EV Traction Wound Field Synchronous Motor

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Abstract

The Electric Vehicle (EV) traction motor is required to improve its efficiency in a low-torque region where the EV is driven frequently. Compared with an Interior Permanent Magnet Synchronous Motor (IPMSM) currently used as an EV traction motor, the Wound Field Synchronous Motor (WFSM) is capable of rotor magnetic flux control using current flow in the windings arranged around the rotor in place of permanent magnets. It is, therefore, possible to expect an improvement of efficiencies in the low-torque region and extension of the constant output range with the WFSM. In addition, there is no concern regarding the supply of rare earth materials because no permanent magnets are used.

In order to verify the advantage of the WFSM, we compared the performance characteristics with the IPMSM of a 100 kW class by electromagnetic field analysis. As a result of the comparison of maximum torque performance and efficiencies, we confirmed that efficiencies were improved in the medium- and high-speed low-torque region, although the torque range was somewhat lowered by a few percent.

1 Preface

For the Battery Electric Vehicle (BEV) and the Hybrid Electric Vehicle (HEV), the improvement of efficiencies is especially required in the low-torque output region where the traction motor is operated frequently, while characteristics of low speed and high torque are maintained and a wide constant output range is secured. The Interior Permanent Magnet Synchronous Motor (IPMSM) is currently widely used as a driving motor because of its high efficiency and high output. As shown however, in Fig. 1 for a Conceptual Diagram of Variable Flux Function, the maximum efficiency yielding point is located in the middle-speed torque region. Accordingly, the maximum efficiency yielding point is apart from the frequent motor driving region and is a difficult issue for maintaining high-efficiency operation. A solution for this issue, adopting a variable flux motor that is capable of switching to an optimal field magnetic flux in compliance with the present operating region is effective. A candidate selected for such a motor is the Wound Field Synchronous Motor (WFSM). Fig. 2 shows a WFSM. As a magnetic field source, this type of motor has a rotor structure where field windings are used in place of permanent magnets. The field magnetic flux can be controlled by a DC current carried from an external circuit.

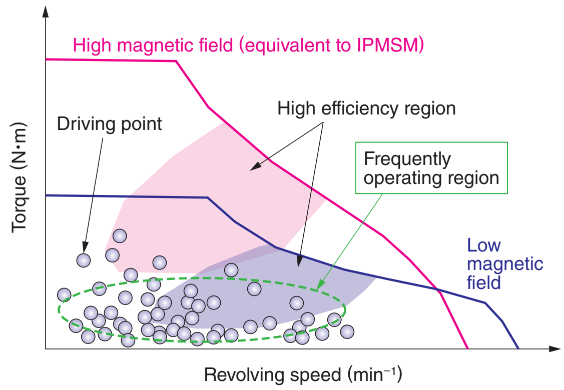

Fig. 1 Conceptual Diagram of Variable Flux Function

During driving, in the frequently operating region, the high efficiency region of the IPMSM shows a large divergence. In a high magnetic field equivalent to the IPMSM, high torque and output can be obtained but cannot be maintained in a high revolution region. Conversely in a low magnetic field, operation is possible in a high revolution region under the same input power condition, though output power is lowered. Since iron loss is lowered, efficiencies in the low-torque region is improved. By making regulation of the field magnetic flux, both driving performance and efficiencies can be favorably maintained.

Recently, research activities have focused on

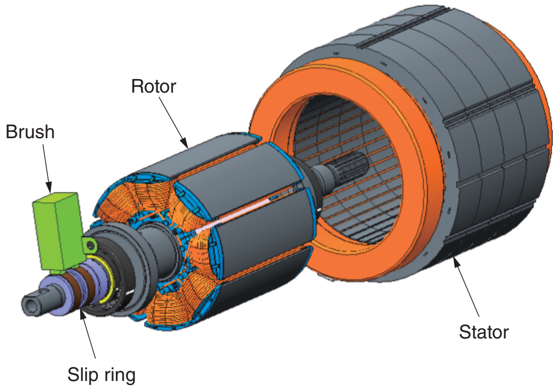

Fig. 2 WFSM

External appearance of the WFSM is shown.

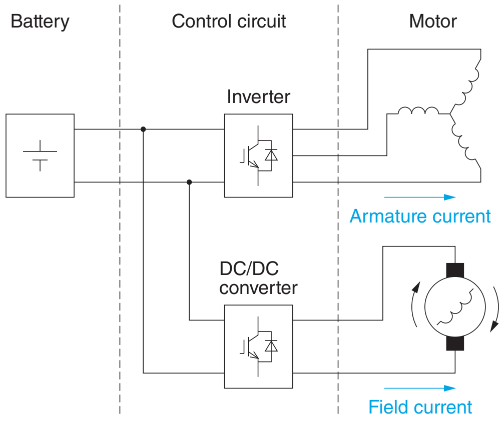

Fig. 3 Driving System of WFSM

The motor is driven by supplying the battery power to the stator and rotor through a control circuit.

the improvement of torque density and efficiency for the WFSM. There is a case when the WFSM is used as an EV traction motor[(1)]. This paper introduces our R&D activities where the WFSM characteristics only for the rotor designed by the field winding system are calculated by the magnetic field analysis method for comparison with the IPMSM of a 100 kW class. We will also show the result of comparison of performance characteristics between the two motor technologies.

