

Development of Electric Motor for “EV-neo”, Electric Motorcycle for Business Use

Naoki KOBAYASHI*

ABSTRACT

A new DC brushless motor, which has an equivalent driving performance to a 50 cm³ displacement scooter engine, has been developed to be equipped in a new electric motorcycle for business applications. The requirement for the maximum motor torque was mitigated by applying reduction gears and the drive unite that can be mounted on the wheel side was realized by reducing the size of the motor, together with the united structure of PDU (Power Drive Unit). In this motor, IPM (Interior Permanent Magnet) structure was implemented to cope with the high rotation speed of the motor, and the concentratedly wound stator coil was implemented for downsizing. The motor performances with the maximum power of 2.8 kW, the maximum torque of 11 Nm, the practical efficiency of 75% or more, and the maximum motor speed of 9000 r/min or more, were achieved, satisfying the specifications required for the drive train unit of business application motorcycles. In production processes, the split core stator structure and the bus rings for coil wiring were adopted to make it possible to manufacture them in the existing mass production facilities for the electric carts production, taking the cost reduction into good account as well.

1. Introduction

The developments of electric vehicles are under way as a means to reduce CO₂ emissions due to the growing concern on environmental issues in recent years. Ever since the start of mass-production of the electric scooter the CUV-ES (Fig. 1) in 1994, we have been continuing the researches for the technology of electric motorcycles up to now. Following that development, further enhancing the conventional techniques and know-how applied to the previous mass production model, we have newly developed the electric motorcycle EV-neo suitable for business applications in 2010 (Fig. 2). The specifications of the new and previous models are shown in Table 1. The new electric motorcycle employs the high-power lithium-ion battery to achieve a quick charge operation which

Table 1 Specifications of previous and developed vehicle models

	Previous model	Developed model
Dimensions L X W X H (m)	1.785 x 0.615 x 1.035	1.830 x 0.695 x 1.065
Vehicle mass (kg)	130	106
Rated output (kW)	0.58	0.58
Maximum power (kW)	3.3	2.8
Maximum torque (Nm)	9	11
Battery type (V-Ah)	Ni-Cd 86.4 V-20 Ah	Lithium-ion 72 V-12.6 Ah



Fig. 1 Previous mass production electric motorcycle (CUV-ES)



Fig. 2 Newly developed electric motorcycle (EV-neo)

* Motorcycle R&D Center

requires only 20 minutes from 0% up to 80% SOC (State of Charge), while the battery package also provides a satisfactory in driving power (discharging performance) and quick charging (charging performance) even in temperatures as low as -10°C . It achieved hill-climbing departure capability of 12-degree with a rider and a 30 kg load, which is comparable to a conventional scooter equipped with a 50 cm³ displacement gasoline-fueled engine. The motor introduced here was developed uniquely targeting the above-mentioned driving performances. In this paper, the technologies applied for this motor development and its performances are discussed.

2. Development Aims

Normally, attempts to realize an adequate driving distance in electric vehicles (EV) result in increased battery load, making the vehicles heavy and costly. Given this, it was particularly emphasized within the development requirements of EV-neo that it should achieve low weight and low cost. Consequently, the requirement for the driving distance should be met while employing the minimum battery load. Based on the above mentioned circumstances, the following were set as the main objectives for the development:

- (1) Reduction of size of drive unit
- (2) Realization of increased power efficiency
- (3) Realization of low cost

In the case of an ordinary engine-powered scooter, the power from the engine is transmitted to the rear wheel via a belt-converter-type transmission system. The belt converter with reduction gears was also used in the CUV-ES, which is the former model earlier mentioned (Fig. 3). For that reason, the motor had to be mounted in the same location as where the engine was originally mounted; hence the entire drive train unit was as bulky as that of an engine-powered scooter. In our development, we aimed at downsizing of the whole drive train unit and enhancing the transmission efficiency by elimination of a belt converter and downsizing of the motor. We also aimed at realization of low cost with increased productivity by employing such a structure that permits motor production to be carried out in the existing mass-production facility for the electric carts manufacturing.

