

Development of a Compact, Highly Efficient Traction Motor for Fuel Cell and Electric Vehicles

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ABSTRACT

This paper describes the development of a high efficiency, compact, high power motor applied as a traction motor for an electric vehicle.

Both magnetic torque and reluctance torque are utilized. In order to reduce the amount of magnetic material, the magnets are arranged so as to be exposed on the rotor surface. The rotor is constructed so that a magnetic salient pole is set between adjacent magnets and a portion of this salient pole is used as a hook so that both edges of the magnets are secured. This structure enabled a 35% reduction in the amount of magnetic material used in comparison to the interior permanent magnet (IPM) type rotor without sacrificing output torque.

The magnetic flux changes in a motor utilizing reluctance torque are great. One obvious problem caused by these changes is the heat generated by the rotor's eddy current. This motor insulates the magnet surfaces to cut off the eddy flow passage between the magnet and rotor yoke Si-Fe sheets. This leads to the reduction of the eddy current loss by up to 1 kW compared to a non-insulated type motor.

As a result, a maximum torque of 238 Nm, a maximum power of 60 kW and a maximum rpm of 11,000 rpm were obtained during testing with this motor. The motor output density was 1.8 kW/kg and torque density was 7 Nm/kg. Further, the total energy conversion efficiency of the motor inverter reached 93% average drive efficiency during Urban Dynamometer Driving Schedule (UDDS) mode operation.

1. Introduction

Today, there are ever-increasing demands for automobiles with reduced environmental impact. One method to address these demands is the development and market penetration of electric and fuel cell vehicles. The traction motors in such automobiles must be high efficiency, high power, lightweight motors.

Honda began leasing its mass-produced electric vehicle, the EV PLUS, in 1997. The motor installed in the EV PLUS is a uniquely developed permanent magnet motor called the "MCF11". This motor produced a power density of 1 kW/kg, a torque density of 6 Nm/kg, and an average drive efficiency of 90% in the Urban Dynamometer Driving Schedule (UDDS) mode.

At the same time, further motor evolution is necessary to facilitate an extended cruising range, lower energy consumption, and lower cost for future electric vehicles.

This paper discusses not only the aims and features of the newly developed next-generation traction motor (Gen II Motor) but also the knowledge gained during development, and the test performance results achieved with the experimental prototype.

2. Targets of Development

The development of the Gen II motor aimed at the following three targets:

- High efficiency and high power at a reduced weight
- Cost reduction
- Noise reduction

With an electric vehicle, highly efficient conversion of electricity to kinetic energy contributes to an extended driving range on a single charge. It is likewise important for reducing fuel consumption when electrical energy is supplied by a fuel cell.

An analysis of energy management simulation⁽¹⁾ has shown that a 1% increase in motor efficiency provides the same effect on reducing the energy consumption of an electric vehicle as when the vehicle weight is reduced by 50 kg (Fig. 1). It is necessary to improve motor efficiency in order to reduce energy consumption effectively.

On the other hand, it is necessary to reduce the motor size since it must be installed in the vehicle together with other components such as batteries and fuel cells. Further, a reduction in the amount of materials used, that is, a reduction

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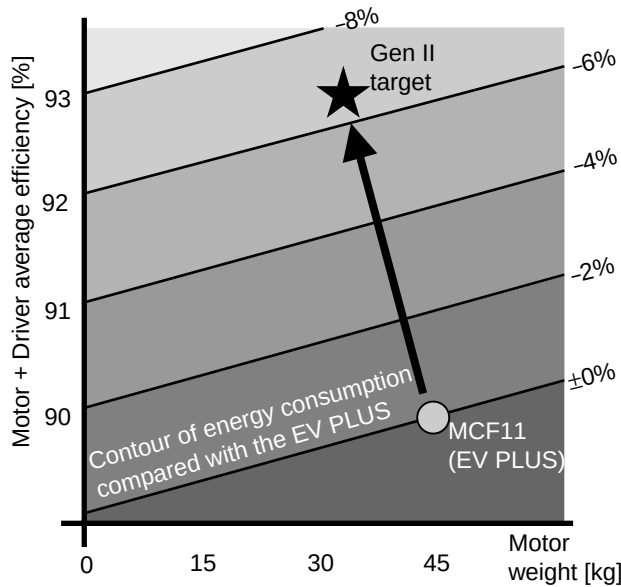


Fig.1 The relation of motor weight and efficiency to vehicle energy consumption during the UDDS mode

in motor size, is required in terms of cost reduction.

As it was necessary to achieve high efficiency and high output with significant weight reductions with the Gen II motor, we aimed for a 3% increase in efficiency and a 25% reduction in weight over the MCF11.

