

Technologies for Low Iron-loss in New SPORT HYBRID i-DCD Motor

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ABSTRACT

The use of generally available materials for the electromagnetic steel sheets in a new motor for a one-motor SPORT HYBRID i-DCD has reduced costs, while the application of heavy rare earth-free magnets has assisted in the avoidance of procurement risk. The thickness of the steel sheets employed in the stator cores was increased from the previous 0.25 mm to 0.35 mm. The increased loss resulting from increased sheet thickness was responded to by modifying the number and position of the caulking dowels used in each stator core in order to reduce eddy current. Iron loss has also been reduced by machining corrugations into the inner circumference of the stator holder in order to reduce the contact area and thus reduce residual stress from press-fitting. In order to help ensure magnet heat resistance with the application of heavy rare earth-free magnets, the configuration of the magnets was changed from a parallel configuration to a V-shaped configuration fitted deep inside the inner circumference of the annulus formed by the rotor cores. In addition to this, the number of divisions of each magnet was changed from four divisions arrayed in the axial direction to two divisions arrayed in the circumferential direction, simplifying the production procedure and helping to realize a level of loss equivalent to that of the previous motor.

1. Introduction

The reduction of CO₂ emissions today, as a result of their environmental effects, is an important issue for the automotive industry, and the development of automotive electrification technologies is proceeding apace. However, given the fact that the cost of the main electrification-related components (motors, inverters, and batteries) remains high, from a global perspective electrification has still not widely spread. In 2013, Honda began to market a one-motor SPORT HYBRID i-DCD as a hybrid system within a set price range, allowing wide-spread use by a larger number of customers. The permanent magnet motor employed in this system (referred to as the “previous motor” below) was independently developed by Honda, and realized a high level of maximum efficiency (96% or higher). The use of 0.25 mm-thin, high-grade materials in the electromagnetic steel sheets employed in the previous motor realized low loss in the electromagnetic sections. However, the cost of thin, high-grade materials is expensive, and the global expansion of their use involves material procurement risks.

The FREED Hybrid that went on the market in 2016 therefore employed a newly developed motor (referred to as the “new motor” below). Employing generally-

available 35A270-grade electromagnetic steel sheets, low-loss technologies were developed in order to realize a high-efficiency motor.

In the previous motor, the heavy rare earths dysprosium and terbium were added to the magnets in order to realize a high level of heat resistance. Heavy rare earths are only mined in specific regions, and therefore represent a materials procurement risk. A heavy rare earth-free technology⁽¹⁾ was accordingly developed and employed in the new motor. This paper will discuss technologies employed to reduce iron loss in the stator and the optimization of the divisions in the heavy rare earth-free magnets.

2. Vehicle System and Motor Specifications

2.1. Vehicle System

The one-motor SPORT HYBRID i-DCD, in which the new motor is employed, features a 7-speed transmission with a built-in motor. The transmission system is compact enough to be fitted in a FIT-class vehicle. Salient pole concentrated windings featuring copper wire wound around split stator cores have been adopted as the winding method for the motor. The development was conducted with a view towards balancing the antagonistic demands of reduced size

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and increased efficiency. Figure 1 shows an external view of the transmission. By disconnecting the engine and the motor in response to driving conditions, the system is able to operate as a hybrid vehicle, driven by the engine and the motor, as an engine-driven vehicle, driven by the engine alone, or as an EV, driven by the motor alone⁽²⁾.

2.2. Motor Specifications

Figure 2 shows the configuration of the motor. Broadly speaking, the motor is made up of a stator and a rotor. The stator is connected to the transmission case, and plays the role of generating a rotating magnetic field by transmitting electricity from the inverter to the three-phase winding coils, continuously generating torque in the rotor.

In the stator component, the stator cores are made up of electromagnetic steel sheets laminated using caulking dowels. The stator cores are sandwiched between insulators in order to maintain insulation, and are wound with magnet wire. Following the formation of an annulus using 18 of the split cores, the unit is press-fitted into a stator holder to fix the stator cores in position (Fig. 3).

By contrast, because the rotor transmits torque to the transmission, it is formed by inserting an annulus, made up of magnets producing magnetic flux, into the interior of an annulus made up of rotor cores formed from electromagnetic steel sheets, which is then press-fitted onto a rotor shaft. The magnets are generally divided into multiple individual magnets in order to reduce loss. 48 magnets are employed in the new motor (Fig. 4).

