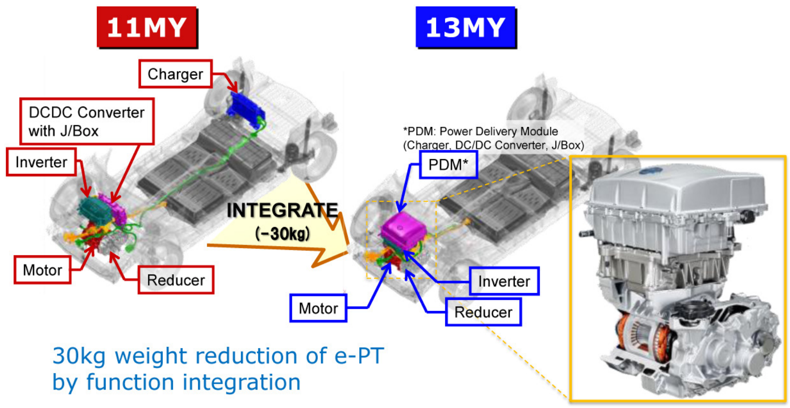


Figure 1. Improvement of e-PT (Integration

2-1. e-PT Weight Reduction

The 30kg weight reduction of e-PT was not only achieved by the integration of electric units, it was also achieved by applying the design optimization to each component such as motor, inverter, and reducer. For this achievement, reconsideration in the respective design of each component of the 11MY specification was implemented (Figure 2).

The motor, the heaviest component in the e-PT and has approximately 40% of the total e-PT weight, implements drastic revision to its design and has the new design in order to reduce the motor weight.

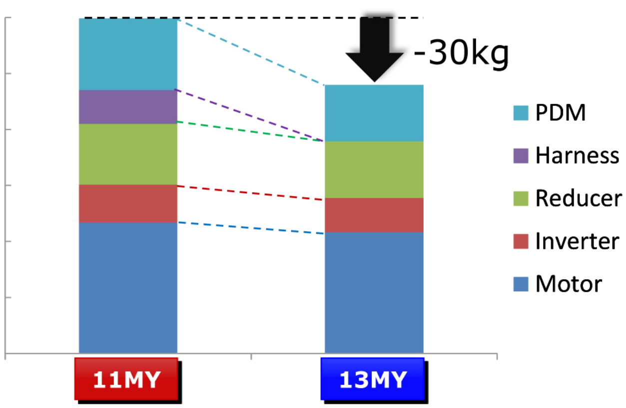


Figure 2. Break down of e-PT weight reduction

2-2. e-PT Noise and vibration Performance

Though the integrated electronic units of e-PT contribute to driving range, it also increases the number of parts which resonate with motor of vibromotive source. Furthermore, the weight of the resonance units has been increased and causing, which lead to resonance with many other parts. As the result, the deterioration of vehicle noise and vibration performance was introduced.

The Figure 3 shows and compares the noise radiation measurement results of the 11MY e-PT and the 13MY e-PT with/without countermeasure. From this figure, the integrated 13MY e-PT causes the significant deterioration of the noise and vibration at low frequency area (1.7 kHz) and a high frequency area (around 6 kHz). However by applying the countermeasure which will be discussed later, the quietness performance superior to the 11MY e-PT at most of the frequency area has been achieved.

2-3. Risk Avoidance of Heavy Rare Earth Procurement

In recent years the prices of the rare earth materials such as Nd, Dy, and Tb have been rising. For example, there was the market fluctuation of rapid rise in the rare earth price in 2011 summer. The prices were increased several times, and became higher compare to the prices in 2006 summer. As just described, the rare earth materials, especially heavy rare earth material such as Dy and Tb, always have the risk of procurement due to the distribution of a producing area. For this reason, it is the critical issue to reduce the amount of rare earth usage in order to avoid procurement risk of heavy rare earth (HRE) used in motor, for a future electric vehicle development and expansion.

