Studies on Less Rare-Earth Permanent Magnet Hybrid Excitation Motor with High Power Density

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Abstract :
Feasibility studies on Hybrid Excitation Motor (HEM) as a candidate of less rare-earth permanent magnet and high power density machine for hybrid electric vehicle drive applications are reported. The basic working principle of the HEM is explained from a viewpoint of its variable field control mechanism. After making the design restrictions and the target specifications clear, the drive performances of a full-sized HEM designed as the motor with the maximum power of 123kW are predicted based on 3D-FEA using JMAG-Studio. Comparisons between the measured and the computed drive characteristics of the downsized test HEM demonstrates that the 3D-FEA based design and performance predictions have reasonable computation accuracy. As a result, it is concluded that the predicted performance of the full-sized machine, its high power density with 3.35kW/kg at the maximum power operation under utilization of 517g rare-earth permanent magnet, is highly expected.

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Studies on Less Rare-earth and High Power Density Hybrid Excitation Motors

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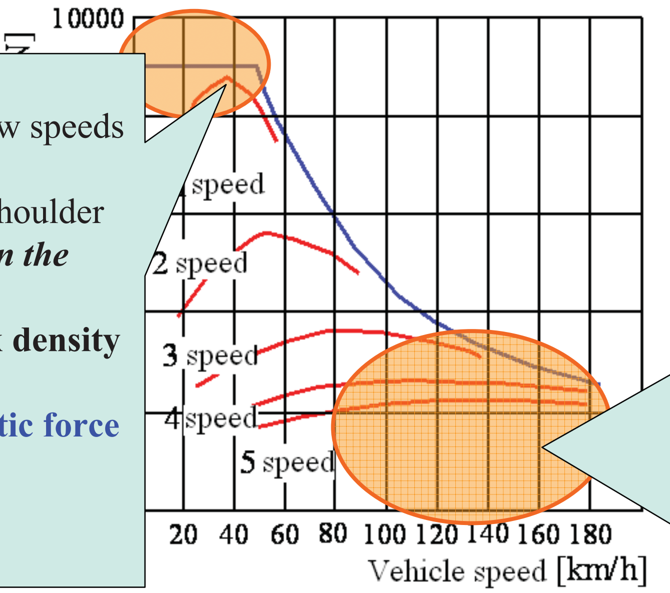
1. Requirements and Design Challenges of Motors for EV/HEV

Wide range of speed - Covering the operation range of torque with a single miniaturized motor.



∝Motor rotation speed

Maximum torque performance at low speeds
・Hill start
・When on road shoulder
Torque ∝ *I B l in the motor design*
B: **Magnetic flux density**
Higher torque
＝Higher magnetic force

High-speed High-output
・Freeway cruising

The tolerance of the inverter component limited by the amount of voltage that can be increased in the circuit

Voltage ∝ *v B l in the motor design*
Higher speed higher output
＝lower flux

1. Requirements and Design Challenges of Motors for EV/HEV

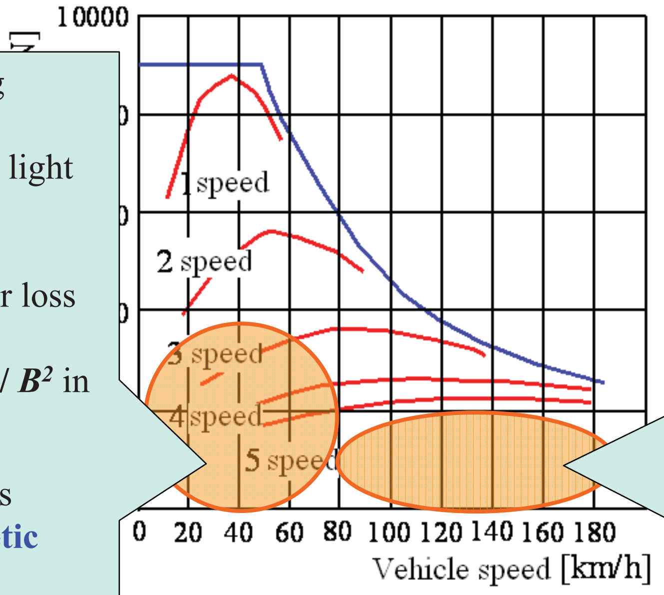
Covering a wide range of operating drive regions efficiently with a single motor

