

Development of Traction Motor for Fuel Cell Vehicle

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ABSTRACT

A DC brushless motor has been developed as the traction motor for the FCX, the world's first commercially marketed fuel cell vehicle.

This motor employs a salient pole type surface permanent magnet (SPM) rotor, which enables it both to produce reluctance torque and to minimize the use of magnets, improving dynamic performance. The inductance value is set at the limit value to ensure output at the maximum rotor speed, which suppresses field-weakening current. The motor, therefore, achieves both high output and high efficiency. Continuous operation at the maximum rotor speed was enabled by suppressing eddy current loss through surface insulation, segmentation of the magnet, and by raising the limit of irreversible demagnetization through the use of magnet materials displaying high coercive force. Strength reliability at high rotor speed was ensured by applying the Weibull theory as a method of evaluating the strength of magnets formed from brittle materials, and by considering the degradation of the magnet as a factor in evaluations.

The employment of the methods described above has resulted in the achievement of a maximum output of 60 kW, a maximum torque of 272 Nm, a maximum speed of 11 000 rpm, and a continuous rated torque of 200 Nm. In addition, an average combined efficiency of 93% in LA4 mode was achieved in the motor and inverter.

1. Introduction

Heightened worldwide awareness of environmental issues has increased the demand for the production of low emission vehicles and the reduction of the level of CO₂ in automotive exhausts to help combat global warming. The development of fuel cell vehicles as one fundamental response to these demands has therefore become an urgent issue.

In December 2002, Honda led the world by marketing a fuel cell vehicle. The use of fuel cells enables a significant increase in power over conventional batteries. Therefore, the development of the Honda fuel cell vehicle aimed at a high

level of dynamic performance to give the vehicle a higher level of commercial viability than an electric vehicle. The power and rotational speed of the traction motor used in the EV PLUS electric vehicle (MCF11 below)⁽¹⁾ marketed in 1997 were significantly increased in the traction motor for the fuel cell vehicle.

Development of the motor proceeded using an already existing prototype small, high-efficiency traction motor⁽²⁾ as a base, for which performance and specification targets were established to enable installation in a vehicle framework of more than 1.6 tons.

This paper will discuss the technologies employed in the

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development of the traction motor for the Honda FCX fuel cell vehicle (MCF21 below) and the level of performance that they have enabled.

2. Development Goals and Target Performance

Balancing the following two factors was a major goal of the development of the MCF21:

- (1) Increased efficiency
- (2) Increased power and larger range of continuous power

Target drive efficiency was established as more than 90% of the average efficiency displayed by the MCF11 in LA4 mode; this level of efficiency would be balanced with the target power performance. The target for the power of the motor was set as described below from the required dynamic performance and various other factors.

The relationship between maximum driving force F_{max} , maximum velocity V_{max} , maximum motor torque T_{max} , and maximum number of motor revolutions N_{max} is shown by Eq. (1).

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

Given the target maximum velocity of 150 km/h and the maximum driving force required for acceleration, the maximum number of motor revolutions, N_{max} , was set at 11 000 rpm on the basis of various considerations, including the available range of reduction ratio in the twin-shaft parallel gearbox and increases in friction. This figure led to a figure of 272 Nm being established as the value for maximum motor torque, T_{max} .

A lowest motor torque (bottom torque) value of 262 Nm or more at 0 rpm was established as generating the minimum driving force required to enable the vehicle to start on a climbing slope. At the same time, the torque constant was set high to ensure that the maximum phase current at 0 rpm did not exceed the allowed current for the inverter, while achieving the above value for bottom torque.

The target for the maximum power of the motor was set at 60 kW, established from the target acceleration performance and the power of the fuel cells. The requirement for continuous running at maximum speed and the necessary torque conditions to maintain the vehicle stationary on a climbing slope using only the accelerator led to a target of possible continuous power output in all power ranges at a torque of less than 180 Nm. Reduction of loss and improvement of cooling performance were further development goals.