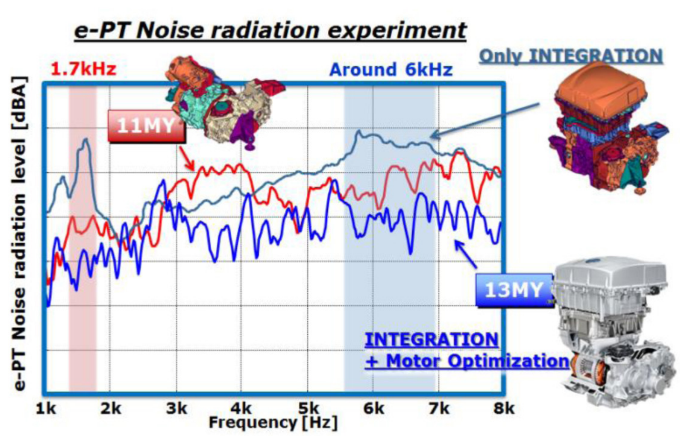


Figure 3. Improvement result of radiation noise

The motor adopted for the 13MY e-PT achieves more than 40% of HRE (Dy) usage reduction per one unit with three countermeasures described later.

3. Improvement of Electric Motor

3-1. Aims of Motor Design

Aims of the motor design adopted on the 13MY are the following.

- Motor weight reduction
- Improvement of the motor noise and vibration performance
- Reduction of the amount of heavy rare earth usage

3-2. Motor Weight Reduction

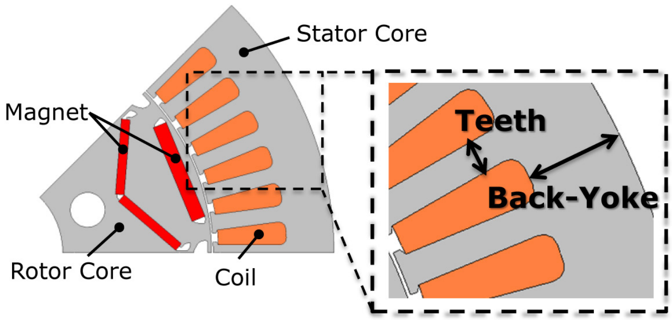
3-2-1. Motor Weight Reduction

The most effective way to reduce motor weight is a volume reduction of iron core. In order to put into practice, reconsideration of the motor electromagnetic circuit shape was conducted to improve torque density.

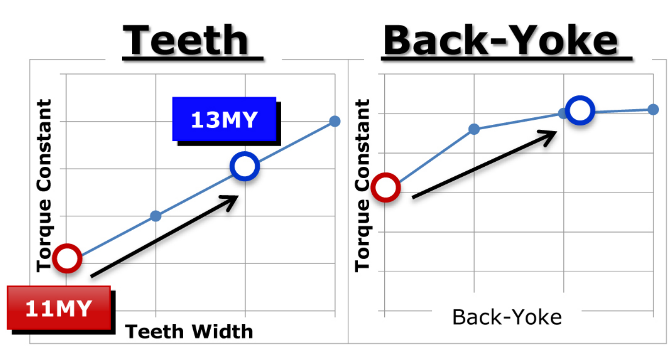
For the NISSAN LEAF 13MY, especially the Teeth shape and the Back-Yoke shape of the stator having the high torque sensitivity have been reconsidered.

Figure 4 shows the torque density sensitivity of the teeth and the back-yoke. According to this figure, by increasing the width of the teeth and the back-yoke, the torque density is significantly increased. The two factors, the optimization of the stator magnetic circuit shape, and the improvement of Remanence (Br) resulting from reducing use of Dy in new magnet (described later in this paper), have contributed to substantial improvement of the torque density by 20%.

Also by leveraging the increased amount of this torque density, the thickness of the motor icon core was reduced from 150mm to 140mm. It led to mass reduction of each parts, iron core, coil, shaft and housing. As the result, motor weight was reduced by 4.0kg (Figure 5).