Multipe operating regions (1)
Low/motor speed light load region

Main loss: Copper loss

Copper loss ∝ 1/ B^2 in the motor

Lower copper loss
＝Higher magnetic force



∝Motor rotation speed

Multiple operating regions (2)
High speed light load region

Main loss: Iron loss

Iron loss ∝ B^2 in the moto.
Lower iron loss
＝lower flux

2. Development Trends of Variable Magnetic Flux Motors

Variable Magnetic Flux

○2009: Toshiba Home Appliance Corporation Nikkei ElectronicsMarch 8, 2010 Issue 3

Switching Coil Connection

○2009: YASKAWA ELECTRIC CORPORATION July Nikkei AT2010

○2009 : Hitachi Appliances Nikkei ElectronicsMarch 8, 2010 Issue 3

Combining magnetic force of permanent magnets and electromagnets⇒Hybrid magnetic motors

○1995 : MEIDENSHA CORPORATION , IEEJ Vol.115-D, No.11, pp.1402-1411

○2003 : Univ. of Wisconsin, Madison(USA)
IEEE Trans. on IA, vol. 39, No.6, pp. 1704-1709, 2003

○2007 : SATIE - Ecole Normale Supérieure de Cachan (France)
Proc. of the 12th EPE 2007

3. Variable Flux Hybrid Magnetic Motor and Rare Earth

1. Rare earth for controlling magnetic force strengthening –
Magnetic force of magnets + Magnetic force of electromagnetics

If the magnetic force, B, necessary for low speed torque and light load low loss is 1:
Only magnet excitation --- Magnetic force of magnets 1 ⇒Magnet ratio 100%
Hybrid excitation --- Magnetic force of the magnets 0.5+ magnetic force of the electromagnets 0.5 ⇒Magnet ratio50%

2. High-speed High Output under battery voltage constraints by controlling magnetic flux weakening
Lower loss higher efficiency --- Magnetic force of the magnets －Magnetic force of the electromagnets

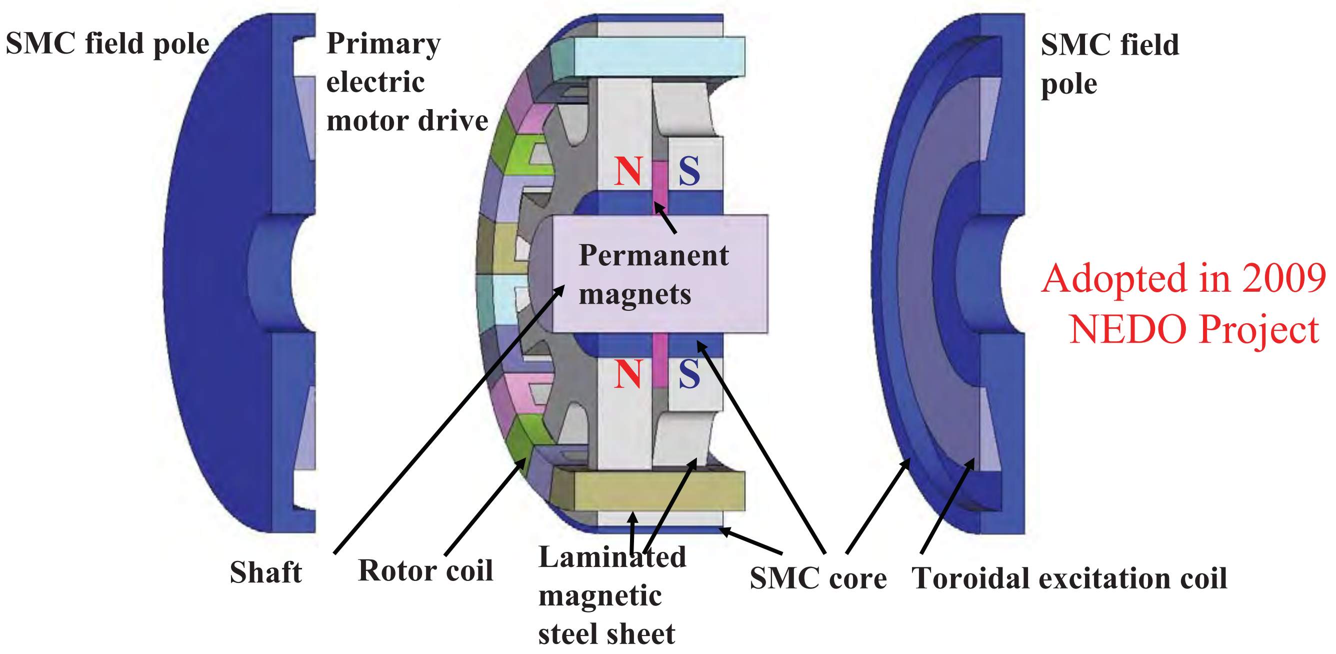
Back EMF caused by eliminating magnetic force, B, and eliminating loss (iron loss)
Hybrid excitation --- Magnetic fore of the magnets 0.5－ Magnetic force of the electromagnets 0.5
⇒ No magnetic force