Further, we aimed to decrease motor noise in consideration of future mass production motors.

3. Features of the Gen II Motor

The appearance of the Gen II motor and its main specifications are shown in Figs. 2 and 3, and Table 1. Compared to the MCF11, the external diameter of the new motor has been reduced by 20%, and its weight has been reduced by 25%.

The Gen II motor is classified as a permanent magnet (PM) motor, the same as the MCF11. A PM motor generates a magnetic field through the arrangement of magnets on its

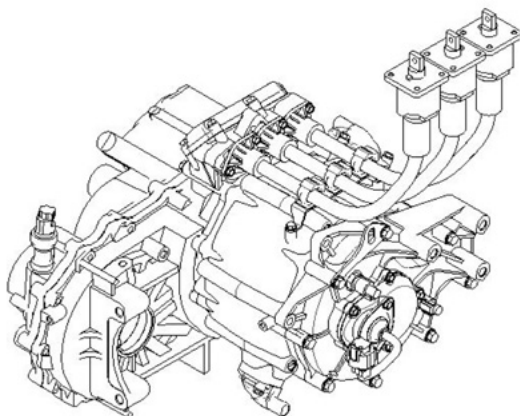


Fig.2 Gen II motor (with gearbox)

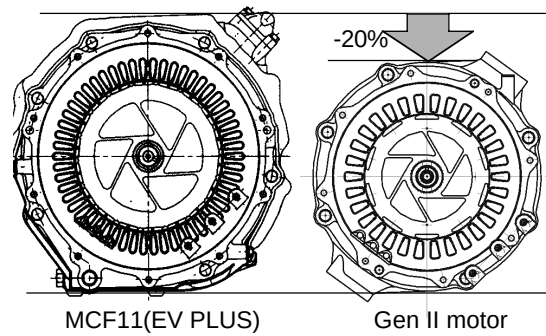


Fig.3 Section of motor

Table 1 Motor Specifications

	MCF11(EV PLUS)	Gen II motor
Type	PM synchronous motor	PM synchronous motor
Phase	3	3
Mass	45kg (without gearbox)	34kg (without gearbox)
Pole	18	10
Magnet	Nd-Fe-B (iHc>2.4MA/m)	Nd-Fe-B (iHc>2.8MA/m)
Rotor type	SPM	Salient SPM
Rotor cover	GFRP	None
Cooling system	Water cooled	Water cooled

rotor. The existence of this magnetic field renders the input of energy unnecessary and thus a PM motor is generally more efficient than other motor designs⁽²⁾. In addition, the Gen II motor uses the new technologies outlined below so as to achieve the aims noted in the preceding section.

3.1. Increasing Maximum Motor Revolution Speed

When the motor was mounted in a test vehicle in combination with a single-speed fixed gear, the relationship among maximum motor torque Q_{max} , maximum motor revolution speed N_{max} , maximum vehicle driving force T_{max} , and maximum vehicle speed V_{max} is described as follows:

$$T_{max} V_{max} = 2 \pi Q_{max} N_{max} \quad (1)$$

This relationship does not depend on gear ratio nor tire radius.

If the N_{max} is set higher, Q_{max} , which is a main factor in determining motor size and weight, can be reduced without sacrificing the vehicle T_{max} and V_{max} .

The N_{max} of the Gen II motor was set at 11,000rpm, 25% higher than that of the MCF11. The N_{max} was set after careful consideration of the balance between the N_{max} and the increased gearbox friction loss resulting from the increase in the revolution speed.

3.2. Use of Reluctance Torque

Below we have shown the basic formulas expressing the torque Tq and back electro-motive force (EMF) voltage V_a for a motor using only the rotational torque produced by the attraction and repulsion of the magnet and the stator pole (hereinafter referred to as "magnetic torque"). When the magnetic flux linkage is ϕ_a , the number of pole pairs is P_n , the electrical angular velocity is ω , the mechanical angular

velocity (revolution speed) is N , and the d- and q-axis currents are i_d and i_q , the following relationships result:

$$T_q = P_n \phi_a i_q \quad (2)$$

$$V_a = \phi_a \omega = P_n \phi_a N \quad (3)$$

The torque/current ratio is the torque constant K_t , while the back EMF voltage/revolution speed ratio is the back EMF constant K_e . Also, when the units K_t and K_e are expressed in a consistent form, we can say, based on formulas (2) and (3), that they take the relationship

$$K_e = K_t \quad (4)$$

When operated at a relatively high revolution speed, this kind of motor produces a V_a greater than the power voltage V_b , thus limiting operation. In the MCF11 motor, however, flux weakening control is used to equivalently suppress the magnetic field, to thereby expand the operating revolution speed range. This flux weakening control⁽³⁾, however, needs a current, which does not contribute to the production of torque, thus causing a drop in efficiency. Fig. 4 indicates the measured current necessary for flux weakening on the MCF11.