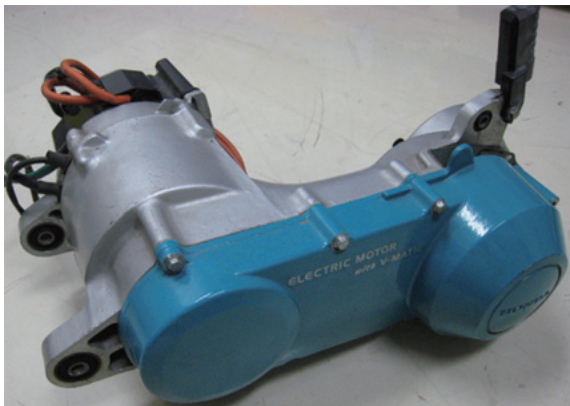


Fig. 3 External view of belt converter-type transmission

Table 2 Major specifications of new and previous motors

	Previous motor	Developed motor
Type	DC brushless	DC brushless
Magnets	Nd-Fe-B	Nd-Fe-B
Number of poles	4	8
Rotor type	SPM	IPM
Winding type	Distributed winding	Concentrated winding
Cooling system	Forced air cooling	Natural air cooling

3. Applied Technologies

Major specifications of the new and previous motors are shown in Table 2 and the entire drive train unit is shown in Fig. 4. Both motors are DC brushless type motors. Compared to the conventional SPM (Surface Permanent Magnet) structure, which was applied to the CUV-ES, the IPM (Interior Permanent Magnet) structure was chosen for the new motor as it excels in the efficiency and strength when spinning at high revolutions.

For cooling of the motor, we selected the natural air cooling assisted by the heat transfer to the drive train unit and by the headwind caused by riding forward. As a result, additional parts to cool the motor were unnecessary, and a weight increase was avoided.

3.1. Drive Unit Configuration

3.1.1. Use of coaxial clutch

The detail structure of the drive train unit is shown in Fig. 5. The automatic centrifugal clutch was employed to improve driving efficiency by avoiding operations in the low-revolution, high-torque zone where the motor efficiency lowers. Also, by avoiding a high stalling torque at 0 r/min, the currents in the motor and PDU are reduced, and temperature rises due to current are suppressed. As a result, the reliability in low-speed, high-load operations such as a start on an uphill slope was ensured without increasing heat resistance of the motor and PDU. Moreover, as the clutch separates the motor from the driving wheel after stopping, it is made easy to manually move the electric motorcycle when the power is turned off.

To downsize the drive train unit, the above-mentioned

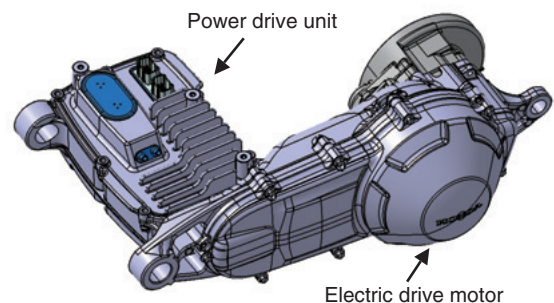


Fig. 4 External view of drive unit assembly (EV-neo)

clutch and motor were laid coaxially. The motor and the clutch were laid on the same axis by using a hollow shaft for motor rotor, inside of which the drive shaft passes through. The coaxial clutch and the downsizing of motor permit mounting of the motor on the wheel side while ensuring adequate lean angle of the vehicle, thus enabling high transmission efficiency and downsizing of the drive train unit.

3.1.2. Integration with PDU

The PDU and drive train were integrated into a single unit to downsize the drive train unit. As the coaxial clutch allows mounting of the motor on the wheel side, the PDU was installed in the space in front of the driving wheel and integrated into the drive train unit. This integration allowed the system to have the swingarm as an adequate heat mass for the natural cooling of the PDU, while, in the CUV-ES, air-cooling system was installed. Also, as the motor and the PDU were connected inside of the unit, the power lines were shortened over 50% from 500 mm to 240 mm. The transmission loss from the PDU to the motor was reduced by more than 50% compared to the system having a PDU separately on the vehicle body. Moreover, the integrated design allowed the elimination of wiring parts protection from excessive bending and the elimination of waterproof structure, which are necessary when wires are connected from outside of the unit. This structure also contributed to the reduction of cost by decreasing the number of parts necessary.

