HEV Motor Comparison of IPMSM With Nd Sintered Magnet and Heavy Rare-Earth Free Injection Magnet in the Same Size

Yo-Han Hwang and Ju Lee

***Abstract*—In the near future, usage of heavy rare-earth element needs to be reduced, due to resource risk and rising price with vehicle electrification. This paper compared two hybrid electric vehicle traction motors of the same size using Nd sintered magnet and heavy rare-earth free magnet. We designed two interior permanent magnet synchronous motors varying only the rotor design and material. A new motor was developed using heavy rare-earth free magnet with performance and size equal to Nd sintered motor. The rotor shape was designed as the one of a synchronous reluctance motor to overcome the lack of heavy rare-earth free motor torque. The motor performance was verified with a series of experiments.**

***Index Terms*—Traction motor, EV, HEV, heavy rare-earth free, Dy free, IPMSM.**

I. Introduction

THE current generation of home electric appliances and electric vehicles/hybrid electric vehicles (EVs/HEVs) uses interior permanent magnet synchronous motors (IPMSMs)that contain rare-earth permanent magnets [1].

The IPMSM has high efficiency, a high power factor, and a high power density. However, rare-earth permanent magnets containing dysprosium (Dy) and terbium (Tb) are expensive and there is concern regarding the stable supply of rare earth materials. On the other hand, a synchronous reluctance motor (SynRM) is driven by reluctance torque [2]. The SynRM does not use permanent magnets, and so sacrifices torque density, power factor, and efficiency compared to the PMSM. However, by adding a proper quantity of PM to the SynRM, the torque density and power factor of the SynRM can be improved. Such motors are referred to as permanent magnet assisted synchronous reluctance motors (PMASynRMs) [3].

The leading rare-earth magnet deposits are not distributed evenly, however, with production in recent years limited to the countries [4]. Further, heavy rare-earth elements usage needs to be reduced because of the risks and cost of working with such a scarce resource. Without heavy rare earth added, Nd magnet will have reduced Hcj, Br. Therefore, to use heavy rare-earth free magnet, engineers need to find ways to overcome this problem. In this paper, we designed IPMSM with heavy rare-earth free magnet by using PMASynRM shape. In this study, Aichi Steel Co. Mag-Fine (MF) heavy rare-earth free bonded injection magnets was used as the magnets of the IPMSM. This study investigated the rotor structure on the performance of the IPMSM with heavy rare-earth free magnets. Generally Nd sintered magnet use Dy, Tb, Ga for diffusion treatment. However Mag-Fine Magnet use Cu, Al for diffusion instead of Dy, Tb, Ga. This is a characteristic of Mag-Fine Magnet.

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TABLE I
Specifications of the Nd Sintered IPMSM and Target of the Heavy Rare-Earth Free Motor

Division	Target
Number of poles	10
Number of slots	60
Max power [kW]	31
Max torque [Nm]	200
Stator internal diameter [mm]	113
Stator external diameter [mm]	160
Stack length [mm]	120
Air gap [mm]	0.6
Max input current [Apk]	340
Torque ripple @Max torque [%]	5↓
Torque ripple @Max rpm [%]	10↓

II. Design of the IPMSM Rotor Structure With Heavy Rare-Earth Free Magnet

A. Nd Sintered IPMSM Model and Specifications

In this paper, motors have same stator but different rotor structure and magnet. Table I shows specifications of the Nd sintered IPMSM. Heavy rare-earth free magnet motor target is same as IPMSM with the Nd sintered magnet.

Fig. 1 is IPMSM rotor core model and real motor sample with Nd sintered magnet.

B. Heavy Rare-Earth Free IPMSM Concept Design

Table II shows Br and Hcb of the Nd sintered magnet and heavy rare-earth free magnet.

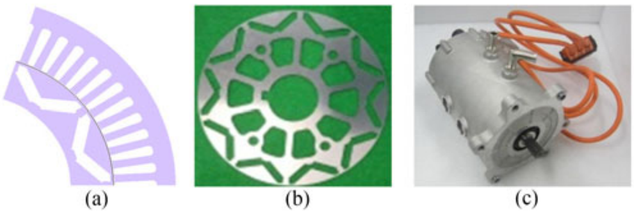

Fig. 1. IPMSM motor with Nd sintered magnet. (a) Rotor core model. (b) Rotor core sheet. (c) IPMSM ASM.