The decrease in efficiency resulting from the factors noted above can be suppressed by decreasing the K_e through the modification of the number of coil turns or the magnetic circuit to thereby reduce the flux weakening circuit. In such cases, however, it is impossible to avoid lowering K_t , which has the same value as K_e . These measures make it possible to reduce the loss at high revolution speeds, but the loss is increased at low revolution speeds, because the current for torque production increased. For these reasons, it is difficult to increase efficiency over a wide range of revolution speeds with motors if only magnetic torque is used.

As a result, with the Gen II motor, we decided to use not only magnetic torque, but also to give magnetic salience to the rotor, thus utilizing the rotational torque produced by the attraction between the salient and stator pole. In other words, the motor would make combined use of reluctance and magnetic torque.

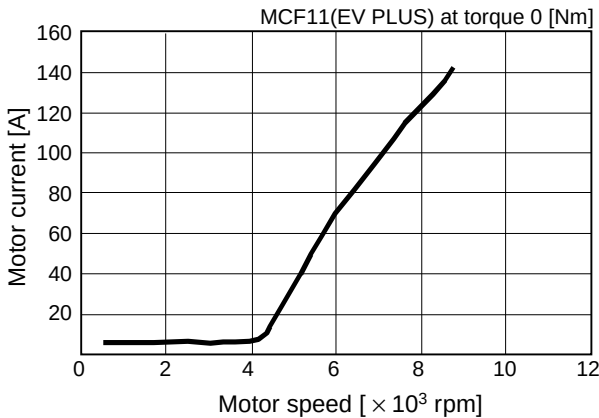


Fig.4 Motor input current for flux weakening

With a motor relying exclusively upon magnetic torque, it is impossible to avoid the principle whereby the torque/current ratio is equivalent to the back EMF voltage/revolution speed ratio. When the motor is designed to utilize reluctance torque such as this motor is, it is possible to keep the back EMF voltage/ revolution speed ratio lower than the torque/current ratio. It is also possible to expand the range of operation revolution speed, as it is not dependent on the flux weakening control, without sacrificing low-revolution number efficiency.

The torque T_q produced by the PM motor utilizing reluctance torque is expressed as

$$T_q = P_n \phi_a i_q + P_n (L_d - L_q) i_d i_q \quad (5)$$

where the d- and q-axis inductance values are L_d and L_q ⁽⁴⁾.

The generation of reluctance torque is dependent upon L_d and L_q having different values, with a greater difference between L_d and L_q resulting in increased generation of reluctance torque. With the Gen II motor, the number of coil turns was increased in order to achieve a high inductance and thereby increase reluctance torque.

The current required for flux weakening, i_d , is shown in formula (6). A high motor inductance increases the L_d , and also has the effect of lowering the flux weakening current.

$$i_d = -\frac{\phi_a}{L_d} + \frac{1}{L_d} \sqrt{\frac{V_b^2}{\omega^2} - (L_q i_q)^2} \quad (6)$$

Fig. 5 depicts a schematic of the foregoing measures.

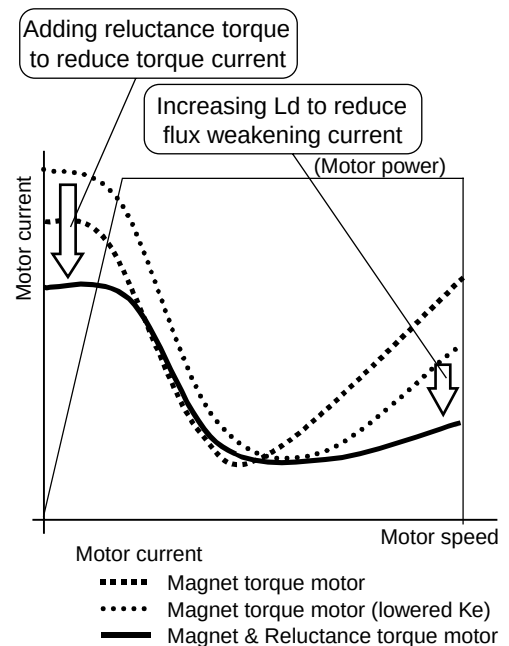


Fig.5 Motor current reduction concept

3.3. Salient Surface Permanent Magnet Rotor

A variety of configurations were considered for the rotor utilizing reluctance torque⁽²⁾. A typical design is the Interior Permanent Magnet (IPM) rotor configuration, in which magnets are embedded within the rotor yoke. Based on the fundamental principle that reluctance torque will be generated if the rotor possesses magnetic saliency, the Surface Permanent Magnet (SPM) configuration, in which magnets are exposed on the surface, can also be used to generate reluctance torque if it is constructed so as to provide magnetic saliency between the adjacent magnets.