3.2. Increased Motor Speed

By applying the reduction gears to the motor while designing the motor to adapt to the high-revolutions,

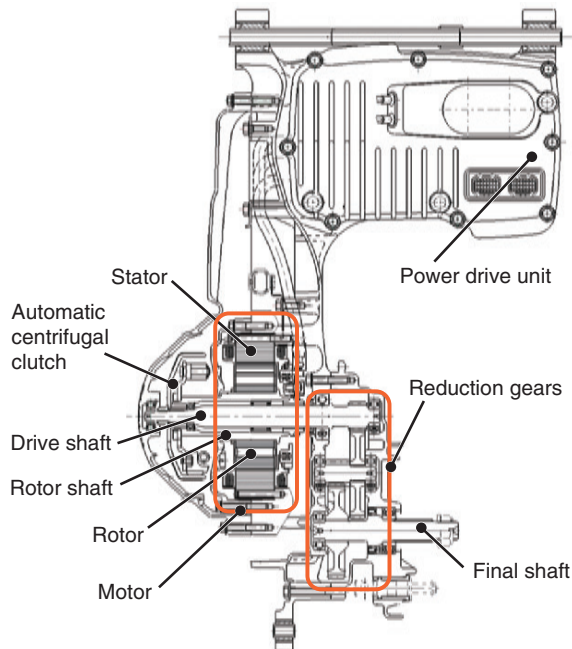


Fig. 5 Sectional view of drive train unit

downsizing and weight reduction of the drive train unit had been achieved.

Incidentally, when the main concern in the system design is focused on the increase of frictions in the drive train caused by the use of reduction gears, the in-wheel motor, which directly drives the wheel, may be one of the solution options. However, compared to a system using reduction gears, the in-wheel motor system requires a larger motor torque due to the limitations of reduction ratio.

In the case of a motor using the magnetic torque, in order to attain higher motor torque, it is necessary to increase the inter-linkage magnetic flux by the magnet and/or the number of poles, which causes an increase of motor outer diameter and/or the stator thickness. As more magnets, magnetic steel plate, and coils have to be used, the motor becomes bulky and its weight increases.

Consequently, we chose to provide the drive train unit with reduction gears and it was set as a target specification to have hill climbing capability of 12-degree carrying a rider and a 30 kg load. With that condition, the necessary torque on the drive wheel axle was 150 Nm. To attain this necessary axle torque considering the motor shape limitations demanded from the manufacturing equipments and the increased friction by the use of high revolution range, we chose the reduction ratio of 13.9, and set goals of maximum torque at 11 Nm and maximum motor speed at 9000 r/min.

3.3. IPM Motor

To eliminate the belt converter, it was necessary to increase motor revolution by 50% compared to the motor of the CUV-ES. Moreover, as efficiency enhancement is necessary across a broader revolution zone, we have chosen the IPM type motor which uses the reluctance torque in addition to the magnetic torque. To ensure rotor strength in high revolutions, the magnet for each pole was split into two pieces and was placed inside of the rotor yoke. Figure 6 shows comparison of SPM and IPM shapes in the rotor yoke and stator core. As for the rotor dimensions, the external diameter was increased by 10% compared to the CUV-ES rotor, and the magnetic flux needed to satisfy the maximum torque requirement was ensured by increasing the number of poles from four to eight. In addition, the shapes of the magnets were made thinner by using magnets

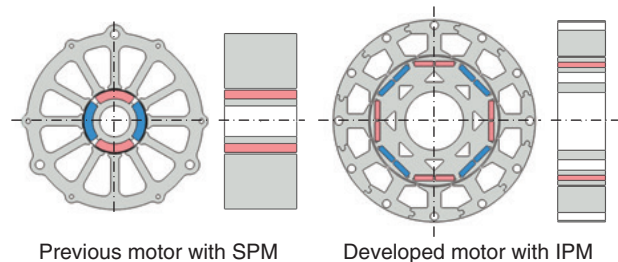


Fig. 6 Comparison of shapes between previous and developed motors

which had greater magnetic power by 7% than the magnets used in the CUV-ES, making it possible to keep the same volume of magnets as used in the CUV-ES, even though the external rotor diameter was increased.