4-1. Electromagnetic Circuit



4-2. Torque Constant Sensitivity of Teeth Width and Back-York Width

Figure 4. Improvement of Electromagnetic Circuit of Stator

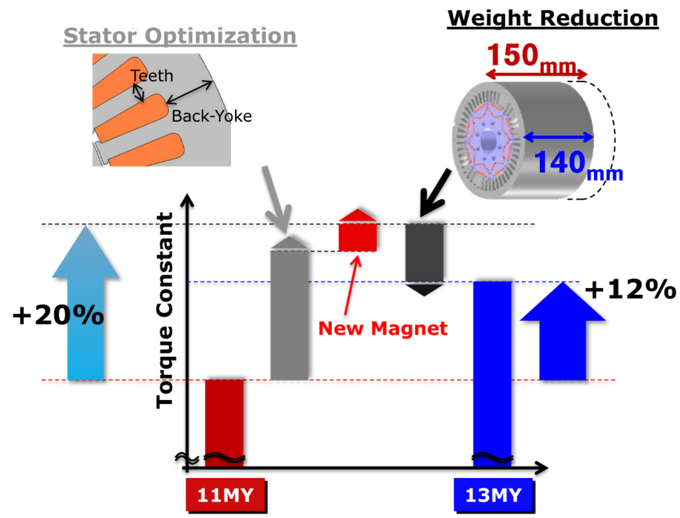


Figure 5. Distribution Torque Performance to Motor Weight Reduction

3-2-2. Countermeasure for Thermal Performance

The light weight motor was achieved by optimizing shape of the stator magnetic circuit. However by increasing the width of the teeth and back-yoke, the space for the coil was reduced compare to the space in the 11MY (Figure 6). It led to the increase in coil resistant, and generated temperature rise problem at coil end area while continuous traveling. As a countermeasure for this problem, the new terminal block which connects to the inverter terminal is placed nearby coil end, and it successfully prevent temperature rise at the coil end.

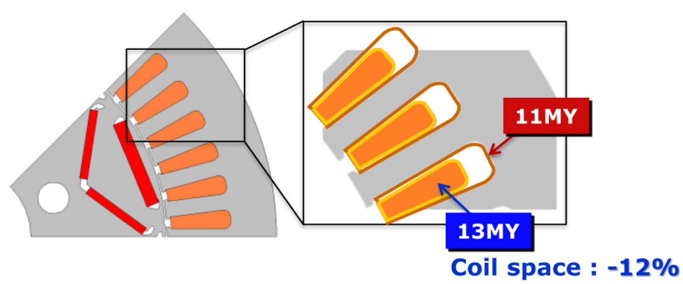


Figure 6. Coil space after optimization

As the new terminal block shown in Figure 7, the water channel is placed nearby the terminal block so that it functions as the coolant for the terminal block. By means of this structure, it makes possible to cool off the coil end temperature efficiently through the terminal block.

Figure 8 shows the breakdown of the cooling performance improvements for the terminal block. The 69% of the heat resistance has been improved by installing the terminal block nearby coil end by enhancing the structure to connect neutral point by changing the terminal block material conduction resin.