The characteristics of the SPM, IPM and Salient SPM are shown in Table 2.

The IPM structure itself allows for inherently strong support of the magnets. However as magnetic bodies exist between the magnets and stator pole, there is the concern that magnetic flux shorting will occur within the rotor. This would result in the torque generated being relatively small for the amount of magnetic material used.

Using magnetic field analysis, the relationship of the torque constant K_t and magnet weight was compared for the IPM and the Salient SPM. The results of that analysis are shown in Fig. 6. Although it should be noted that the hook structure used to support the magnets in the Salient SPM was not modeled, the results of the analysis indicated that compared to the IPM, the Salient SPM would allow at least a 40% reduction in the amount of magnetic material used.

We also constructed IPM and Salient SPM prototypes and compared their actual operation. Results of the comparison confirmed that the Salient SPM required only 65% of the magnetic material used in an IPM to generate the same amount of torque (Fig. 7). Further, the Salient SPM rotor used in measurements was provided with the hook-shaped magnet support depicted in the structural diagram of Table 2.

Based on the above, we decided to use the Salient SPM in the Gen II motor as it would allow for a reduction in the amount of magnetic material used.

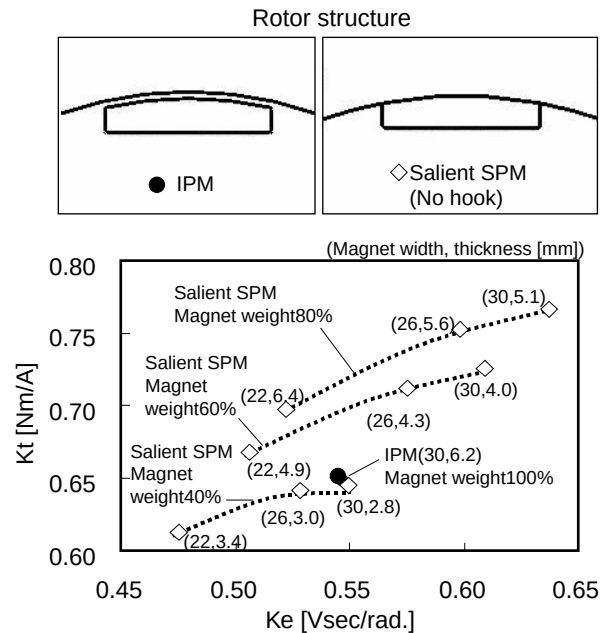


Fig.6 Calculation results of K_t , K_e by rotor structure and magnet shape

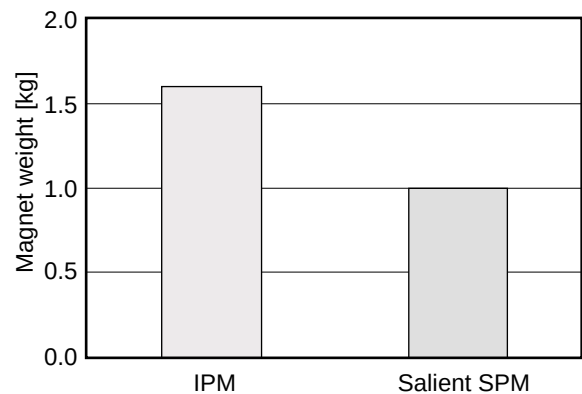


Fig.7 Amount of magnetic material used to reach the same motor torque

Table 2 Characteristics due to rotor structure

Type	SPM with non-magnetic cover	IPM	Salient SPM
Application	MCF11 (EV PLUS)		Gen II motor
Structure			
Reluctance torque use	Impossible to use	Possible to use	Possible to use
Magnetic air gap	Big air gap	Small air gap	Small air gap
Short magnet flux	Little	Short circuit due to magnetic flux in rotor	Little
Magnet torque/Magnet weight	Not so good	Not so good	Good
Rotor-stator magnetic linkage	Low inductance	High inductance	High inductance
Rotor eddy current	Small	Big	Big

3.3.1. Rotor Strength

The rotor in the Gen II motor is not furnished with a cover to prevent the magnets from separating. Instead, both edges of each magnet are held in place by hook-shaped protrusions constructed in the salient portion of the yoke. The shapes of the magnets and hooks were optimized by non-linear analysis as shown in Fig. 8. Destructive prototype testing showed the designs were capable of withstanding revolution speeds above 20,000 rpm.