2 Characteristics

To the IPMSM, the WFSM is superior as itemized below.

(1) Variable magnetic flux function efficiency is improved in the medium- and high-speed low-torque regions.

(2) The variable magnetic flux function range of constant output can be extended.

(3) There is no concern regarding the supply of materials (rare earth metals) for permanent magnets.

There are some issues, however, that efficiencies in low-speed high-torque regions, due to the effect of copper losses in field windings, a reluctance torque tends to be low because of the limitations of the core shape and the maximum torque per unit volume is low.

3 Specifications

3.1 Driving System

Fig. 3 shows the driving system of the WFSM. A three-phase inverter is used to supply stator armature currents by a conventional method and DC currents regulated by a DC/DC converter are fed to the field windings set around the rotor. Since currents are fed to the rotating body, brushes and slip rings are used for the supply of field currents. For this reason, there is a possibility of increasing the casing volume to secure a room to accommodate these brushes and slip rings.

3.2 Motor Specifications

Table 1 shows the specifications and contents of the design of the motor used for analysis and

Table 1 Specifications and Contents of Design

Motor specifications after comparison and study plus contents of design are shown.

	Item	IPMSM	EESM
Specification	Maximum torque	200 N·m	
	Maximum output	100 kW	
	Maximum revolving speed	12,000 min^{-1}	
	Maximum armature current	340 A_{rms}	
	Maximum DC voltage	350 V	
	Maximum field current	—	15 A
Design	No. of poles	8	
	No. of slots	48	
	Stator core outer diameter	200 mm	
	Rotor outer diameter	128.6 mm	
	Core length	100%	107.5%
Electromagnetic steel sheet characteristics	Layer sheet thickness	0.35 mm	
	Iron loss density W10/50	0.91 W	
Rotor	Field source	Permanent magnet (NdFeB)	Field winding
	Cooling system	Air-cooling	Oil-cooing

Fig. 4 shows the analytical model. The basic IPMSM is designed to use a rotor core where permanent magnets are embedded in a V-shaped formation. For the WFSM analysis, the shape of the stator cross-section is made identical with that of the IPMSM and only the rotor is replaced by the externally excited type of design. Since the WFSM is subject to a reduction of torque density due to a decrease in the inductance ratio, the core length is extended. For the cooling of the WFSM field windings, adoption of air cooling or oil cooling is considered adequate for structural reasons. In the case of air cooling, however, a substantial increase in the overall volume of casing is anticipated. Consequently, we are promoting a mechanical design on the basis of the oil-cooling method.

Optimization of teeth width is carried out as shown in Fig. 4 (b). Fig. 5 shows the result of teeth width optimization. If the teeth width is extended, the magnetic reluctance is lowered in the magnetic path of the rotor while the number of coil turns is decreased because the slot area is narrowed. As a result of this optimization approach, we suppressed the increase in the core length to 7.5%.

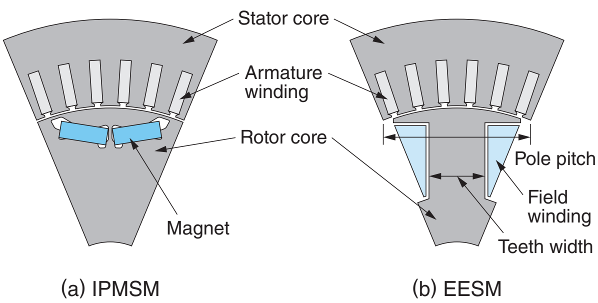

Fig. 4 Analytical Model

An analytical 1/8 model used for field analysis is shown.

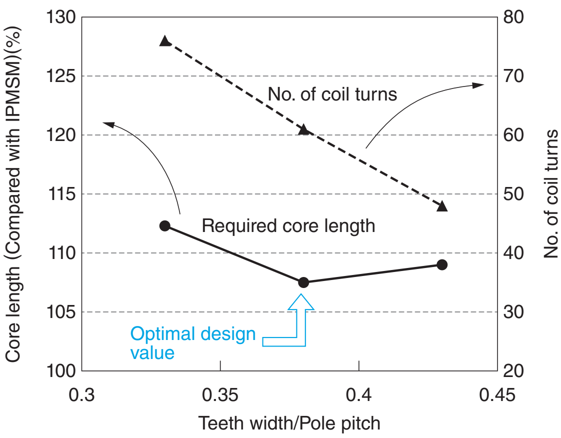

Fig. 5 Result of Teeth Width Optimization

The number of coil turns and changes in required core length are shown when the teeth width is changed as shown in Fig. 4. The teeth width when the required core length becomes minimum is deemed an optimal value.