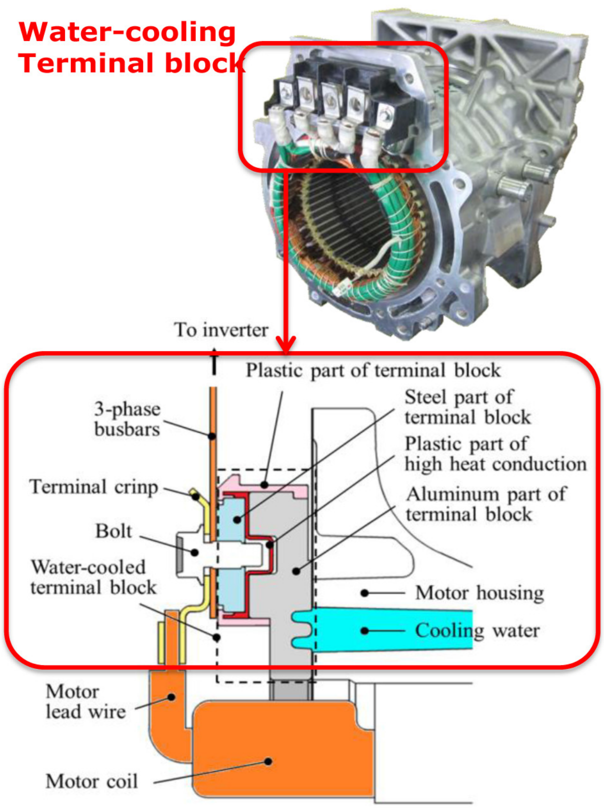


Figure 7. Structure of Terminal Block

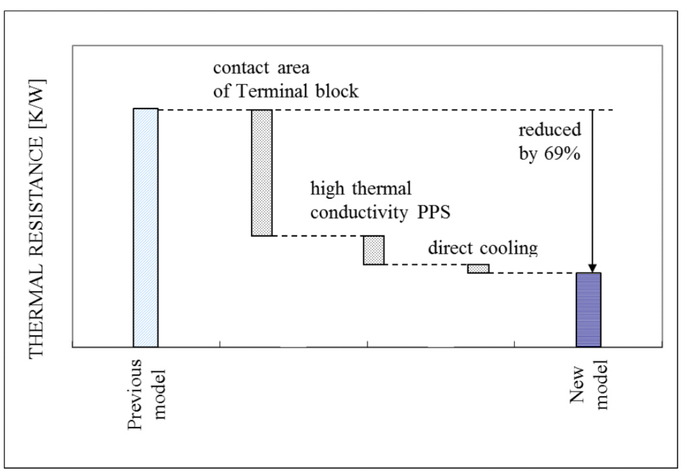


Figure 8. Breakdown of Water-cooling Terminal block performance

3-3. Improvement in Motor Noise and Vibration Performance

According to the e-PT noise radiation measurement shown in the Figure 3, the integration exerted a bad influence on the e-PT Noise radiation level at 2 places, low frequency area (at 1.7 kHz) and High Frequency Area (around 6 kHz). To elucidate the phenomena, the influence degree to the noise radiation in each part was analyzed (Figure 9). As the result, analysis showed that the main cause for the noise radiation generated at 1.7 kHz was the PDM (structural component), and the noise radiation generated at 6 kHz was motor.

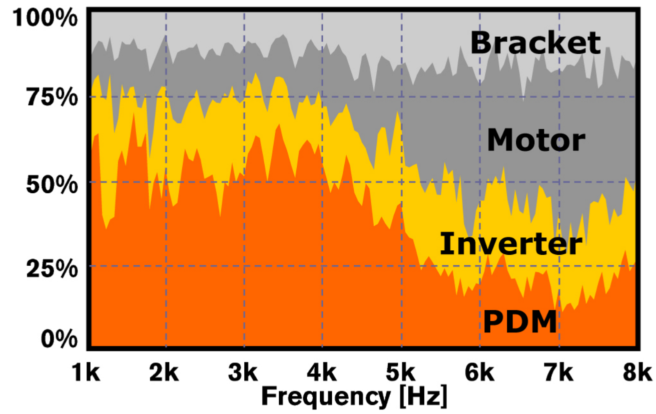


Figure 9. Radiated Noise influence rate

3-3-1. Countermeasure for Noise Radiation at 1.7 kHz

Further investigation to the root cause of noise radiation at 1.7kHz was conducted. As the result, the noise radiation was only caused when motor was combined with reducer, which means motor itself did not generate noise radiation as shown in Figure 10.