Table 1 compares the specifications of previous motor and the new motor.

Table 1 Comparison of specifications

		Previous motor	New motor
Type		IPMSM	
Phase		3	
Number of poles		6	
Coil turns		55	
System voltage [V]		173	
Maximum motor power [kW]		22	
Maximum motor torque [Nm]		160	
Volume [L]		2.57	
Stator	Plate thickness [mm]	0.25	0.35
	Number of caulking points	2	1
	Holder	Press fit	Low-contact press fit
Rotor	Magnet layout	Axial: 4	Circumferential: 2
	Heavy rare earth magnet	Applied	Not-applied
	Number of magnets	96	48
	Magnet Br [T]	1.27	1.35
	Magnet H _{ej} [kA/m]	>2294	>1500

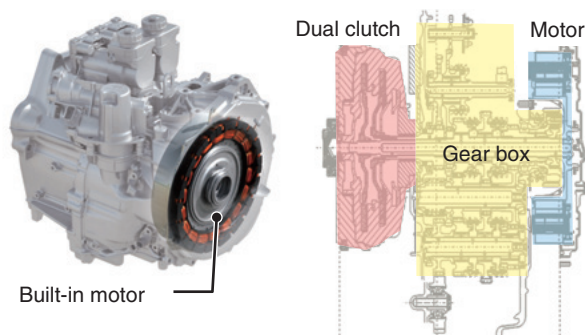


Fig. 1 Layout of 1-motor SPORT HYBRID system

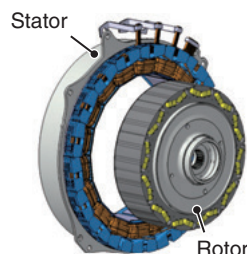


Fig. 2 Motor components

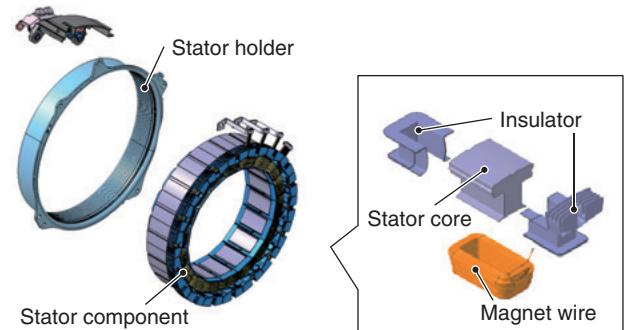


Fig. 3 Stator component parts

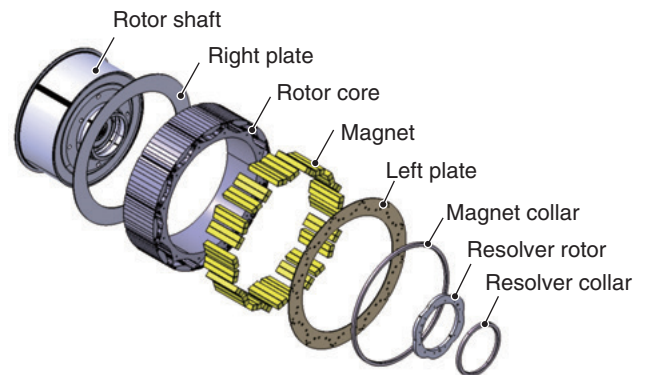


Fig. 4 Rotor component parts

3. Development Aims

In the previous motor, the stator cores were formed from 0.25 mm thick (thinner than 0.35 mm or 0.50 mm) high-grade materials in order to reduce iron loss. If it was possible to form the stator cores from more generally available grades of materials, it would help to ensure global procurability, and a cost reduction effect could be predicted. Looking towards global procurement, 0.35 mm 35A270-grade electromagnetic steel sheets have been employed for the stator cores in the new motor.

Iron loss in the electromagnetic steel sheets employed in the stator cores can be found using Eq. (1). Iron loss is the sum of the first term on the right-hand side of the equation, hysteresis loss, and the second term, eddy current loss, is affected by sheet thickness.

$$W = fB^{1.6} + f^2 B^2 t^2 \quad (1)$$

B : Flux density

f : Frequency

t : Thickness

Magnetic field analysis showed that increasing sheet thickness from 0.25 mm to 0.35 mm would increase iron loss during motor operation by 50% against the previous motor. The effect of this increase would reduce motor efficiency, potentially resulting in a decline in the fuel economy of the vehicle. It was therefore essential to employ technologies to reduce loss.