3.3.1. Combined Use of Reluctance Torque

When the motor torque with combined use of reluctance torque is denoted as T_q , the torque constant of magnetic torque as K_t , the torque constant of reluctance torque as K_{rt} , the electric currents for d axis and q axis as i_d and i_q respectively, the inductances for d axis and q axis as L_d and L_q respectively, the number of pairs of magnetic poles as P_n and the electromotive force constant as K_e , the motor torque T_q can be expressed by the formulae (1), (2) and (3). The first term in the right side of the formula (1) indicates the magnetic torque, and the second term indicates the reluctance torque.

$$T_q = K_t \cdot i_q + K_{rt} \cdot i_d \cdot i_q \quad (1)$$

$$K_t = P_n \cdot K_e \quad (2)$$

$$K_{rt} = P_n (L_d - L_q) \quad (3)$$

In the motor with SPM structure, which is also applied to the CUV-ES, L_d and L_q are equivalent, and no reluctance torque is produced, i.e. only the magnetic torque is produced.

When the induced voltage in the motor exceeds the voltage of the power source during high-speed operation of the motor, it is necessary to apply field-weakening control in order to restrict the magnetic field generated by the magnets. However, as the application of field-weakening current for magnetic field restriction does not contribute to the torque generation, the efficiency of motor generally declines.

For motors with SPM configuration, in which magnetic torque is solely generated, it is necessary to suppress the increase of induced electromotive force when enhancing efficiency at high revolutions by reducing the field weakening current. Though an increase of induced electromotive force can be controlled by reducing K_e by changing the number of turns of coils, K_t also decreases at the same time as shown in the equation (2). This means that the efficiency in low-revolution with high-torque operations goes down because the decrease of K_t causes an increase of necessary current to produce torque, though the efficiency at high revolutions is enhanced. In the SPM-type motor using only the magnetic torque, it is therefore difficult to enhance efficiency across a wide revolution range.

Meanwhile in the case of IPM-type motor, which uses the reluctance torque in addition to the magnetic torque, the magnetic torque under the same current condition decreases because K_t decreases along with a decrease of K_e just like in the SPM-type motor. The decrease of magnetic torque, however, can be compensated by the reluctance torque indicated by K_{rt} . It is therefore possible to maintain efficiency at the time of low revolutions while preventing

lowering of efficiency in high revolutions resulting from the field weakening control. It is therefore possible to enhance the efficiency for wider revolution speed range compared to the motors with SPM structure because high revolution operation is feasible without depending on the field weakening control not sacrificing the efficiency at low revolution⁽²⁾.

From the equation (3), the reluctance torque occurs from the variance between L_d and L_q , and L_d becomes larger than L_q in the case of the IPM type. Accordingly, the reluctance torque can be added to the magnetic torque when the current phase angle is 90-180 degrees⁽³⁾. In the case of the new motor for EV-neo, by the modification of rotor shape, we have attained such a rate of reluctance torque that is more than 20% of the entire torque when producing the maximum torque. Figure 7 shows the results of the developed motor on magnetic field analysis of the current phase angle and the produced torque.