Challenges

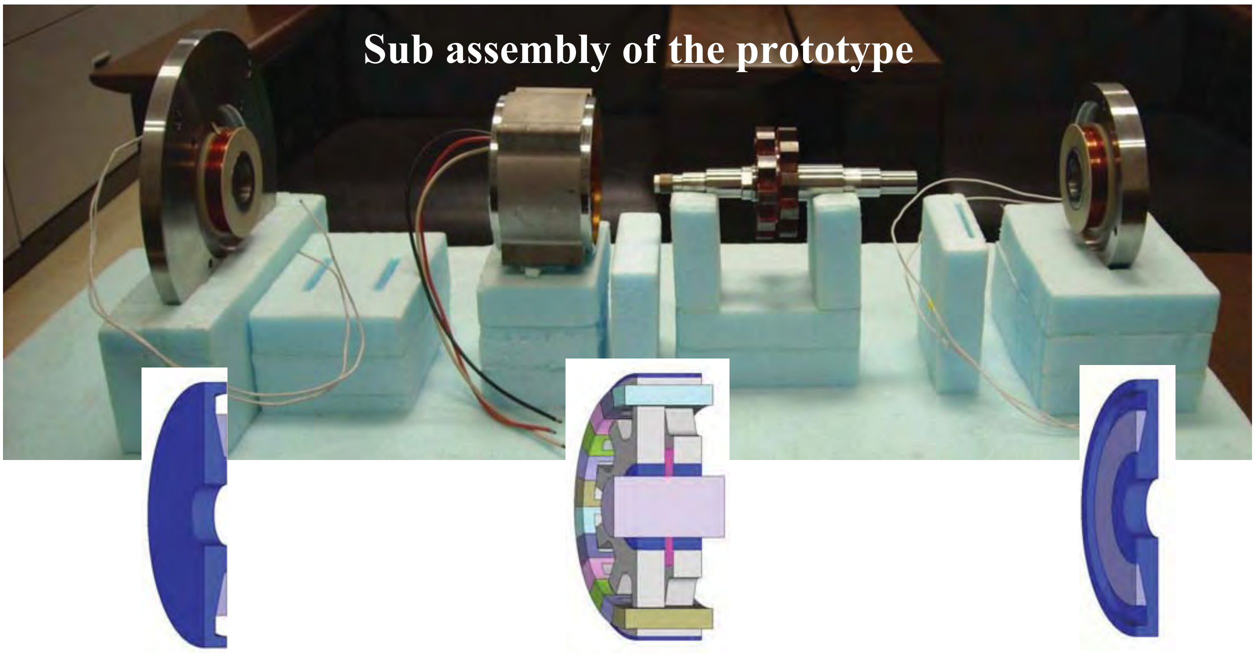
Constructing a motor structure that efficiently utilizes both the magnetic force of the magnets and electromagnets.