TABLE II
COMPARISON OF THE MAGNETS

Division	Nd Sintered magnet	Heavy rare-earth free magnet
Magnet Br [T]	1.31	0.67
Magnet Hcb [kA/m]	987	478

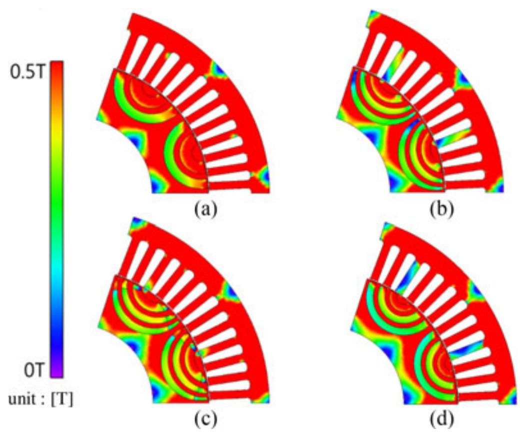

Fig. 2. Concept rotor models for heavy rare-earth free motor. (a) 2-layer. (b) 3-layer of different thickness. (c) 3-layer of different thickness and barrier. (d) 3-layer of same thickness.

TABLE III
COMPARISON OF THE CONCEPT MODELS

Division	(a)	(b)	(c)	(d)
Torque [Nm]	182.2	183.5	166.2	182.4
Magnet Volume [mm^3]	288,350	295,680	247,370	290,660
Ripple [%]	4.45	9.98	8.13	6.96

There are models of concept design for IPMSM with Heavy rare-earth free magnet in the Fig. 2. SynRM rotor shape was used to overcome the lack of heavy rare-earth free motor torque. Table III shows performance and magnet volume of concept models.

We selected model (a) concept among the concept models, because (a) model's torque and ripple is better than others, have lowest magnet volume. In the case of 3-layer structure, it was hard to satisfy the target performance due to the given rotor size is small. And magnets have demagnetization points.

Table IV and Fig. 3 Shows the correlation between design variables. As the results, torque is not dependent on magnet volume. Model M1, M5, M6 has high torque, among them M1 model magnet volume is small.

TABLE IV
CORRELATION BETWEEN DESIGN VARIABLES

Division	Layer	Magnet volume [mm^3]	Torque [Nm]	Ripple [%]
M1(a)	2	288,350	182.2	4.45
M2	2	317,340	178.5	3.24
M3	2	340,400	175.1	4.48
M4	2	337,070	175.3	5.70
M5	2	316,500	184.2	3.30
M6(d)	3	290,660	182.4	6.96

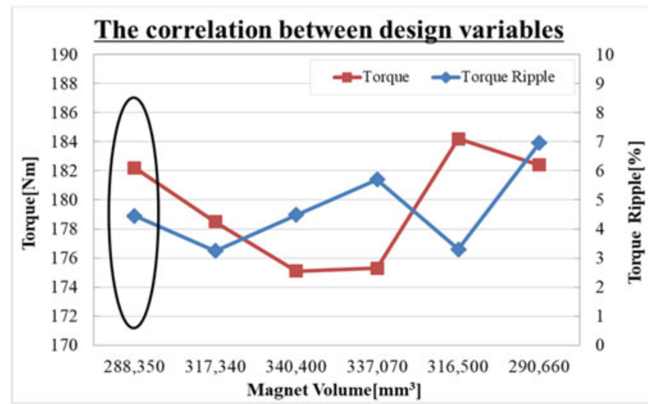

Fig. 3. The correlation between design variables.

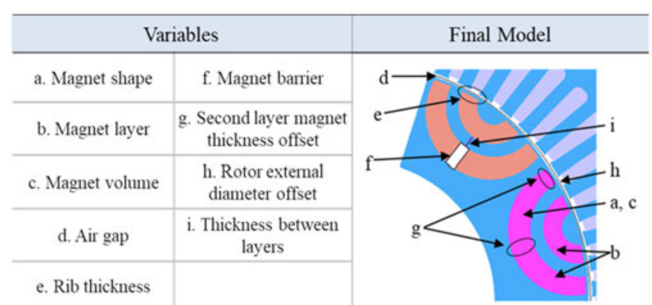

Fig. 4. Design variables and final heavy rare-earth free IPMSM.