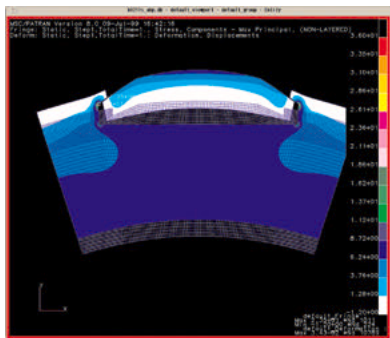


Fig.8 Nonlinear analysis used to optimize hook and magnet shape

3.3.2. Resistance to Irreversible Demagnetization

Significantly reducing the weight of magnets, increasing inductance, and exposing magnets on the rotor surface all contribute to increasing demagnetizing fields for the magnets. In order to maintain the magnets' resistance to irreversible demagnetization in the presence of large demagnetizing fields, we decided that the Gen II motor would be equipped with Nd-Fe-B magnets, which possess a coercive force of more than 2.8MA/m at room temperature. These magnets also have a coercive force of more than 1.0MA/m at 180 degrees Celsius (Fig. 9).

Magnetic field analysis also confirmed that the hook shapes used to support the magnets had the effect of enhancing the local permeance of the corners of the magnets (Fig. 10).

As a result of these combined effects, the Gen II motor

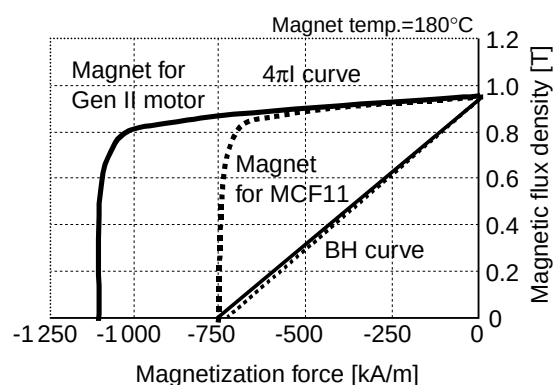


Fig.9 Properties of the magnetic material

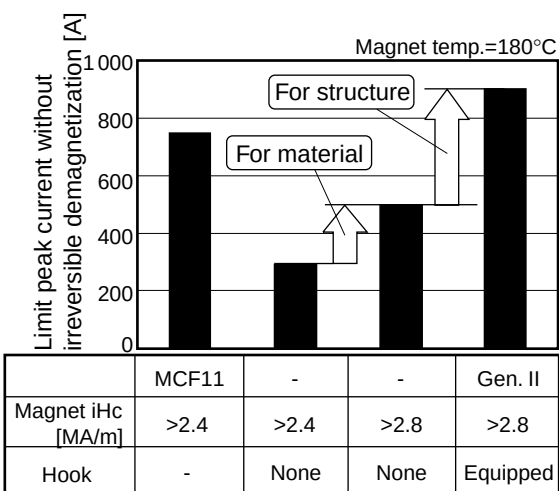


Fig.11 Simulation results of resistance to irreversible demagnetization

was provided with resistance to irreversible demagnetization equal to or greater than that of the MCF11 (Fig. 11).

3.4. Reducing Rotor Eddy-Current Loss

A PM motor utilizing reluctance torque has a tendency to experience higher iron loss in the rotor. In order to make the motor generate high reluctance torque, the salient

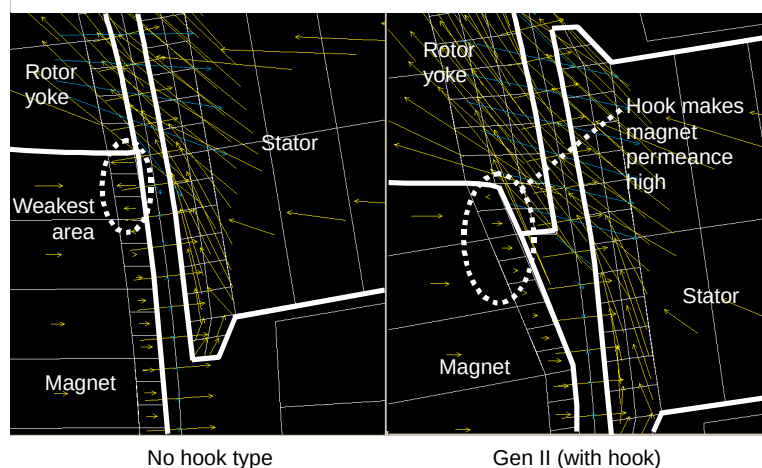


Fig.10 Motor flux density vector under high demagnetizing field conditions

magnetic material must be arranged near the stator and a higher inductance must be set. This results in a strong magnetic connection between the stator and rotor and magnetic flux fluctuations inside the rotor that are higher than those experienced within the conventional motor which uses only magnetic torque. It is believed that these flux fluctuations are responsible for generating the eddy current inside the rotor conductor.