3.3.2. Rotor Strength

To make a motor to bear high rotation speed operation, rotor strength becomes an issue. In order to relieve the stress on the rotor yoke due to centrifugal force, the magnet for each pole was divided into two pieces, and those were positioned inside the yoke (Fig. 8). The number of positions designed for bearing the stress was increased from two to three by adding the center rib to the both ends of the

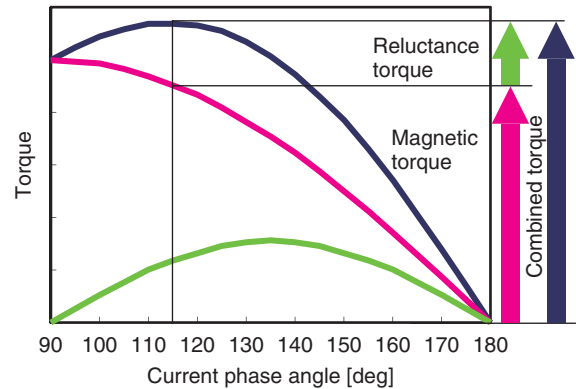


Fig. 7 Torque characteristics in relation to current phase angles

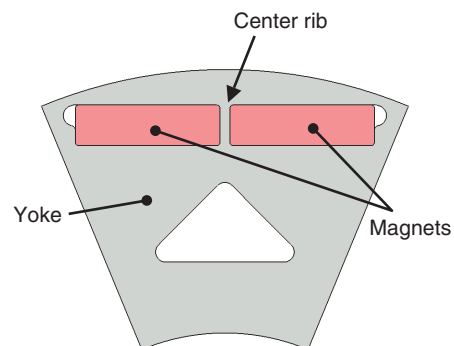


Fig. 8 Rotor structure

magnet. This made it possible to reduce the concentration of stress caused by centrifugal forces and to fulfill the requirement for the rotor strength at high revolution speed.

3.3.3. Elimination of Magnet Pasting

The efficiency of production had been enhanced by eliminating the process of pasting magnets to the rotor yoke and the cost was reduced by that. The use of adhesive was making the production efficiency enhancement difficult because it required the process controls for adhesive application and heat hardening. With IPM structure, which is adopted this time, magnets are maintained in the positions where they are originally inserted into the yoke because they are enclosed within the motor yoke. However, a clearance of around 0.1 mm is necessary between the rotor yoke and the magnets for insertion of the magnets, and the magnets can move within this clearance space. With this clearance, magnets can move and hit the rotor yoke repeatedly and that may result in cracks and wear on rust-prevention coatings applied to the magnets. In order to respond to this issue, a highly flexible nickel sulfamate coating was employed. To tackle this issue, the application of nickel sulfamate coating was intended and the conditions of application such as thickness of the coating were examined to meet the durability requirements by conducting vibration tests assuming accelerations and decelerations of the vehicle. By these measures, the feasibility was verified for elimination of the magnet pasting.

3.4. Concentrated Winding in Stator

Whereas the distributed winding had been adopted in the motor for the CUV-ES, the concentrated winding, which permits lowering of coil end height, was employed for the stator winding. Figure 9 shows the stator shape. With the employment of concentrated winding, the coil end height was reduced by 52% compared to that for the CUV-ES, contributing to the downsizing of the motor. In addition to the employment of concentrated winding, in order to make the motor shape suitable for mounting on the wheel side, the stator outer diameter was increased by 17% and the stator thickness was reduced by 31% from the motor of the CUV-ES (Fig. 10).

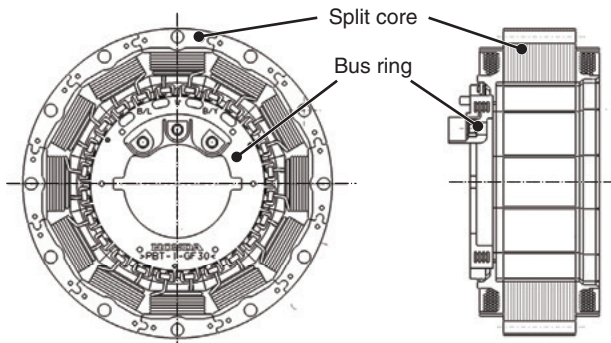


Fig. 9 Structure of stator

3.4.1. Split Core

To allow manufacturing using the existing motor mass-production equipment, the split core stator, which is the same structure as formerly developed motors, was employed⁽⁴⁾. The use of split core stator allowed application of the existing bobbin-type winding machine suitable for the concentrated winding. Also, when compared to the manufacturing of one-piece stator core, the split structure allowed the yield rate enhancement of material, and this contributed to cost reduction. The shape of the split core structure is shown in Fig. 11.