Considerations of decline in voltage with degradation of the fuel cells led to the establishment of a minimum source voltage of 260 V to ensure maximum motor power. It is a goal of this development that a balance between the contradictory characteristics of a high torque coefficient and the required power at maximum rotational speed be achieved under this voltage condition.

3. Technologies Employed in the Motor

Table 1 shows the main specifications of the MCF21, and Fig. 1 shows a schematic of the motor, including the reduction box.

To make the drive shafts of equivalent length to produce no torque steering against the high drive torque, the right shaft has been made a half-shaft, and a support has been fitted to the right side of the motor housing. This structure has made it possible to move the large diameter drive shaft

Table 1 Comparison of motor specifications

		MCF11 (EV PLUS)	MCF21 (FCX)
Type		PM synchronous motor	PM synchronous motor
Phase		3	3
Pole		18	12
Rotor	Type	SPM	Salient SPM
	Cover	GFRP	None
Magnet	Material	Nd-Fe-B	Nd-Fe-B
	iHc	> 2388kA/m	> 2785kA/m
Cooling system		Water cooled	Water cooled

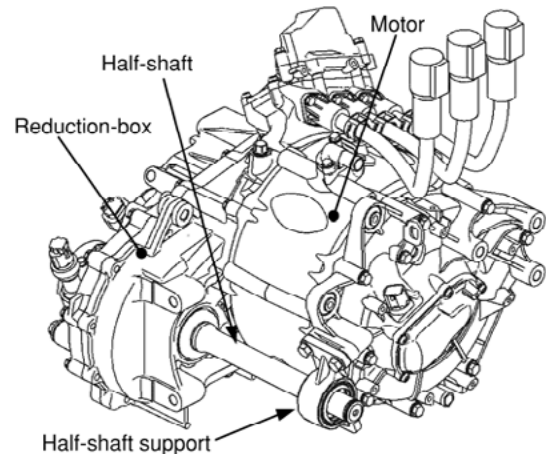


Fig. 1 Appearance of MCF21

inboard section from the rear of the motor to outside the motor, which has in turn enabled the distance between the shafts of the one-speed fixed reduction gear to be reduced. In combination with a 5% reduction in the external diameter of the motor, a 52 mm reduction of the length from the center of the differential shaft to the front of the motor in comparison to the MCF11 has enabled the space required to house the motor to be reduced.

3.1. Basic Motor Configuration

To achieve high efficiency in all driving modes, a reluctance torque permanent magnet (PM) motor, the benefits of which had been demonstrated from previous research⁽²⁾, was selected as the basic type of motor to be employed. To limit the use of high-cost magnets, a salient pole surface permanent magnet (SPM) type was utilized for the rotor⁽²⁾. Figure 2 shows a cross-section view of the basic structure of the salient pole SPM rotor.

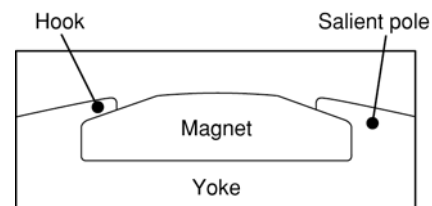


Fig. 2 Rotor structure of salient SPM

3.2. Reluctance Torque PM Motor

The torque generated by a reluctance torque DC brushless

motor, T_q , can be shown by Eq. (2), where ϕ_a is the flux linkage due to the magnet, P_n is the number of pole pairs, i_d and i_q are the d- and q-axis currents respectively, and L_d and L_q are the d- and q-axis inductances respectively⁽³⁾.

$$T_q = P_n \phi_a i_q + P_n (L_d - L_q) i_d i_q \quad (2)$$

A difference between L_d and L_q is a condition of generation of reluctance torque; as the difference between the two increases, a greater amount of reluctance torque is produced.

The current i_d required for field weakening can be found from Eq. (3), where ω is electrical angular velocity, and V_b is source voltage.

$$i_d = -\frac{\phi_a}{L_d} + \frac{1}{L_d} \sqrt{\frac{V_b^2}{\omega^2} - (L_q i_q)^2} \quad (3)$$

Utilizing high inductance to increase L_d has the effect of reducing the current required for field weakening⁽²⁾.