In Table IV, M1 is the concept model (a) and M6 is the concept model (d) of Fig. 2.

C. Heavy Rare-Earth Free IPMSM Detail Design

We conducted the detail design with 9 variables to satisfy target specifications for the IPMSM with heavy rare-earth free magnet. Fig. 4 shows design variables and final model. 9 variables are related to the rotor. These are factors that affect motor power, demagnetization and torque ripple. We can derive these variables from concept models and design experience.

In this design review, the impact of the demagnetization was larger on the second layer. So the thickness of the second layer magnet was thicker than first layer.

Fig. 5 shows demagnetization region of rotor magnet on the 150 °C, max current and current angle. Table V is design results of the IPMSM with heavy rare-earth free magnet. As the results, heavy rare-earth free IPMSM meet the target. The selection of magnet amount considered the characteristic of the heavy rare-earth free magnet and material cost. Upon reviewing the

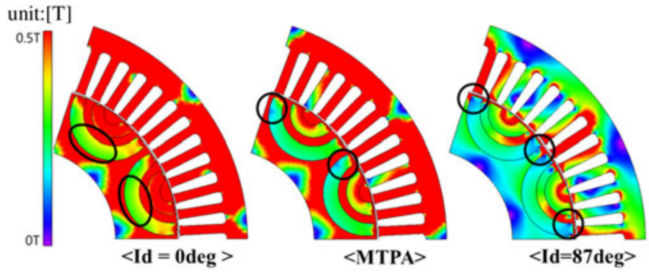

Fig. 5. Demagnetization weak region of rotor magnet.

TABLE V
DESIGN RESULTS OF THE IPMSM WITH HEAVY RARE-EARTH FREE

Division	Nd Sintered	Final design	Proto model
Number of poles	10	←	←
Max Power [kW]	31	←	26.8
Air gap [mm]	0.6	←	←
Stator diameter [mm]	160	←	←
Stack length [mm]	120	←	←
Max. torque [Nm]	200	←	173
Base Speed [RPM]	1480	←	←
Max. input current [Apk]	340	←	←
Torque ripple @Max torque [%]	3.8	2.5	2.3
Torque ripple @9000 rpm [%]	9.8	9.6	5.5
Max current density [Apk/mm^3]	40	←	←
Magnet amount [mm^3]	164,400	330,360	254,300

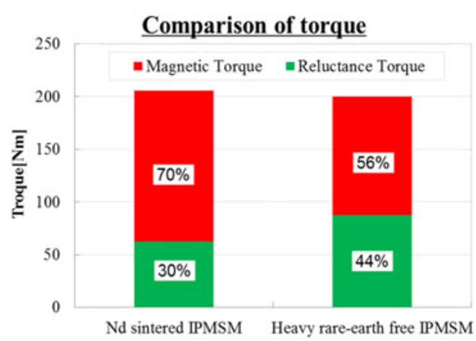

Fig. 6. Comparison of torque components of IPMSM models.

material costs, the target magnet amount can reduce the cost of material by 5% less than Nd sintered IPMSM.

Fig. 6 shows the torque components according to IPMSM models. To compensate for insufficient torque, reluctance torque has been increased. But torque ripple level was satisfied the target.

III. PROTOTYPE PRODUCTION AND TEST RESULTS

A. Prototype Product

A review of prototype for design verification was conducted. The applied magnet of the final model is the injection radial magnetizing type but prototype is made as a split processing axial magnetizing type to reduce the proto costs. Because magnet injection mold is expensive. Fig. 7 shows the results of a magnetic field according to the magnetizing method and segmentation. The flux linkage rms value of condition (a) is