The employment of heavy rare earth-free magnets made it necessary to apply measures to realize heat resistance in the magnets. The magnet layout was therefore changed from the parallel layout employed in the previous motor to a V-shaped arrangement in which the magnets are fitted deep in the inner circumference of the annulus formed by the rotor cores. Reducing the magnet loss that is a factor in iron loss is possible. However, while loss is generally reduced in proportion to the fineness of the divisions in the magnets, increasing the number of divisions also increases machining costs. It is therefore necessary to balance reduced magnet loss with reduced machining costs.

The following two technological aims were therefore set in order to realize a level of iron loss in the new motor equivalent to that of the previous motor:

- (1) Realization of technologies for the reduction of iron loss in the stator
- (2) Realization of the optimal number of divisions in the heavy rare earth-free magnets

4. Technologies for the Reduction of Stator Iron Loss

4.1 Optimization of Caulking Dowel Shape

The stator cores are formed by the lamination of

electromagnetic steel sheets through which magnetic flux is readily able to pass. When the electromagnetic steel sheets are pressed, they are caulked using caulking dowels, helping to enable them to maintain their shape. As Fig. 5 shows, in the previous motor, two caulking dowels were positioned at a distance in each stator core in order to help control twisting when the cores were laminated.

In addition, the surfaces of the electromagnetic steel sheets were coated with an insulating film in order to help control loss by insulating the eddy current between the sheets. However, when the caulking dowels are pressed into place, the insulating film peels and neighboring sheets come into contact, resulting in eddy current loss occurring in the conducting sections.

As Eq. (1) indicates, eddy current loss is also greatly affected by magnetic flux density. Loss can be considered to further increase in the high-rotation range because frequency is high, and in the high-torque range because magnetic flux density is high. In the new motor, therefore, single caulking dowels have been positioned in the centers of the core teeth, where there is a minimal change in magnetic flux density, as shown in Fig. 6. The issue in employing single caulking dowels was a twisting of the cores when the electromagnetic steel sheets were laminated.

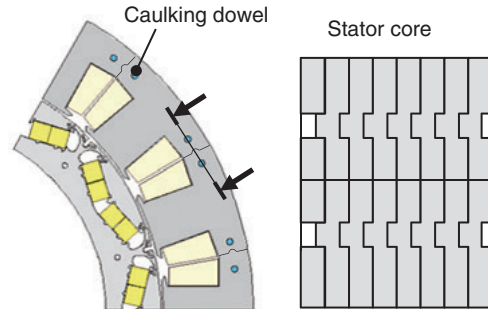


Fig. 5 Caulking dowels in stator cores

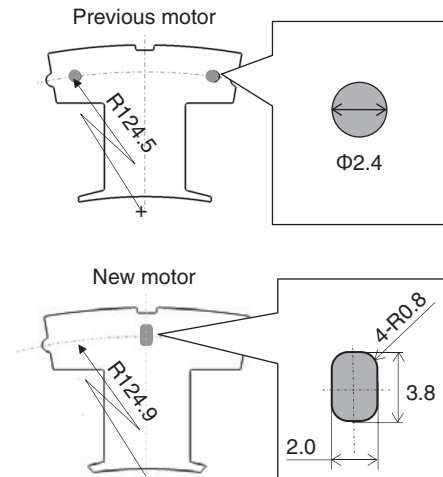


Fig. 6 Caulking shape

The shape of the caulking dowels was therefore changed from a circular to an oval shape. The use of a caulking shape having a width between two faces made it possible to constrain the direction of rotation of the divided stator cores.

Figure 7 shows the results of a magnetic flux density analysis at the points of maximum load frequency in JC08 mode. Positioning caulking dowels at points where magnetic flux density is low controls the fluctuations in

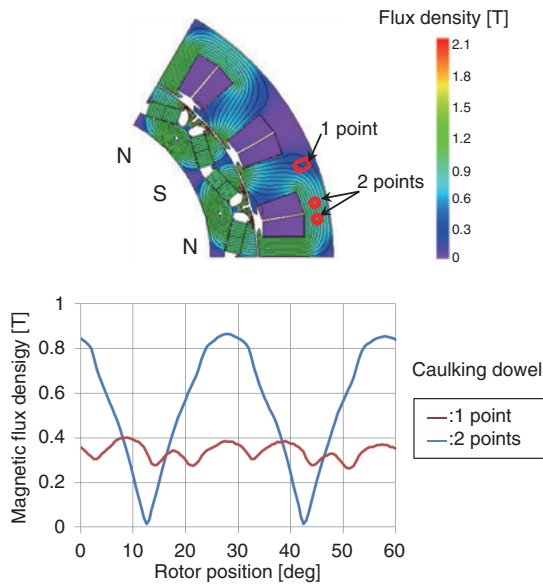


Fig. 7 Number of caulking points and results of analysis

magnetic flux density associated with rotor phase, reducing iron loss.