However, achieving high inductance reduces the maximum power at the voltage limit. The maximum power when magnetic saliency is taken into consideration can be expressed by Eq. (4) when approximated on the d-axis in Fig. 3.

$$P = V_{b \max} \frac{\phi_a}{L_d} \quad (4)$$

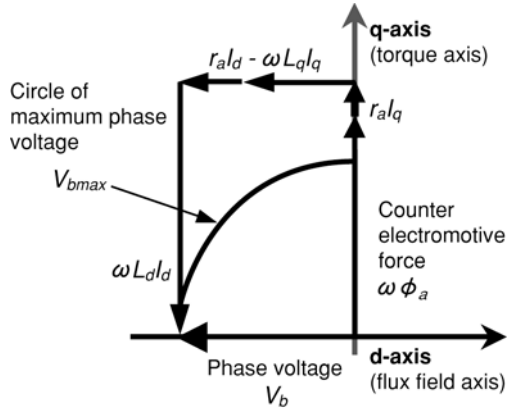


Fig. 3 Vector diagram of operating point at maximum power

The power at maximum rotational speed in particular makes a direct contribution to ensuring maximum vehicle velocity. For these contradictory requirements in the MCF21, inductance L_d was set as the limit value (maximum value) at which the target power at maximum rotational speed could be ensured, while the current required for field weakening was minimized. In addition, magnetic circuit simulations were utilized to enable the design of a form ensuring a maximum difference between L_d and L_q under the above conditions. As the measurement results in Fig. 4 show, it has been possible to ensure that the reluctance torque component increases by up to 38% against magnet torque.

To make maximum use of both types of torque, it is necessary to provide an accurate and appropriate current phase degree at all rotational speeds, including 0 rpm, and full digital vector control was therefore adopted. In addition, a Variable Reluctance (VR)-type resolver, which enables position detection even when rotation has stopped, has been utilized to detect the magnetic pole.

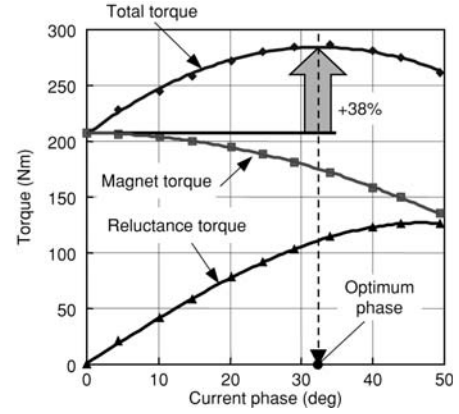


Fig. 4 Torque characteristic and current phase

3.3. Technologies Utilized to Achieve High Rotational Speed

Equation (4) shows that power at the maximum rotational speed of 11 000 rpm, at the same time as being limited by the size of inductance L_d , is proportional to the flux linkage due to the magnet, ϕ_a . The flux linkage due to the magnet varies during driving because of changes in the flux density caused by changes in the temperature of the magnet. In Nd-Fe-B magnets the flux density decreases as temperature increases. Because of this characteristic, flux linkage ϕ_a decreases as temperature rises due to the increase in eddy currents generated by making the motor high-revolution, causing a consequent decrease in maximum power in Eq. (4).

In the MCF21, stable generation of the target power at the maximum rotational speed established for the voltage limit under conditions of high inductance has been guaranteed by controlling the temperature of the magnet and increasing the limit of irreversible demagnetization. In addition, the employment of a method enabling strength to be ensured in magnets formed from brittle materials has ensured strength reliability in the high-speed rotor.

3.3.1. Ensuring power at the limit voltage by control of magnet temperature

The maximum power at the rated voltage is determined by the value of inductance, and drops, as the calculated values in Fig. 5 show, with the reduction in flux linkage that occurs as the temperature of the magnet rises. From Fig. 5, it is also possible to obtain the upper limit for allowable magnet temperature determined from the value for motor power required to ensure maximum speed and the thermal characteristics of the magnet.