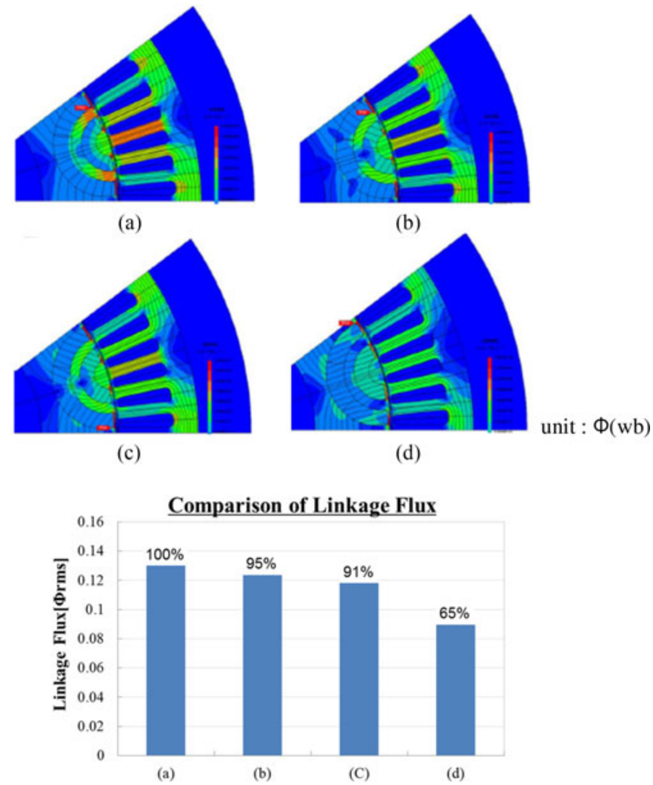

Fig. 7. The results according to the magnetizing and segment. (a) Radial/Injection. (b) Axial/5Segments. (c) Axial/4Segments. (d) Axial/2Segments.

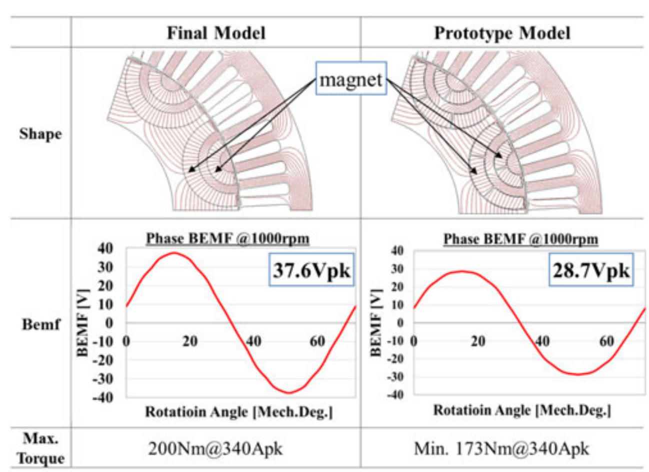

Fig. 8. Comparison of final model and prototype model.

0.129 Φ (rms). Assuming that condition (a) value is 100%, the rms value of flux linkage of the other conditions is shown in the graph of Fig. 7 below. As a result, condition (b) is selected for prototype production. The flux linkage value of the condition (b) is better than others except condition (a). Since there is a difference between final model and prototype, the representative performance of prototype has been reviewed.

Fig. 8 is the 5 segment magnet shape and torque result of prototype review. In the prototype model, the torque is higher than the lowered bemf ratio, because reluctance torque ratio

(a) (b)

Fig. 9. Heavy rare-earth free prototype model. (a) Prototype rotor. (b) Prototype motor with reducer.

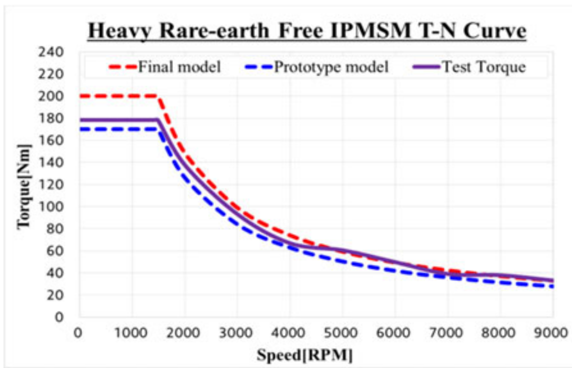

Fig. 10. Heavy rare-earth free prototype test result.

TABLE VI
IRREVERSIBLE DEMAGNETIZATION TEST RESULT OF THE PROTOTYPE

Division	Before testing	After testing	Error	Result
Phase U	28.3 Vpk	28.3 Vpk	0%	OK
Phase V	29.2 Vpk	29.4 Vpk	+0.68%	OK
Phase W	28.6 Vpk	28.5 Vpk	−0.34%	OK

increased in total torque. Fig. 9 is heavy rare-earth free prototype product.

If the prototype motor having 5 segment magnet can meets the analysis torque performance, the injection type final model also is expected to meet target performance same as IPMSM with Nd sintered magnet.