3.4.2. Self-bonding Wires

Self-bonding wires, which can be fixed to each other by adhesion after they are heated, were employed for the coils. Figure 12 shows a cross-section of a self-bonding wire. An

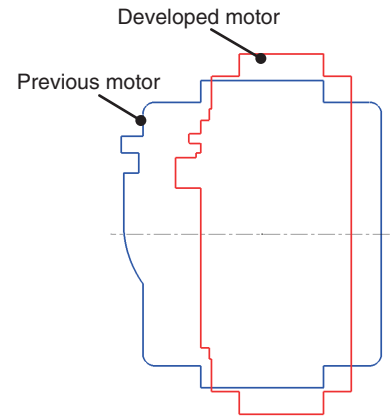


Fig. 10 Comparison of contours of new and previous motors

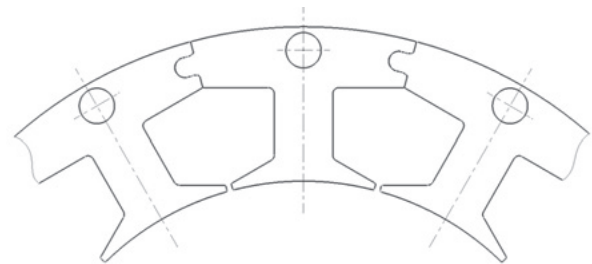


Fig. 11 Split core structure

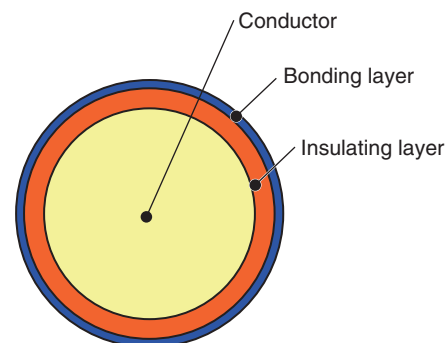


Fig. 12 Cross-section of self-bonding magnet wire

insulating layer is placed between a base layer formed by a conductor and an upper bonding layer. Wires of the coils can be fixed together by applying heat on the coils melting the uppermost bonding layer after the winding process. As the use of self-bonding wires had made it possible to dispense with the wire adhesion process using impregnated varnish, it was realized to increase the productivity by reducing the number of processes.

3.4.3. Bus Ring

To connect the concentrated-winding coils, the bus-ring was employed. Figure 13 shows structure of the bus-ring. The equivalent circuit, after completion of connection between coils and bus rings, is shown in Fig. 14, which shows the composition of four coils connected in parallel for each phase of UVW. By locating the bus-ring in the inner side of the coil ends, the thickness of the motor was reduced as an increase of motor thickness caused by connecting wires was reduced, enabling the miniaturization of electrodes in the bus-ring as well.

Fusion was used as the method to connect the coils and the bus ring. As Fig. 15 shows, firstly, the coil end is mechanically bound to the U-shaped section of the bus ring temporarily. Next, the heat generated by the prior current, which goes through in vertical direction in the figure between the poles, removes the films of the insulating layer. Following this, electrical bonding is completed