In the new motor it was possible to achieve the target power by maintaining the temperature of the magnet below the upper limit. Figure 5 also shows test measurements of the change in power with rising magnet temperature. It was confirmed that magnet temperature reaches a point of equilibrium below the upper limit for temperature, and as a result the output power comes to equilibrium at the target power level. The differences between the results of calculations and measurements are believed to occur because the temperature of the magnet differs with measurement position and overall distribution.

Applying an insulating surface treatment to the magnet to reduce the amount of heat generated in the salient pole section of the yoke by eddy currents is known as a method of controlling the temperature of magnets⁽²⁾. Because eddy currents in the interior of the magnet also caused its temperature to noticeably rise in the MCF21, in addition to

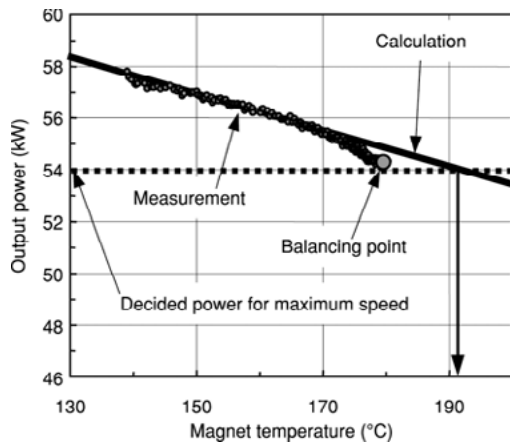


Fig. 5 Output at maximum speed

application of the surface treatment, the magnet was divided in the axial direction to control the production of eddy currents.

In addition, the resistivity of the metal plating used to prevent corrosion in the magnet is approximately 1/20 – 1/80 that of the magnet materials. It was therefore judged that the level of heat generated by eddy currents in the metal plating layer could not be ignored, and would contribute to increasing the temperature of the magnet. As Fig. 6 shows, increasing the divisions of magnet by 30% or more is required to maintain the temperature of a magnet with a metal plating at the same level as that of a magnet without a metal plating. The metal plating was therefore eliminated and the insulating surface treatment was relied on to prevent corrosion, requiring no increase in the number of divisions.

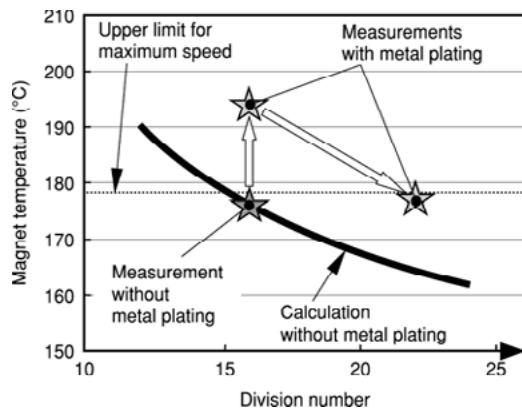


Fig. 6 Magnet temperature by division number

3.3.2. Ensuring toughness against irreversible demagnetization

Studies have already demonstrated that high-inductance surface-mounted permanent magnet rotor-type motors increase the demagnetizing fields acting on the magnet, and that the employment of a hook structure to hold the magnet is effective in increasing its toughness against irreversible demagnetization⁽²⁾.

In combination with the magnet temperature control discussed above, in the MCF21, the employment of a high coercive force Nd-Fe-B magnet, able to maintain coercive force of 756 kA/m or more at 200 °C, means that no irreversible demagnetization occurs at the temperatures or currents generated during driving, as shown in Fig. 7. Results of calculation and measurement points are shown in the figure.