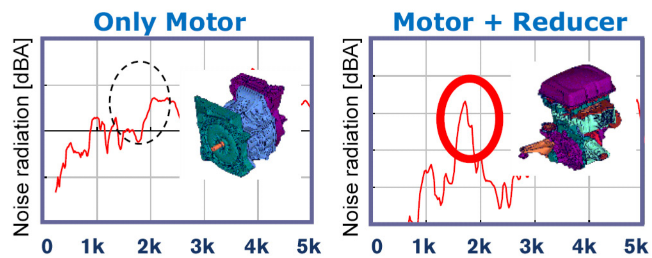


Figure 10. 1.7kHz Noise Radiation factor examination

Another investigation to, the resonance phenomenon was conducted if motor was combined with reducer. As shown in Figure 11, if the rotor which has two sections was combined with reducer, it vibrated sympathetically with reducer natural frequency of 1.7 KHz.

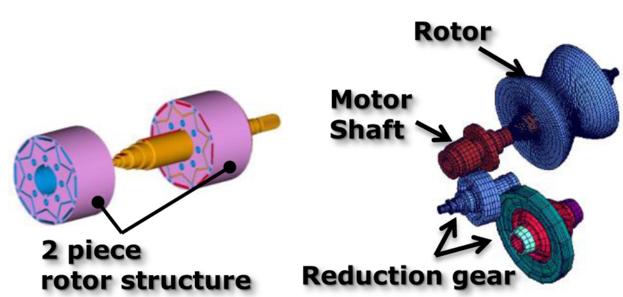


Figure 11. Structure of Rotor with Reducer

In order to avoid such resonance, improve the natural frequency in the direction of rotor torsion from 1.7 kHz to 2.2 kHz. The noise radiation generated at 1.7 kHz has been resolved as shown in Figure 12.

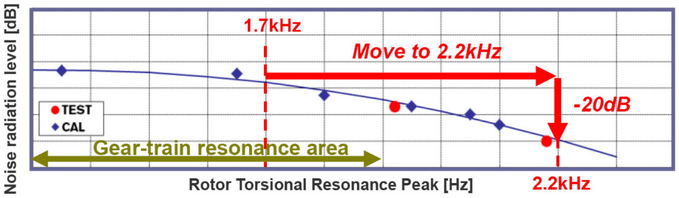


Figure 12. Rotor Torsional Resonance

3-3-2. Countermeasure for Noise Radiation at 6.0 kHz

The main cause of the noise radiation generated around 6 kHz, High Frequency Area, was vibration of the high frequency wave caused by motor itself (Figure 8). The countermeasure for this phenomenon was to suppress the motor electromagnetic excitation force generated from motor itself to reduce the noise radiation around 6 kHz.

In general, it is known that a permanent magnet type motor produces torque by the rotational direction force which are generated nearby air gap with attracting force and repulsive force between revolving magnetic field created by coil and a magnet. Concurrently with the rotational direction force, the radial force is also generated. This radial force is the source of the high frequency noise radiation which vibrates motor to the radial direction.

The force Pr[Pa] is the motor electromagnetic excitation force and is calculated by the following Maxwell's stress formula.

$$P_r = \frac{1}{2\mu_0}(B_r^2 - B_t^2)$$

μ_0: *Magnetic permeability of vacuum* $4\pi \times 10^{-7}$[*N/A*^{2}]

B_r: *Radial component of magnetic flux density*[*T*]

B_t: *Tangental component of magnetic flux density* [*T*]

In order to reduce the electromagnetic excitation force, the shape of the motor electromagnetic circuit which generates torque shall be optimized to achieve smaller electromagnetic excitation force. For this purpose, the shape optimization was applied to the 2 shapes, "I. Width of Magnet Around Rotor" and "II. Periphery Shape of Rotor Core". These optimizations have the high impact on the magnetic field nearby air gap.

Width of Magnet Around Rotor

The rotor for the NISSAN LEAF motor uses three magnets per pole. The width shape of the magnet placed around the periphery of the rotor impact to the magnetic field nearby air gap area, thus, it was considered for optimization. Figure 13 indicates sensitivity of an electromagnetic excitation force against the magnet width. As shown in this figure, the electromagnetic excitation force can be substantially reduced by selecting optimal value for the magnet width.