Initially, the Gen II motor was designed to reduce eddy current loss by utilizing a rotor yoke made of the same laminated Si-Fe sheet steel as the MCF11. It was discovered, however, that greater-than-anticipated rotor heating would occur. When the temperature distribution in the rotor was measured, the results shown in Fig. 12 were produced, indicating variations in temperature distribution depending on the part of the rotor. Particularly high temperatures were measured at areas where the salient parts contacted the magnets.

When we considered the reason for this phenomenon, we discovered that since the punched surface of the laminated steel plate was in contact with the conductive magnet, an

eddy current loop composed of the magnets and Si-Fe sheets was formed as indicated in Fig. 13.

The eddy current in this loop can be suppressed by maintaining an insulating coating between the magnets and the Si-Fe sheet (Fig. 14). To this end, we tried coating the magnets with a resin, and performed the experiments again. The difference in motor loss with and without the insulation coating is shown in Fig. 15. A reduction in loss was detected during high-revolution speed, high-current operation, reaching a maximum 1 kW effect.

It is believed that eddy current loss depends on frequency and size of flux change, and that the loss is particularly generated under high revolution speed and high current conditions. Since this trend was evident in our results as well, we theorized that the insulation had the effect of reducing eddy current within the rotor.

3.5. Elimination of Resonance Noise

In the case of the EV PLUS, motor noise became quite noticeable at vehicle speeds around 80 km/h, when the motor reached a revolution speed of approximately 5,000 rpm (see