4. Rare earth hybrid excitation motor for HEVdrives

20-pole 24-slot concentrated winding hybrid excitation motor



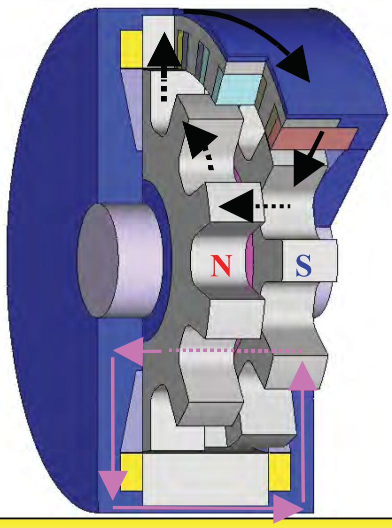
4. Rare earth hybrid excitation motor for HEVdrives



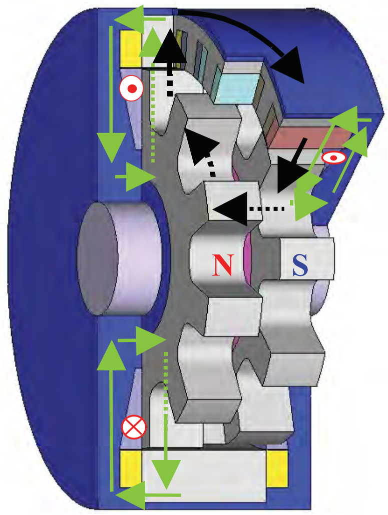
4. Rare earth hybrid excitation motor for HEVdrives

Operating Principles - Controlling Magnetic Flux Strengthening

<Excitation without control>



<Excitation with magnetic flux strengthening control>

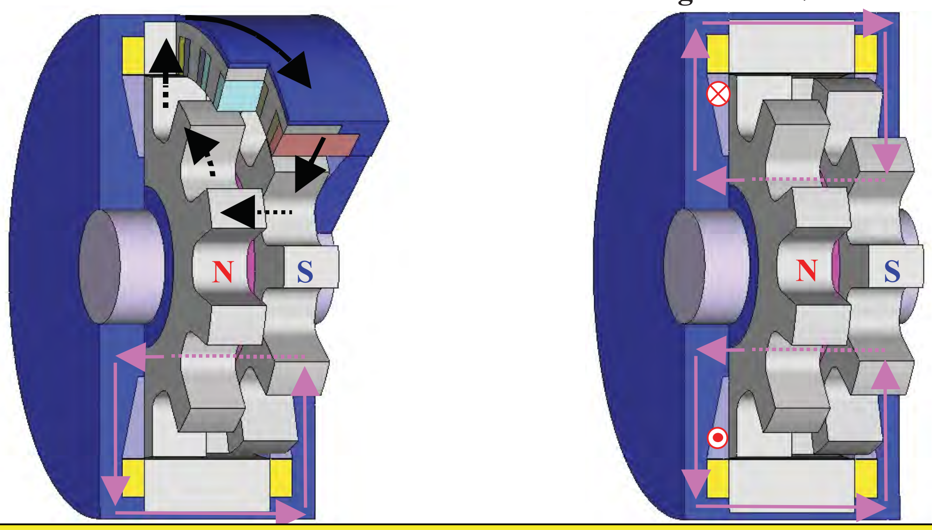


Magnetic flux of permanent magnets + excitation magnetic flux $T_m=P_n(\phi_m+\phi_f)i_q$ → **Higher torque by** increasing the excitation magnetic flux