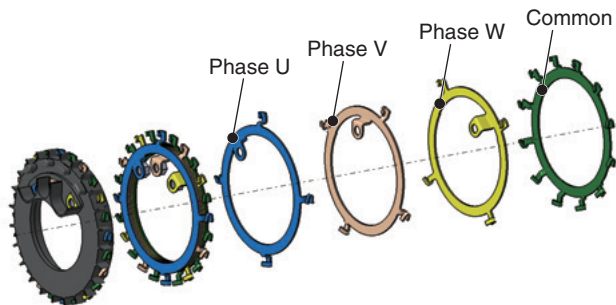


Fig. 13 Structure of bus-ring

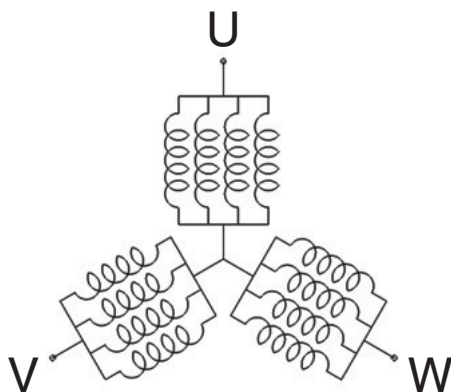


Fig. 14 Equivalent circuit for the motor

by fusing the surface of conductor by means of primary current. The application of fusing technique contributed to the enhancement of productivities through making the time required for wire bonding shorter by eliminating the process of removing insulating layers needed in other wire bonding methods.

As for the bus ring configuration, the exclusive design was implemented for the inner structure in which the creeping distances between electrodes of each phases are enlarged. This enabled the shapes of bonding portions to be the same structure commonly handled with bus rings used in exiting motors while enhancing the isolation performances. This made it possible to share the use of existing fusion equipment, resulting in cost reductions.

3.5. Rotation Angle Sensor

The employment of a Hall IC-type rotation angle sensor to the rotor and the application of PDU, with an error correction function to the detection angles, made it possible to eliminate the mechanical adjustments of sensor positions, increasing the productivity while reducing the working hours needed when sensor components are to be replaced. Figure 16 shows the detailed layout of the sensor. Hall IC-type sensors have the characteristic to produce errors when operated at high temperatures, and the sensor was therefore positioned on the opposite side of the clutch in order to

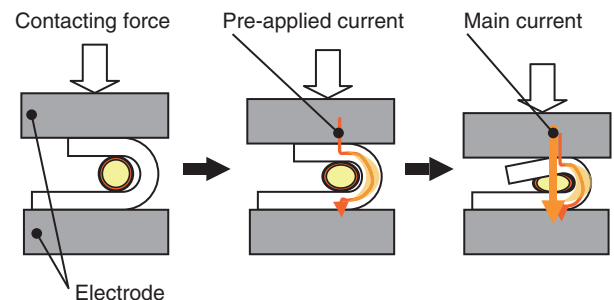


Fig. 15 Process of welding by fusing

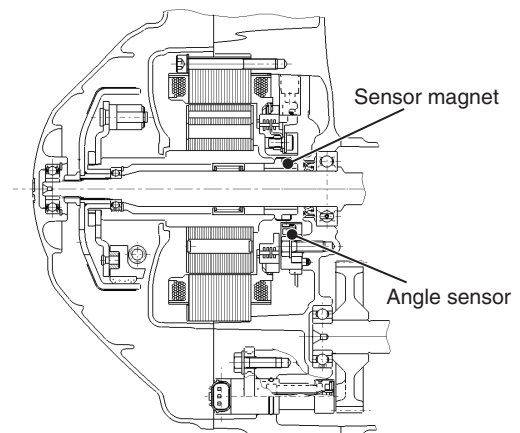


Fig. 16 Layout of angle sensor

ensure the reliability. By locating the ring magnets for the sensors on the inner side of the bus ring, any increase of the sensor dimension in the axial direction had been mitigated, contributing to the size reduction of the motor.

In brushless motors, the variations in output power and efficiency are derived from the angular sensing errors caused by the deviations in positions of installed sensors and/or positions of the magnetic phase of the sensor magnet, because the current control to the motor is performed referring to the index angular signals generated by the angular position sensor. In order to cope with this issue, the installation position of the sensor was mechanically adjusted for the motor used in the CUV-ES, and it was challenging to increase the productivity. In the EV-neo, the circuit, which compares the motor induced voltage waveforms with the sensor signals, was included within the PDU in order to detect angular errors, and it was made possible to correct these errors electronically in the process of the inspections for complete vehicles while increasing the productivity as well. This correction function contributes to the reduction of working hours when parts are replaced for maintenances as it is possible to adjust angle errors without dedicated tools.