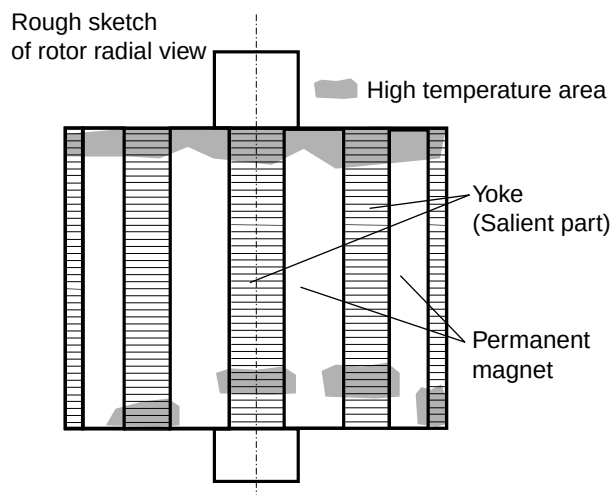


Fig.12 Rotor surface temperature distribution

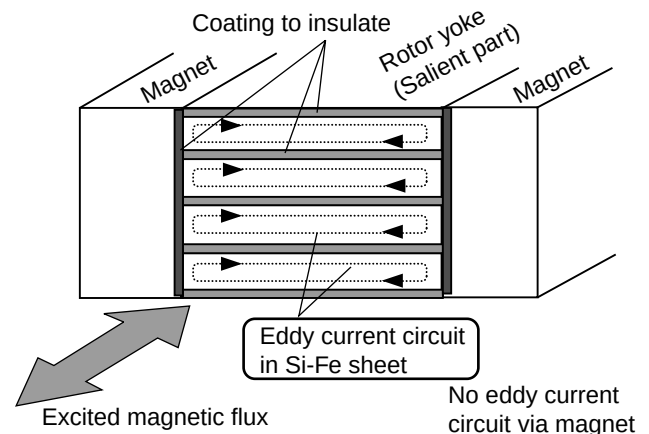


Fig.14 Eddy current behavior with insulation between magnets and Si-Fe sheets

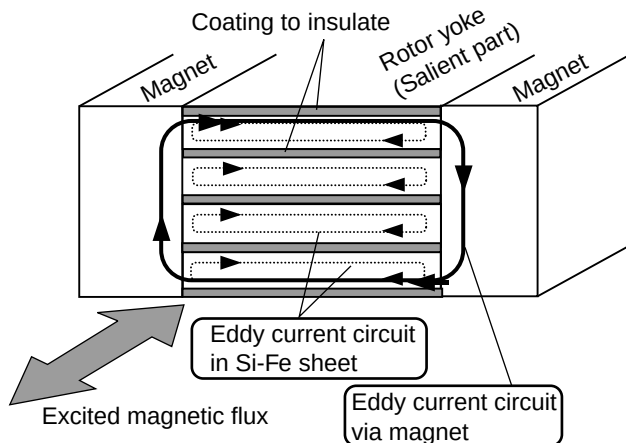


Fig.13 Eddy current behavior with no insulation between magnets and Si-Fe sheets

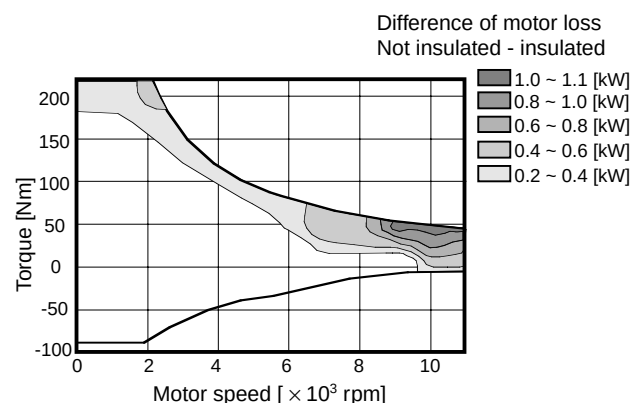


Fig.15 Effect of insulation between magnets and Si-Fe sheets

Fig. 16). When this noise was analyzed in detail, it was discovered that the peak of a very obvious noise, perhaps a resonance noise, occurred at this point (Fig.17).

The factors involved in this resonating noise were studied using eigenvalue analysis, frequency response analysis, and hammering tests, whereupon it was discovered that the resonance was occurring as a result of expansion and shrinkage of the stator cylinder. The expansion and shrinkage mode of a cylindrical shape can be expressed by the formula for the equivalent mode, which is the mode for the elongation of a plane such as that formed by cutting and flattening the cylinder in the axial direction. As a result, the resonating frequency fr can be expressed as

$$fr = \sqrt{\frac{E Trp Wrp}{Lrp Mst}} \quad (7)$$

where the Young's modulus of the stator is E , the return path height is Trp , width is Wrp , length is Lrp , and stator mass is Mst .

The three-phase current generates the attraction-and-repulsion force between the rotor and stator. This force becomes the excitation force whose primary excitation frequency fe is expressed as

$$fe = 6N Pa \quad (8)$$

A noticeable resonance noise is generated when fe and fr coincide at motor revolution speed Nr .

$$Nr = \frac{1}{6Pn} \sqrt{\frac{E Trp Wrp}{Lrp Mst}} \quad (9)$$

The resonance revolution speed Nr can be shifted from the range of actual operating revolution speeds by changing the parameters on the right side of formula (9). However, a

Table 3 Motor performance

	MCF11 (EV PLUS)	Gen II motor
Max power [kW]	49	60
Max torque [Nm]	275	238
Max speed [rpm]	8750	11000
Max torque × Max speed [k Nm rpm]	2406	2618
UDDS ave. efficiency [%]	90	93
Resonant speed [rpm]	4800	11600

particularly effective means of substantially shifting Nr is to change the number of pole pairs.

To fulfill these conditions, the Gen II motor was designed with five pole pairs so that the resonance noise occurred at 11,600 rpm, a point that exceeds the maximum normal operating revolution speed of 11,000 rpm.

4. Motor Performance

The measured performance of the Gen II motor is shown in Table 3.

4.1. Power Performance

Experimental results produced with the Gen II motor include a maximum torque of 238 Nm, a maximum power of 60 kW, and a maximum motor revolution speed of 11,000 rpm. The power density of the motor is 1.8 kW/kg, and torque density is 7 Nm/kg.

The sum of the multiplication of the maximum motor torque and the maximum motor revolution speed for the Gen II exceeds that for the MCF11, which means maximum revolution speed or maximum driving force can be improved over a vehicle equipped with the MCF11 (see formula (1)).