4 Result of Analysis

4.1 Current Control

In the same manner as for conventional IPMSMs, the armature current phase is controlled to a maximum torque in the vicinity of a maximum torque value and maximum efficiency control is performed in other regions. If the resultant voltage by these controls should exceed the limit level, flux weakening control is then carried out. In the case of the WFSM, optimal control for field currents is carried out in addition to the armature current. Fig. 6 shows this optimization of the field current. In this figure, the changes in motor efficiencies when the field current is changed are shown, observed at several operating points in the low-torque region. Since there is an operating point where efficiency is maximized by the effect of the field current, it is necessary to perform optimal control of armature and field currents.

4.2 Maximum Output Performance

Fig. 7 shows maximum torque curves when armature currents, field currents, and DC voltages are limited. It is recognized that both IPMSM and WFSM satisfy the maximum torque and output as specified.

4.3 Efficiencies

Fig. 8 shows an efficiency differential map.

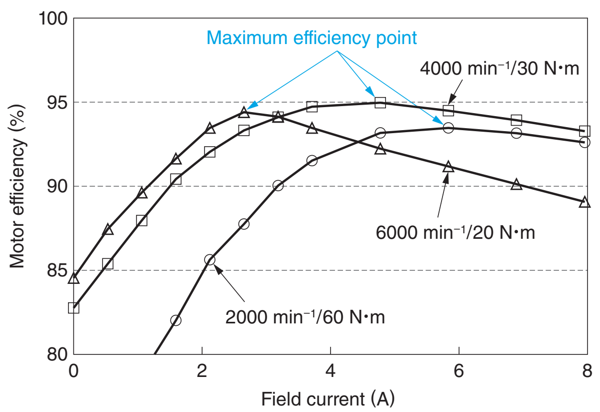

Fig. 6 Optimization of Field Current

Changes in efficiency in compliance with field current is shown. A field current to yield a maximum efficiency is selected.

Efficiencies of overall unit, including the motor and the control circuit, are calculated for the IPMSM and WFSM respectively, so that the amount of changes in the WFSM from the IPMSM can be defined. Since iron loss is reduced by the effect of the variable field function, efficiencies are improved in the medium- and high-speed low-torque region. Conversely, efficiencies worsen in the low-speed high-torque region because the effect of an increase in copper losses in field windings becomes greater. Even in the high-speed medium-torque region, however, efficiencies are improved by virtue of reduction of a weaker field current and harmonics-related magnetic flux.

Fig. 9 shows the efficiency difference between the WFSM and IPMSM at a 10% torque (20 N·m) where the operational frequency is generally high during driving and **Fig. 10** shows the contents of losses for the WFSM and the IPMSM, respectively. Although the ratio of copper loss to inverter loss is

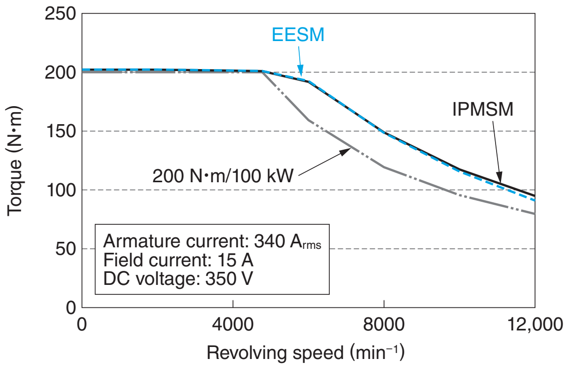

Fig. 7 Maximum Torque Curves

Torque curves are shown for the outputs available when armature current, field current, and DC voltage are limited. The specified output performance is satisfied.

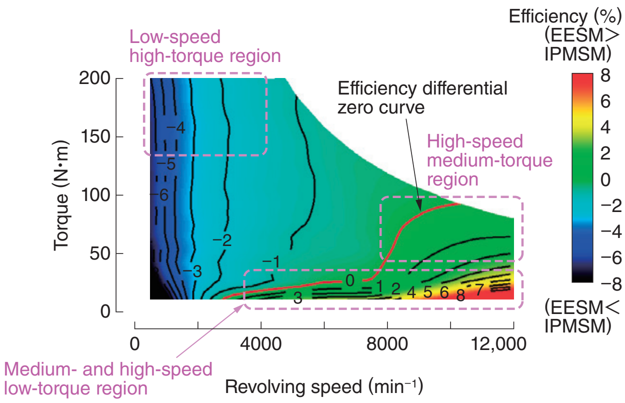

Fig. 8 Efficiency Differential Map

A difference in efficiency between the WFSM and IPMSM is shown. The value is on the lower-torque side of the efficiency differential zero curve and the WFSM is superior to the IPMSM.