4.2. Low-contact Press-fitting

The stator employed in the new motor is formed by press-fitting an annulus formed from 18 divided cores into an annular stator holder. It is known that iron loss in electromagnetic steel sheets increases under compressive stress⁽³⁾, and it was therefore considered that reducing the number of sections in contact and thus limiting the number of high-stress areas would control overall loss to a low level.

In the new motor, corrugations have been machined into the press-fitted surface of the stator holder, and the stator core and the stator holder make line contact at the apices of the corrugations.

Figure 8 shows the results of a stress analysis of press-fitting stress in a stator core following low-contact press-fitting. While the contact areas in sections (5) and (6) in Fig. 8 display high compressive stress, compressive stress is low in section (1). A consideration of the overall compressive stress contours suggests that iron loss gradually increased with contact area. In addition, based on the results of calculation of iron loss in the stator cores for each stress distribution, it was estimated that low-contact press-fitting reduced iron loss by an average of 11% in the stator as a whole.

Figure 9 shows a photograph of a section of the internal circumference of an actually machined stator holder. Finishing and machining of the press-fitting surface of the stator holder has simplified the setting of the tightening margin between the stator holder and the stator cores when

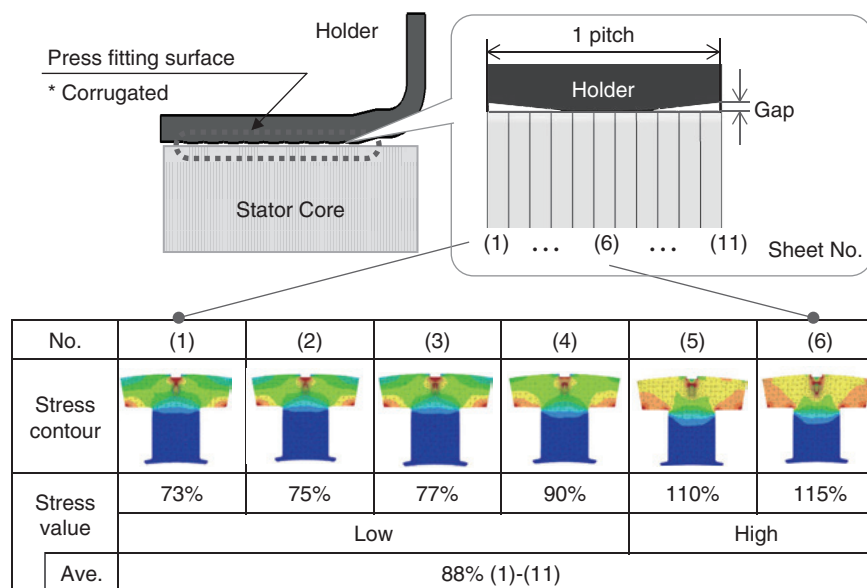


Fig. 8 Low-contact press-fitting characteristic

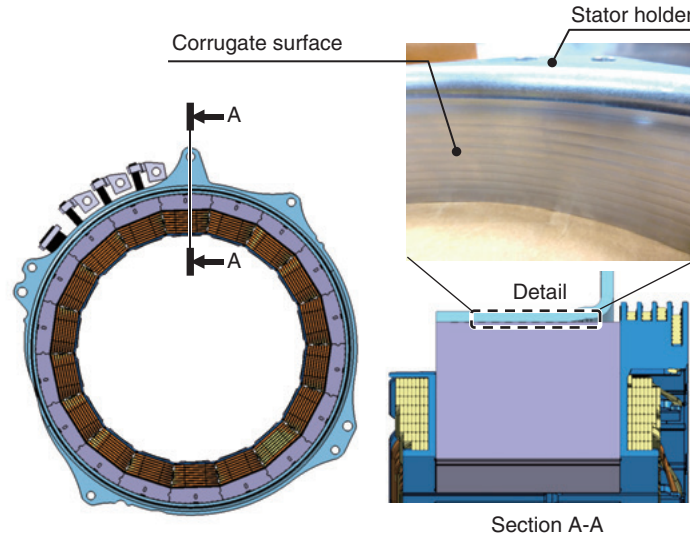


Fig. 9 Corrugated surface of stator holder

press-fitting. This has enabled to manage the tightening margin to the optimal setting for the necessary holding force and for iron loss.