4. Rare earth hybrid excitation motor for HEVdrives

Operating Principles - Controlling Magnetic Flux Strengthening

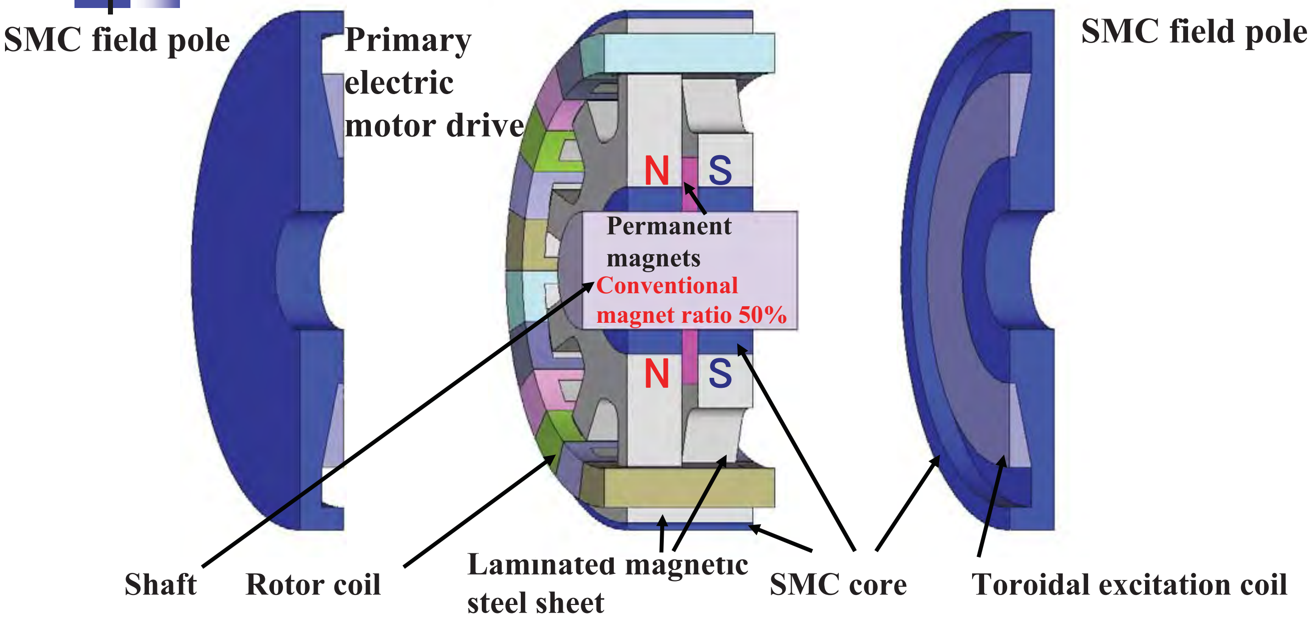
＜Excitation without control＞　　＜Excitation with magnetic flux weakening control＞



DC short circuit in the magnetic flux of permanent magnets → Lowers iron loss at high rotation speeds

Reduces the flux linkage of the stator coil → Enlarging the speed range by controlling the back EMF

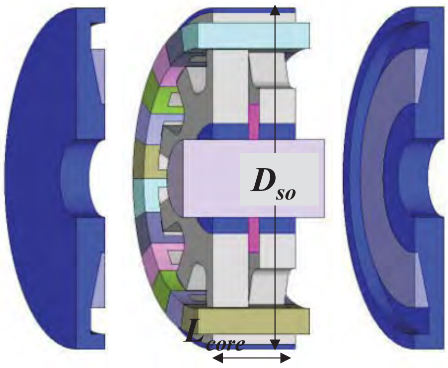
4. Rare earth hybrid excitation motor for HEVdrives



Rotor structure: Flat cylindrical magnets and laminated electromagnetic steel → Higher output via higher rotation speeds

Stator structure: Concentrated windings in multi-pole slots → Higher winding factors and higher torque

5. Design Specifications of Motors for HEV Drives



Dimensions of the primary motor tested*
Stator diameter D_{so}: ϕ264mm
Stack length of stator/rotor coreL_{core}:70 mm

Characteristics of primary drive motors for automobiles
(1) Uses Neodymium magnets
(2) Controlling magnetic field weakening – highly efficient at high speeds
(3) Controlling magnetic field strengthening – Higher torque at low speeds
(4) Compact & robust structure

Current density of rotor winding:
20[Arms/mm^2] (standard water cooled)
Maximum inverter voltage:
650[V_{dc}](Present standard)
Magnet dimensions:
Outer Diameter : 115 mm
Inner diameter (shaft) : 60 mm
Thickness : 9 mm
Amount used: 68 cm^3 (517 g)

5. Design Specifications of Motors for HEV Drives

<Design constraint conditions>

Motor diameter	**264 [mm]**	**Magnets**	**< 550 [g]**
Stack length of primary core	**70 [mm]**	Maximum inverter current	240[A_{rms}]
Maximum current density (Stator coil)	20 [A_{rms}/mm^2]	Inverter DC_{max} voltage	650 [V]
Maximum current density (Excitation coil)	20 [DCA/mm^2]	Maximum component tolerance	900 [V_{0-p}]

<`Performance specifications>

Max. speed	**20,000 [r/min]**		
Max torque	**More than 210 [Nm]**	Desired torque density	More than 6 [Nm/kg]
Maximum output	**More than 123 [kW]**	**Desired output density**	**More than 3.5 [kW/kg]**