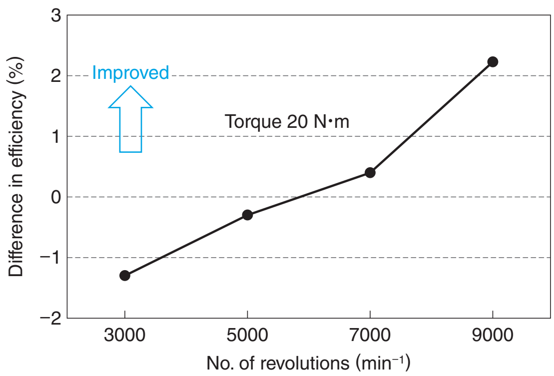

Fig. 9 Efficiency Difference in Low-Torque Region

Difference in efficiency of WFSM to IPMSM is shown at a 10% torque (20 N·m). Efficiencies are improved in higher-speed region.

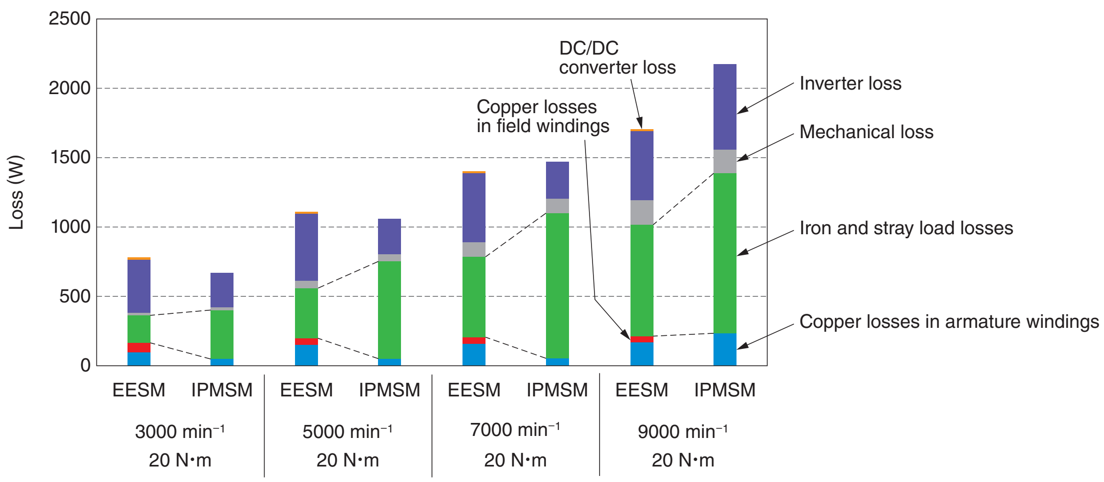

Fig. 10 Contents of Losses in Low-Torque Region

Contents of losses in the WFSM and IPMSM are shown at a 10% torque (20 N·m). In the WFSM, iron loss and stray load losses are reduced.

relatively high in the WFSM, the ratio of iron loss to stray load loss is conversely lowered. As a result, efficiencies are improved in the high-speed region where iron loss is predominant.

5 Postscript

As a result of the comparison of performance characteristics between the WFSM and IPMSM, the following result is obtained:

(1) Compared with the IPMSM, efficiencies of the WFSM tend to worsen in a lower-speed higher-torque region. Despite this, efficiencies are improved in the medium- and high-speed low-torque region. For this reason, the WFSM is suitable for frequent use in this region and for applications to motor operation that often causes dragged rotation.

(2) Due to the effect of reluctance torque reduction and magnetic saturation, the core volume is increased by 7.5% compared with the IPMSM when the same output power must be assured. If a space for brushes and slip rings used to supply field current is considered, the overall volume of casing is expanded. It is, therefore, necessary to provide for some allowance in the equipment installation space.

As described, the WFSM involves some issues: volume expansion and efficiency deterioration in some characteristic regions. There are, however, possible advantages over the IPMSM in terms of applications and stable cost; so it is, therefore, a candidate as an EV traction motor.

《References》

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(2) S. Sakurai, T. Suwazono, T. Mizuno, K. Nagata, T. Ashikaga: "Performance Comparison Study of Wound Field Synchronous Motor and Interior Permanent Magnet Synchronous Motor," EVS 31 & EVTeC 2018, No.20189411