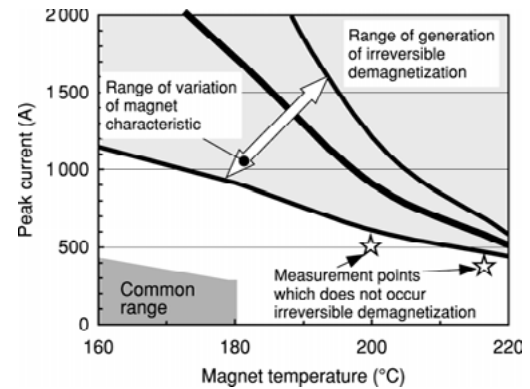


Fig. 7 Results of simulation of resistance to irreversible demagnetization

3.3.3. Ensuring rotor strength

As shown in Fig. 2, the salient pole SPM rotor utilized in the MCF21 is provided with hook sections extending from the salient pole section of the yoke to hold the magnet. This structure takes the burden of the centrifugal force exerted on the magnet with the hook sections and the strength of the magnet itself. Figure 8 shows the results of calculations conducted for a nonlinear structural analysis of the distribution of stress on the magnet and the yoke section.

In tests, the hook structures of the yoke designed on the basis of this analysis have demonstrated a fracture strength of more than 17 500 rpm.

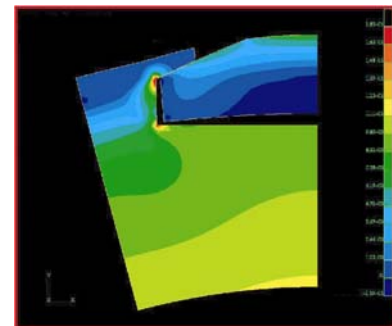


Fig. 8 Nonlinear analysis of salient SPM Rotor

However, because Nd-Fe-B magnets are constructed of brittle materials, conventional design methods used to ensure strength do not guarantee reliability. It has been shown that the fracture behavior of these magnets can be explained by weakest link theory. The probability of fracture of the magnets obeys a Weibull distribution, and it is possible to apply the Weibull theory to their strength characteristics⁽⁴⁾.

In the MCF21, this method was used to design a form which guaranteed a sufficient ratio of safety against the maximum stress to enable the reliability targets (probability of fracture) to be achieved. Consideration was also given to the drop in strength caused by degradation of magnetic strength demonstrated by fracture tests on magnets in the forms in which they will be used. Figure 9 shows a Weibull plot illustrating these concepts. The utilization of this method to develop technologies applicable to actual vehicles has made it possible to ensure strength in a surface-mounted permanent magnet without an anti-scattering cover, has increased the rate of utilization of the magnetic flux, and has contributed to a reduction in the amount of use of the magnet, thereby ensuring strength reliability in the high-speed rotor.

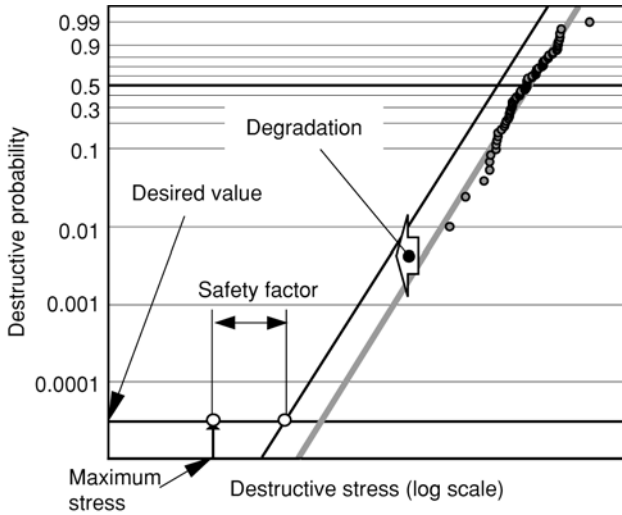


Fig. 9 Weibull plot for magnet strength

3.4. Setting Rotor Skew

Skewing the rotor magnet was one of various methods, including shaping the waveform of the magnetic flux, utilized to control the maximum phase current while increasing the bottom torque at 0 rpm. Skewing was achieved by dividing the entire rotor into two in the axial direction and setting the two pieces at different angles forward and backward in the direction of rotation. This structure is no more difficult to assemble in production than a structure with no skew.