5. Optimization of Divisions in Heavy Rare Earth-free Magnets

AS the use environment for the main traction motors fitted in automobiles features high temperatures and strong demagnetizing fields, a high level of heat resistance, i.e. holding force (H_{cj}), is demanded from the magnets used in the motors. A reduction in heat resistance represented an issue in using heavy rare earth-free magnets. This necessitated responses via the magnetic circuits⁽¹⁾, in addition to a reduction in the opposing magnetic field.

Increasing the number of divisions in a magnet is known to reduce internal eddy current loss in the magnet⁽⁴⁾. In the previous motor, magnets were divided into four and arrayed in the axial direction for each pole in order to control heat generation in the magnets, resulting in a total of 96 magnets. At the same time, because machining costs increase with the number of divisions in the magnet, it is also necessary to minimize the number of divisions.

Figure 10 shows a contour diagram of the eddy current generated in the interior of a magnet when an opposing magnetic field is imparted to it. As this diagram indicates, because the eddy currents generated in the interior of the magnet cancel each other out, there is a difference in the eddy currents in the interior and those at the ends of the magnet. Based on these results, it was considered effective to reduce the area receiving eddy currents generated in the interior of the magnet.

A parameter study using a three-dimensional magnetic field analysis was therefore conducted to help minimize

the number of divisions in the magnets and achieve the same level of iron loss as the previous motor. Based on the results, rather than dividing each magnet into four and arraying the parts in an axial direction, as in the previous motor, in the new motor each magnet was divided into two and arrayed in a circumferential direction, as shown in Fig. 11.

Figure 12 shows the results of magnetic field analyses conducted in order to determine the effect of the presence or absence of divisions in the magnets and differences in the arrangement of the divisions on iron loss in the magnets. The analyses were conducted at 7000 rpm and 30 Nm, conditions under which eddy current loss is at its maximum in the new motor. In addition to indicating that dividing the