4. Motor Performance

4.1. Output

With the above-mentioned techniques applied, we attained the target motor output performance; maximum power 2.8 kW, maximum torque 11 Nm, maximum motor speed 9000 r/min. Compared to the motor for the CUV-ES, the torque density was increased by 37%, and the motor weight was reduced by 11%. Figure 17 shows results of output measurement. With the increase of maximum torque by 22% and maximum motor speed by 52% compared to the motor for the CUV-ES, we achieved the following: the performance of the departure on a 12-degree uphill slope with a rider and a 30 kg load on the vehicle, and a maximum speed performance using the fixed reduction ratio without using a belt converter.

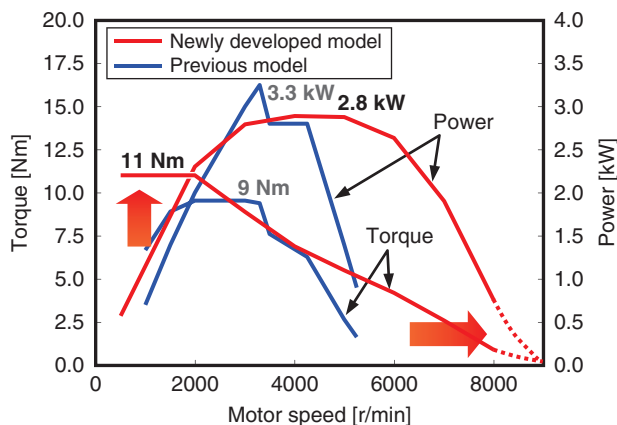


Fig. 17 Comparison of output performance for developed and previous motors

4.2. Efficiency

We attained the maximum motor efficiency of 92.7%, and 75% or higher efficiency in the actual vehicle operation zone. The result of confirmed efficiency is shown in Fig. 18. As the performance as a whole vehicle, the range of 34 km at a constant speed of 30 km/h was achieved, by reducing friction in the drive system through the elimination of a belt converter and the elimination of forced air cooling system together with the weight reduction by downsizing.

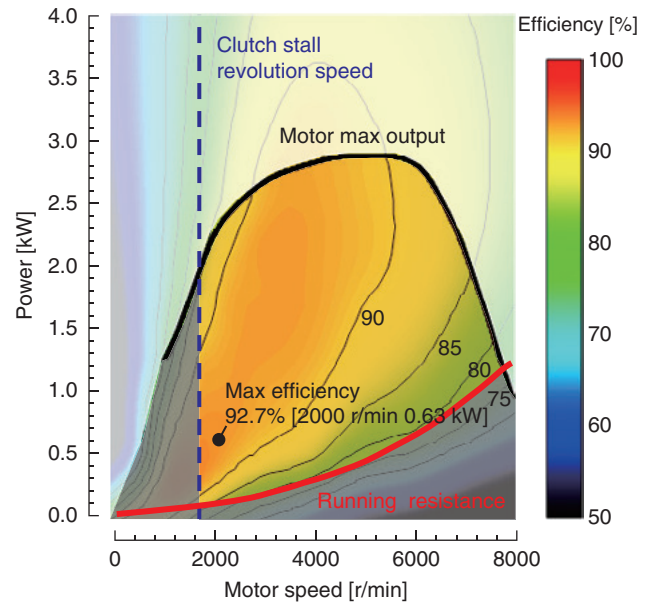


Fig. 18 Measured motor efficiency characteristics

5. Conclusion

The following has been achieved through the development of the motor for the electric motorcycle of business applications.

- (1) The drive train unit was downsized through the coaxial layout of automatic centrifugal clutch and motor, and the size reduction of the motor by adoption of concentrated winding to the stator coils.
- (2) A high-revolution motor was realized through the development of IPM motor, exclusively designed for electric motorcycles.
- (3) The cost reduction was achieved through the production efficiency enhancement by making the motor to be manufactured in the existing production facilities by adopting the same structure as the formerly developed motors, such as split core stators and bus rings for coil wire bonding.

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■ Author ■



Naoki KOBAYASHI