Periphery Shape of Rotor Core

The new Groove shape shown in Figure 14 is adopted for the 13MY. As shown in this figure, the change to the angle between d-axis and the center groove effect to an electromagnetic excitation force, so by placing the groove on to the lowest point of the electromagnetic excitation force, the further reduction of the electromagnetic excitation force has been achieved.

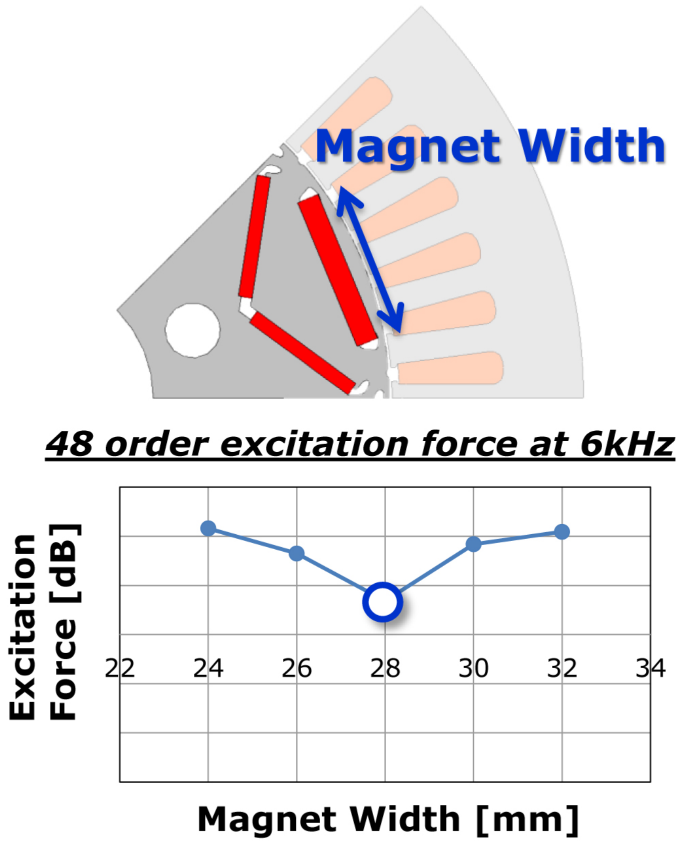


Figure 13. Sensitivity of magnet width to electromagnetic excitation force

3-3-3. Result of the Countermeasure for Noise and Vibration

Figure 3 shows the result of the noise radiation measurement of the e-PT motor which has applied the resonance improvement at the 1.7 kHz low frequency area and reduction of motor electromagnetic excitation force at the 6 kHz high frequency area.

The problem areas at 1.7 kHz and around 6 kHz have been substantially improved in the 13MY Motor. Even though inverter, reducer, and PDM are all integrated into one unit in the 13MY, the quietness performance superior to the 11MY e-PT at most of the frequency area has been achieved.