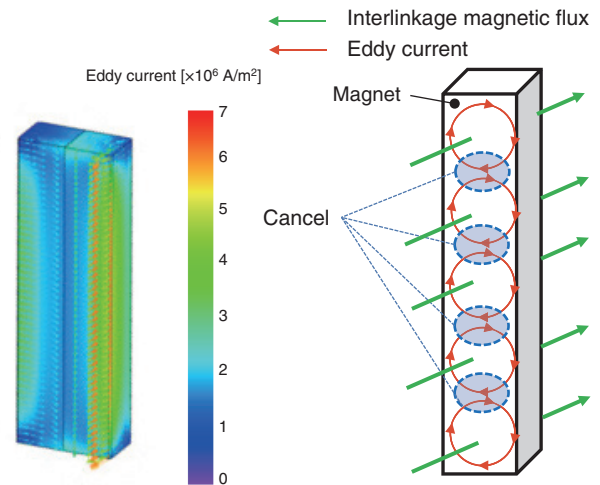


Fig. 10 Analysis of magnet loss

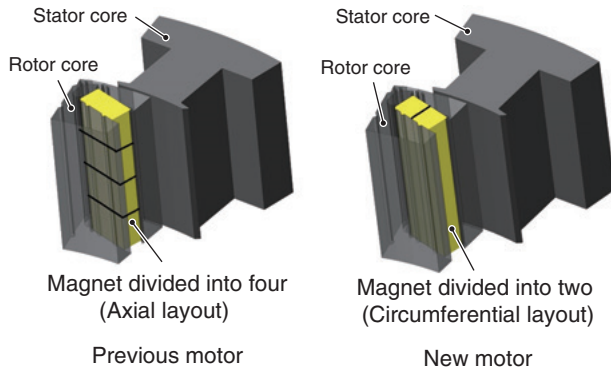


Fig. 11 Magnet division

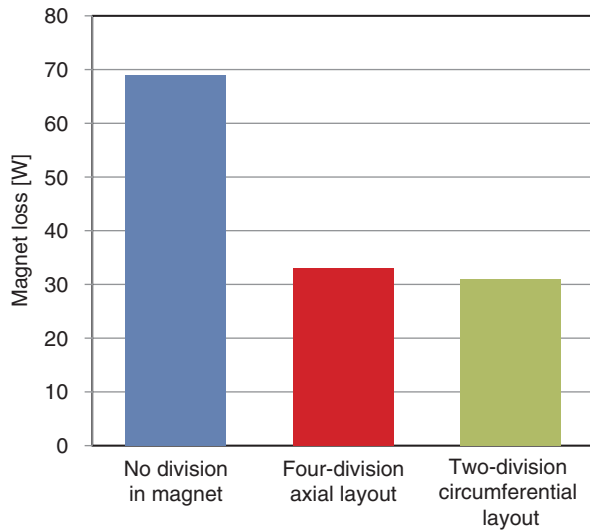


Fig. 12 Comparison of magnet loss

magnets halves iron loss, the results indicated that it would be possible to realize the same or a lower level of loss than the previous motor.

6. Results of Motor Loss Evaluation

Figure 13 shows a comparison of the results of motor loss measurements for the previous motor and the new motor. The depth of color shows the difference in loss when loss in the new motor is subtracted from loss in the previous motor. The new motor achieves the same loss as the previous motor in the JC08 fuel economy mode operating range. In addition, loss has been reduced against the previous motor in the high-loss high-rotation and high-torque regions.

Figure 14 shows the effect on motor loss during JC08 mode operation. Here, motor loss per unit time was integrated, and the previous motor was used as the base (100%). These results demonstrate that while the use of generally available materials for the stator cores increased

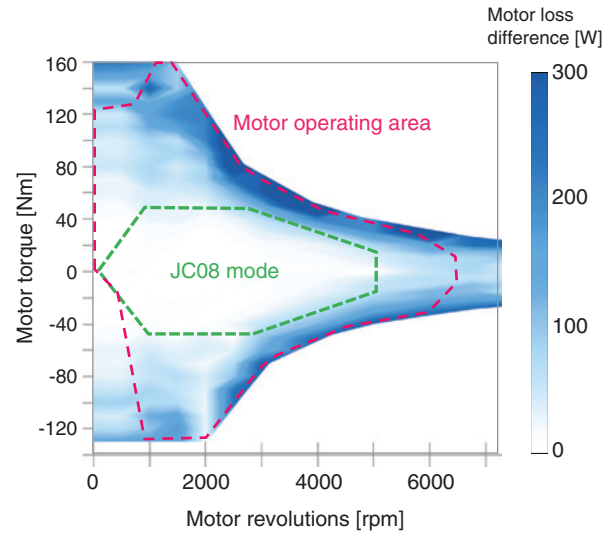


Fig. 13 Comparison of motor loss

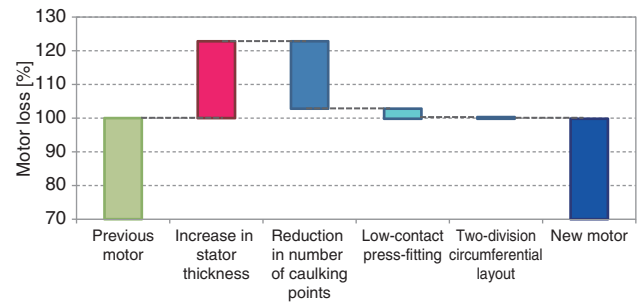


Fig. 14 JC08 mode motor loss

motor loss against the previous motor, the use of single caulking dowels and low-contact press-fitting, and the method of dividing the magnets, realized the same or a lower level of loss in the new motor as in the previous motor.

7. Conclusion

The employment of low-loss technologies in a new motor made it possible to realize the same level of loss as the previous motor in a framework of the same size without the use of heavy rare earths.

- (1) Iron loss was reduced by employing single stator caulking dowels in positions of low magnetic flux density. In addition, reduction of the number of contact points where the stator cores are press-fitted into the stator holder reduced loss by an average of 11%.
- (2) Optimization of the layout of the divisions in heavy rare earth-free magnets realized the same level of loss as the previous products using the minimum necessary number of divisions.

The use of generally available grades of materials in the electromagnetic steel sheets employed in the stator cores and the reduction of the number of divisions in the magnets reduced costs against the previous motor.

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