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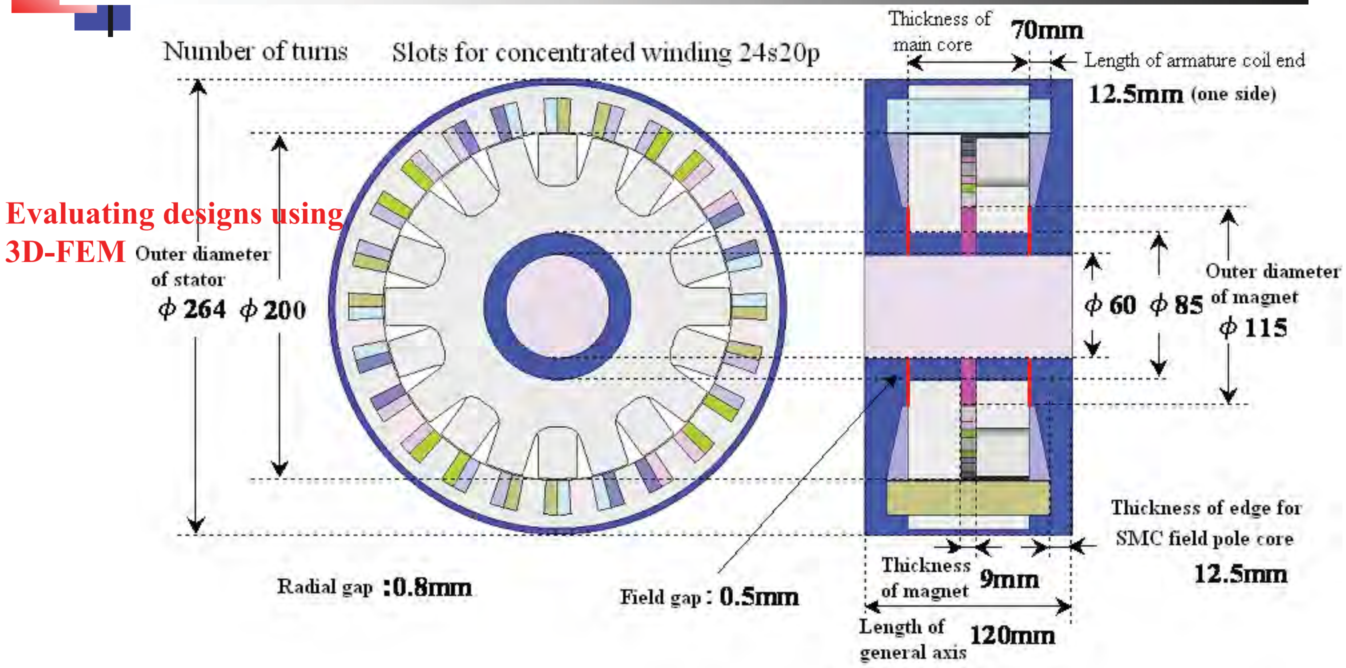
6. Estimating 3D-FEADesign Geometry and Performance



I.Ozawa, et.al, "Less Rare-Earth Magnet-High Power Density Hybrid Excitation Motor Designed for Hybrid Electric Vehicles Drives", Proc. of 13th European Conference on Power Electronics and Applications (EPE2009), No.772(2009)