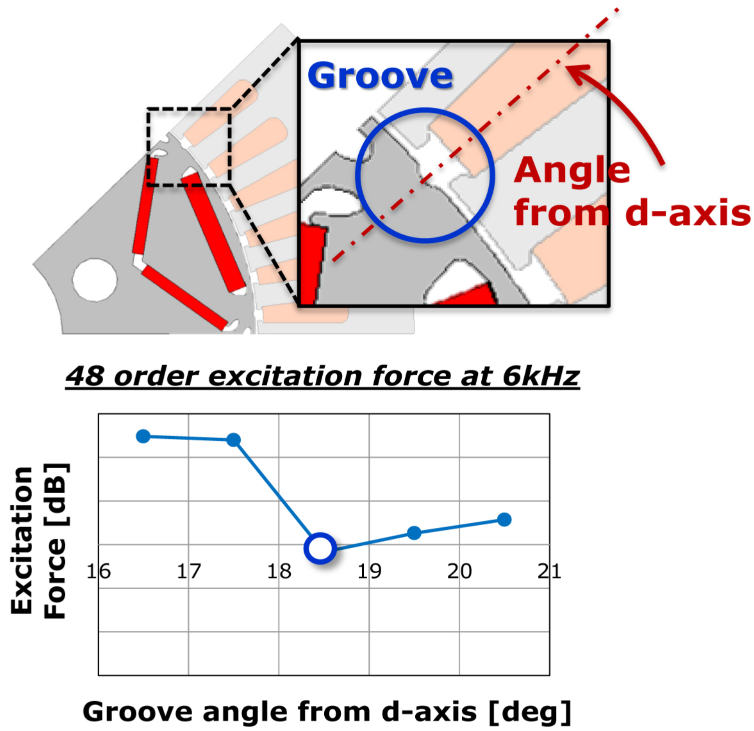


Figure 14. Sensitivity of Groove angle from d-axis to electromagnetic excitation force

4. Reducing the Amount of Heavy Rare Earth (HRE) in Motor

The 13MY motor has adopted the following three countermeasures to reduce the amount of HRE usage.

- Lower the magnet temperature
- Reduce an addition amount of HRE to the magnet material
- Reduce magnet mass used in a motor

As for the reduction of magnet mass usage, the 7% reduction has been achieved as a result of the reduction of motor weight and the electromagnetic excitation force stated previously. Other two countermeasures are described below.

4-1. Lower the Magnet Temperature

The magnet used in electric Vehicle are required to have the high heat resistance performance in order to withstand the high temperature environment in the motor while continuous traveling condition.

In general, the high heat resistance is provided by adding HRE like Dy or Tb to the magnet materials. Especially the magnet used in motor for electric vehicle which used under high temperature environment requires addition of large amount of HRE, therefore, lowering the highest temperature of magnet is an effective method for reducing the amount of HRE to be added to magnet.

For the purpose of reducing the noise radiation around high frequency area, groove is newly created around rotor periphery. This groove reduces the electromagnetic excitation force, the main cause for the high frequency noise radiation. It is also effective for iron loss within a motor loss especially for reducing iron loss of stator (Figure 15).

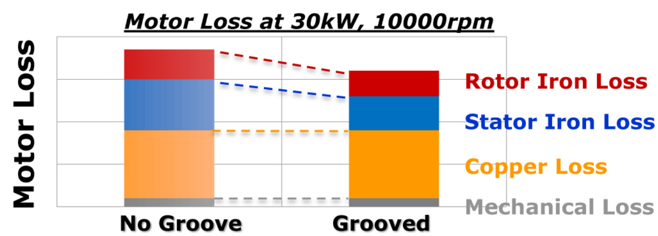


Figure 15. Motor loss comparison

According to the verification of lower magnet temperature effectiveness resulting from less motor loss with new groove, as shown in Figure 16, it is an efficient item to suppress the highest reachable temperature of magnet under continuous traveling condition. It also suppress the graded of magnet heat resistance and also contributes reducing the amount of HRE usage.

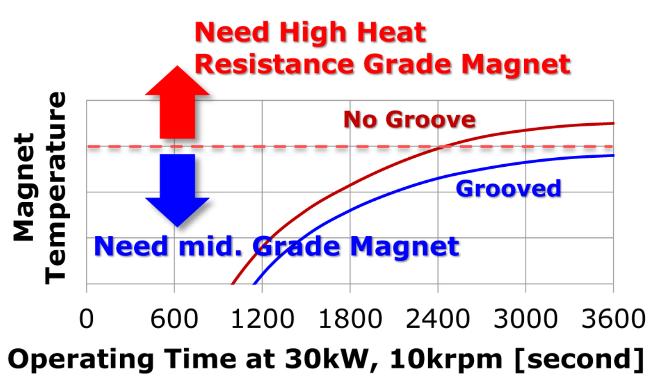


Figure 16. Magnet temperature decrease

4-2. Reduce Addition Amount of Heavy Rare Earth

The new magnet technology has been adopted for the 13MY. The 13MY motor ensures the same heat resistance performance with less HRE usage. Figure 7 shows the schematic diagram of this new magnet technology. With the conventional technology, HRE was added during the melting process of magnet raw material in order to distribute uniformly within the magnet crystal. However HRE attached around crystal had great impact to the heat resistance performance. Therefore, with the new technology, HRE is impregnated from magnet surface after sintering a magnet so that it is effectively diffused only to the grain boundaries.