As Fig. 10 shows, an area of skew angle was determined in which the combination of base torque ripple and skew angle produces the maximum results in terms of minimizing the drop in average torque with the lowest angle of skew. At identical conditions of bottom torque, the maximum phase current can ultimately be reduced by 14%.

At the same time, the electromotive force (maximum voltage) at maximum rotational speed has been reduced to contribute to the preservation of the high-voltage system. The average drop in the voltage of electromotive force caused by the skew is 2%, while a drop in peak voltage of 9% has been achieved.

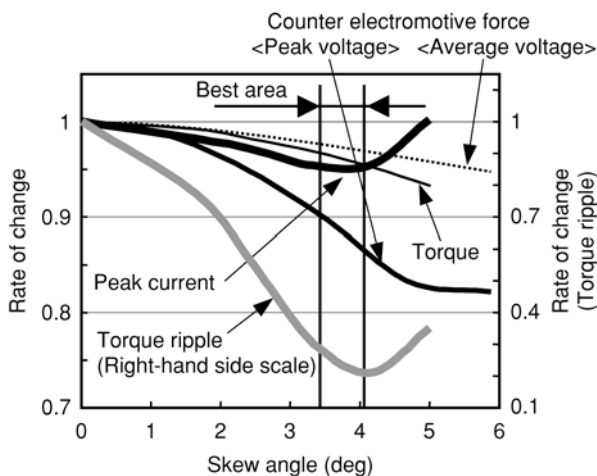


Fig. 10 Characteristic of torque, current and electromotive force by rotor skew angle (calculation)

3.5. Stator Cooling Technologies

To maintain high power over the continuous power range, copper loss has been reduced and the heat resistance of the stator has been lowered. Measurements taken in the heat paths from the winding to the water jacket on the exterior of the stator demonstrate that heat resistance is largely dependent on the area of the sections connecting the winding and the stator. The results of these measurements are shown in Fig. 11. On the basis of these results a balance was achieved between the amount of winding and the number and form of the slots required to reduce phase resistance (loss) and increase the area of the sections connecting the winding and the stator, thereby enabling target cooling performance to be achieved.

By this means, winding temperature is maintained within the allowable limits even when continuous current is flowing at the levels attained when torque reaches 200 Nm or when the motor is running at the maximum rotational speed, at which the current for field weakening is at its peak.

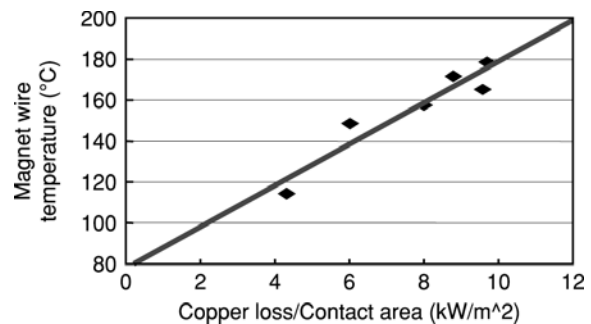


Fig. 11 Heat resistance

3.6. Motor Control

As mentioned above, full digital vector control has been adopted to provide motor control. To increase effective voltage at high rotational speed, the system switches to one-pulse control and does not perform pulse width modulation (PWM) switching, thus ensuring maximum power.

Control parameters are expressed in the form of a map. The use of an instantaneous analysis system for motor performance⁽⁵⁾ to determine the parameters reduced the time formerly required to formulate detailed map data by one-half, contributing to a reduction in the length of the development period.

4. Motor Performance

Table 2 shows the achieved performance of the MCF21. Maximum torque multiplied by maximum rotational speed is used as an indicator of the breadth of the power range of a motor. This measure is increased by 24% in the MCF21 over the MCF11.