B. Performance Test Results

Fig. 10 is T-N test results and Table VI is irreversible demagnetization test result and bemf wave. Irreversible demagnetization test condition is that supply the maximum current to the d-axis at the high coil temperature 150 °C. And test motor is soaked at 120 °C for one hour before irreversible test.

Fig. 11 is efficiency map of Nd sintered motor and heavyrare earth free prototype motor. Prototype motor efficiency is higher than Nd sintered motor at the high speed. We can know that the prototype motor is more suitable for the high speed operation region. Because heavy rare earth free magnet loss is less than Nd sintered magnet in the high speed region.

Prototype model Bemf and performance meet the predicted values according to the test results. Therefore, the injection type heavy rare-earth free IPMSM is expected to meet the target performance.

The difference between final design and prototype model is just magnet shape. Final design is injection type and prototype

200	76.22%	81.47%								
190	77.81%	82.79%								
180	79.29%	83.96%								
170	80.54%	85.01%								
160	81.71%	85.97%								
150	82.84%	86.90%								
140	84.05%	87.86%	90.33%							
130	85.07%	88.65%	90.60%							
120	86.12%	89.48%	91.78%							
110	87.14%	90.15%	92.28%							
100	88.17%	90.86%	92.76%	94.54%						
90	89.15%	91.51%	93.17%	94.68%						
80	89.86%	92.07%	93.54%	95.00%	93.46%					
70	90.76%	92.62%	93.80%	95.16%	93.42%					
60	91.45%	93.10%	94.27%	95.27%	93.62%	91.51%				
50	92.11%	93.47%	94.15%	95.19%	93.59%	91.08%	89.33%	87.89%		
40	92.65%	93.78%	94.10%	94.98%	93.50%	90.83%	88.43%	86.78%	85.72%	81.91%
30	92.80%	93.43%	93.56%	94.25%	92.74%	89.62%	86.86%	84.78%	84.22%	83.33%
20	92.34%	92.81%	92.21%	92.80%	91.05%	87.34%	83.54%	80.95%	79.31%	76.62%
10	89.56%	89.30%	87.93%	88.32%	85.59%	81.42%	74.56%	70.39%	68.26%	64.93%
T/N	1000	1400	2000	3000	4000	5000	6000	7000	8000	9000

(a)

178.5	66.85%	76.13%								
170	68.04%	76.58%								
160	70.74%	78.70%								
150	70.94%	78.08%								
140	72.76%	79.75%	84.03%							
130	74.39%	81.12%	84.59%							
120	76.36%	82.57%	85.62%							
110	77.93%	83.79%	86.63%							
100	79.43%	84.98%	87.65%	91.18%						
90	80.98%	86.05%	88.48%	91.35%						
80	82.35%	87.12%	89.29%	92.07%						
70	83.85%	88.13%	90.13%	92.72%	92.46%					
60	85.15%	89.01%	90.75%	93.27%	93.40%	92.13%				
50	86.56%	90.10%	91.46%	93.67%	94.41%	92.91%	92.52%			
40	88.02%	91.01%	92.13%	94.08%	94.97%	94.66%	93.46%	92.20%	91.48%	91.39%
30	89.62%	91.94%	92.72%	94.37%	95.35%	95.49%	94.30%	93.27%	91.62%	93.82%
20	91.22%	92.84%	93.23%	94.48%	95.33%	95.62%	94.67%	93.54%	92.38%	91.29%
10	92.62%	93%	92.66%	93.41%	94.12%	94.52%	93.76%	92.01%	90.42%	89.42%
T/N	1000	1530	2000	3000	4000	5000	6000	7000	8000	9000

(b)

Fig. 11. Efficiency map of Nd sintered motor and prototype motor. (a) Nd sintered motor efficiency map. (b) Prototype motor efficiency map.

is 5 segment types. Magnet material elements are same. The injection type can fill magnet pocket in the rotor, so motor performance can be improved.

IV. CONCLUSION

With this work we demonstrated that heavy rare- earth free motor can produce the same power density as Nd sintered motor.

A SynRM rotor shape was used to overcome the lack of heavy rare-earth free motor torque.

We demonstrated that at high speed, the loss of the heavy rare-earth free magnet is less than the loss experienced by of a Nd sintered magnet.

This study shows the promise of a possible commercialization for heavy rare-earth free motors. The production of such motors could reduce the demand of expensive rare earth materials.

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