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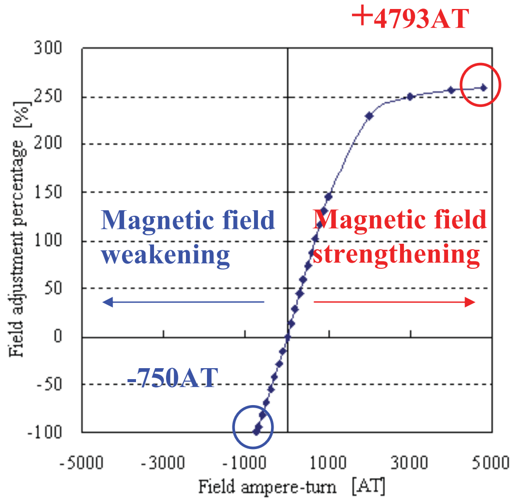
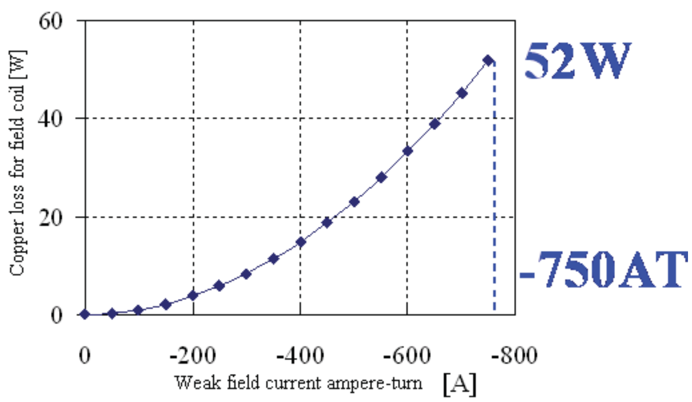
6. Estimating 3D-FEADesign Geometry and Performance

＜Magnetic field weakening/strengthening adjustment capabilities＞



＜Copper loss of excitation winding at -750AT＞



Weakening -100%~ Strengthening +258%

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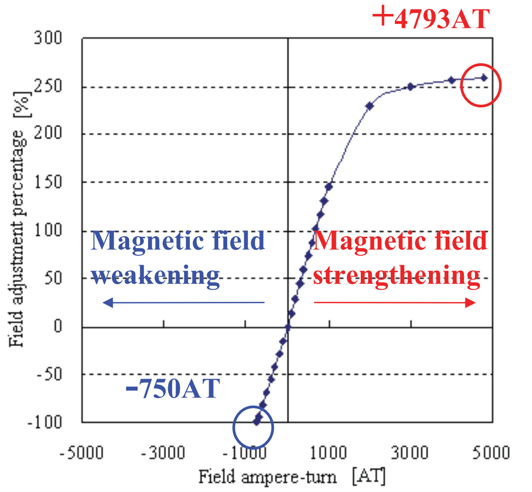
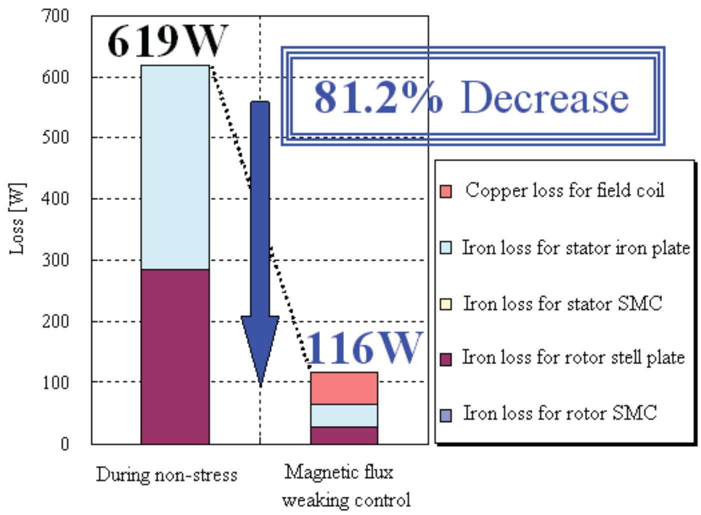
6. Estimating 3D-FEA Design Geometry and Performance

＜Magnetic field weakening/strengthening adjustment capabilities＞



Weakening -100%~ Strengthening +258%

＜Dragging iron loss at 20,000 r/min＞



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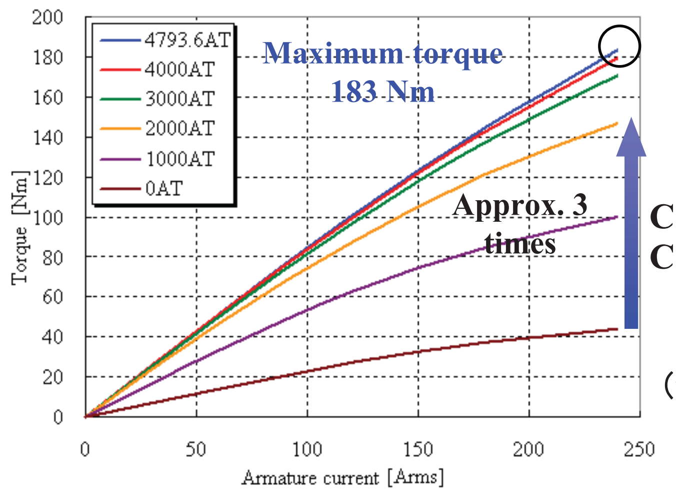
6. Estimating 3D-FEA Design Geometry and Performance