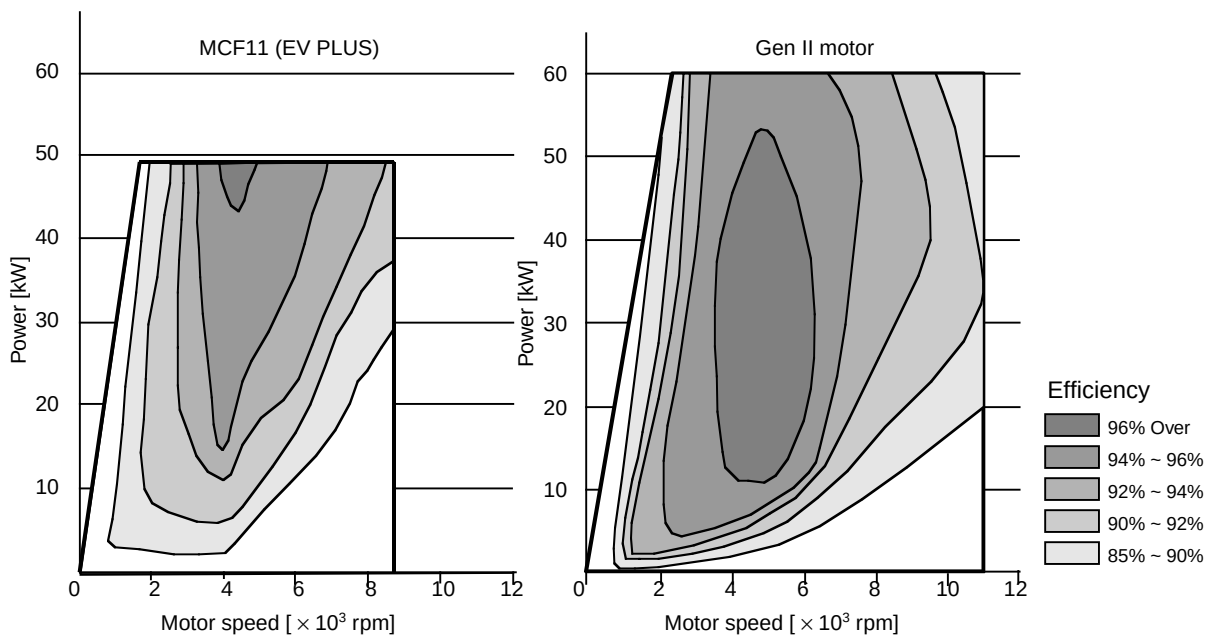


Fig.16 Motor efficiency and power performance (Inverter efficiency included)

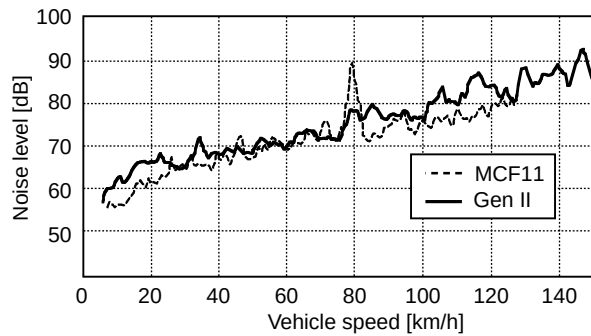


Fig.17 Acoustic noise of the vehicle

4.2. Efficiency

Fig. 16 shows the measured results of the overall motor and drive inverter efficiency. Compared to the MCF11, the Gen II motor achieves high efficiency over a wide range of revolution speeds.

The average efficiency when operating in the UDDS mode is 93%, indicating an improvement in efficiency of 3% over the MCF11's 90%. This increase is equivalent to a 30% reduction in power plant loss within the mode.

4.3. Noise

Fig. 17 shows interior noise measurements during gradual acceleration when the Gen II motor was installed in a test vehicle. The graph illustrates that the peak noise generated from resonance in the MCF11 is not produced by the Gen II motor anywhere within its range of actual operating revolution speeds. Further, these measurements were achieved when the MCF11 model was equipped with a plastic sound-insulation cover placed around the stator housing, while the Gen II sound measurements were achieved without such a device.

It should be noted that when measurements were made of resonance-acceleration in the motor housing, resonance generation was confirmed at the design revolution speed of 11,600 rpm.

5. Conclusion

This paper has discussed the development of a new traction motor for use in future electric and fuel cell vehicles. By combining the use of reluctance torque in the motor, the operating range was expanded and the efficiency was increased so that an average UDDS efficiency of 93% was obtained. The new motor also demonstrated high performance with a compact size, achieving a torque density of 7 Nm/kg.

This research also produced the following new knowledge:

- (1) The shape of the Salient SPM rotor has a large effect on reducing the amount of magnetic material required compared to the IPM rotor configuration.
- (2) The eddy current loss in the rotor is reduced by using Si-Fe sheets in the rotor and by providing insulation between the magnets and Si-Fe sheets.
- (3) By predicting the operating range wherein cylindrical

expansion and contraction resonance is generated and by changing the fundamental motor design characteristics, it is possible to suppress the generation of resonance.

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