Table 2 Motor performance

Type	MCF11 (EV PLUS)	MCF21 (FCX)
Maximum power (kW)	49	60
Maximum torque (Nm)	275	272
Maximum speed (rpm)	8 750	11 000
Max. torque x Max. speed (kNm rpm)	2 406	2 992
LA4 ave. efficiency (%)	90	93
Maximum efficiency (%)	96	97

4.1. Power

Test results show that the new motor has achieved a power outline following the targets set in development, with measurements of 60 kW for maximum power, 272 Nm for maximum torque and 11 000 rpm for maximum rotational speed. Continuous rated power was ensured below a torque of 200 Nm. Test results are shown in Fig. 12. Figure 13 shows a driving force curve for the fuel cell vehicle plotted on the basis of these results.

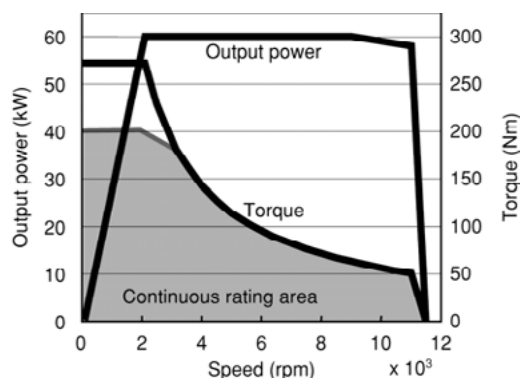


Fig. 12 Motor output performance

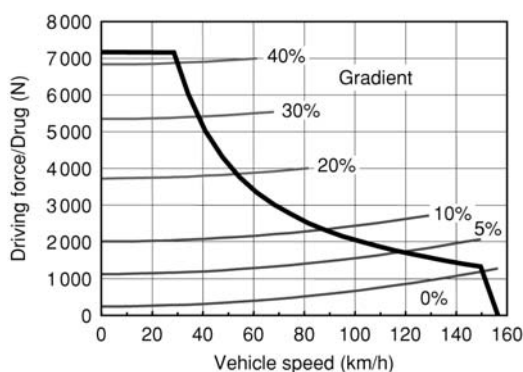


Fig. 13 Driving force curve

4.2. Efficiency

Figure 14 shows the results of measurements of the combined efficiency of the motor and the inverter used for traction, and the driving force locus in LA4 mode.

An average efficiency of 93% was measured when providing driving force in LA4 mode. This figure is a 3% improvement over the 90% efficiency of the MCF11 in the same mode, and this 3% increase in efficiency corresponds to a 30% reduction in loss.

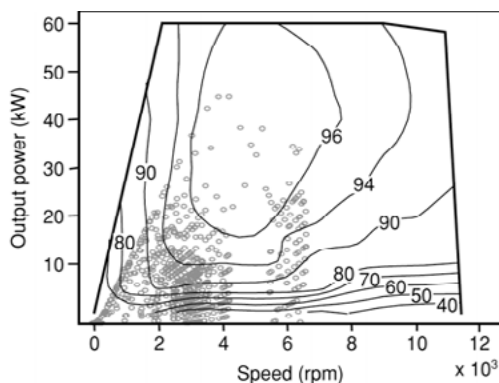


Fig. 14 Motor efficiency (including inverter efficiency) and driving force locus of LA4 mode

5. Conclusion

A new motor was developed and installed as a traction motor for a fuel cell vehicle.

- (1) By using power up to the voltage limit, high rotational speed was balanced with a high torque constant.
- (2) The high torque constant has centralized the efficiency of the motor in the low speed range, increasing efficiency in LA4 mode.
- (3) Skewing the rotors has controlled the maximum phase current when the motor is stalled, enabling the size of the inverter to be reduced.
- (4) The Weibull theory was applied to the strength of Nd-Fe-B magnets, enabling strength reliability to be ensured in a surface-mounted permanent magnet rotor.

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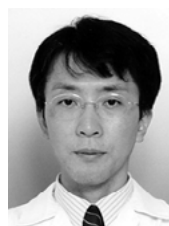
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