The 13MY e-PT successfully reduces the large amount of HRE, especially Dy, used in motor without influencing the heat resistance performance by adopting the new magnet (Figure 18).

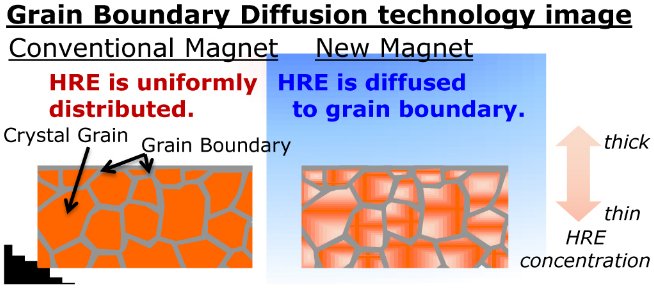


Figure 17. Grain Boundary Diffusion technology

It is generally known that heat resistance performance would be increased by adding HRE to magnet, but it would cause decrease of Remanence (Br).

To overcome the deterioration of torque performance caused by adopting the high heat resistance magnet to motor, new type of magnet that uses less Dy is adopted on the 13MY. The new magnet contributes improvement of torque performance and minimizes deterioration of Remanence (Br) while keeping high heat resistance.

By applying these three countermeasures for HRE usage reduction, Dy usage is reduced by 40% compare to the usage in the 11MY.

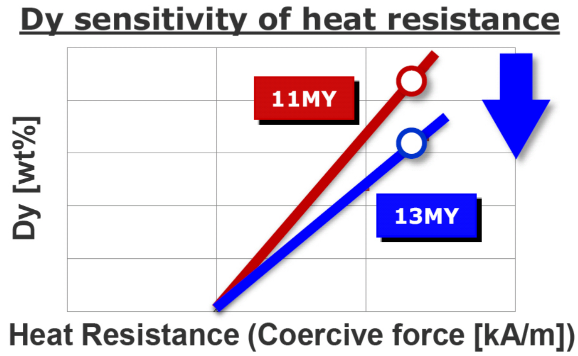


Figure 18. Dy sensitivity of heat resistance

5. Summary/Conclusions

This document described about the motor technology newly designed for the Electrical Vehicle NISSAN LEAF 13MY. The new type of motor have solved the all problems associated with lighter weight, noise and vibration performance, and reduction of HRE usage, and contributes further improvement of NISSAN LEAF performance.

The following are the successful point of motor.

- Motor weight reduction by 4kg
- Enhanced Quietness of motor noise and vibration performance
- Reduction of HRE (Dy) usage per a motor by 40% or more

References

1. Sato, Y., Ishikawa, S., Okubo, T., Abe, M. et al., “Development of High Response Motor and Inverter System for the Nissan LEAF Electric Vehicle,” SAE Technical Paper 2011-01-0350, 2011, doi:10.4271/2011-01-0350.
2. Oki, S., Ishikawa, S., and Ikemi, T., “Development of High-Power and High-Efficiency Motor for a Newly Developed Electric Vehicle,” *SAE Int. J. Alt. Power.* 1(1):104-111, 2012, doi:10.4271/2012-01-0342.
3. Shimizu, H., Okubo, T., Hirano, I., Ishikawa, S. et al., “Development of an Integrated Electrified Powertrain for a Newly Developed Electric Vehicle,” SAE Technical Paper 2013-01-1759, 2013, doi:10.4271/2013-01-1759.

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ISSN 0148-7191

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