＜Stator current vs. torque characteristics＞



43Nm@240Arms－ 0AT

146Nm@240Arms－ 2,000AT

Copper loss of rotor coil 3.25 kW @ 240 Arms
Copper loss of excitation coil 0.49 kW @ 2,000 AT

（with a coil temperature of 100 degrees Celsius）

Max. torque: 183 Nm（87.1% of desired value）rotor torque density: 83.6 Nm/L
Excitation magnetic force 2,000 AT＝0.5 kWcopper loss with 3 times the torque constant up

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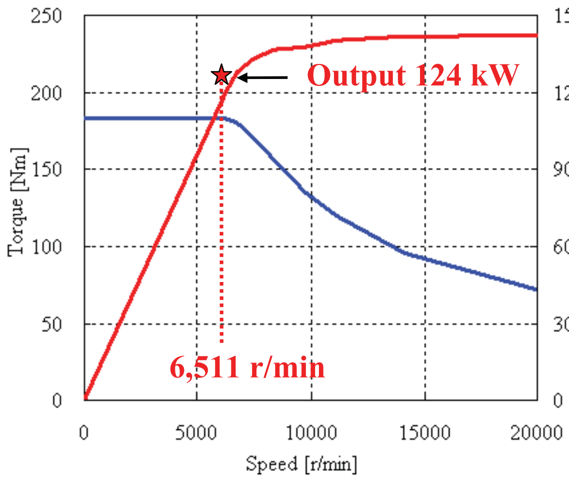
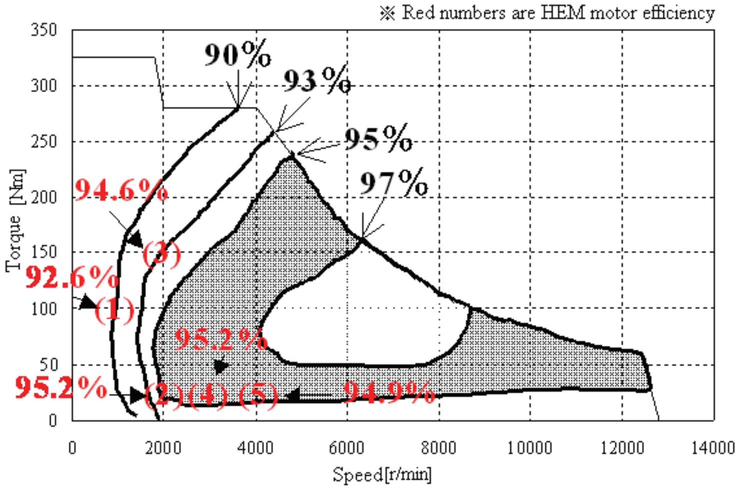
6. Estimating 3D-FEA Design Geometry and Performance

＜Rotation speed vs. torque & output characteristics＞



＜Motor efficiency at multiple operating points＞



Maximum output: 124 kW @ 6,511 r/min PF = 0.65 The desired output is achieved

Output density: 124 kW/37.0 kg ＝ 3.35 kW/kg (97.1% of desired output density)

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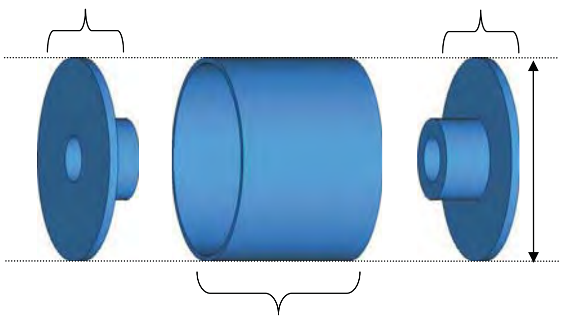
7. Evaluating the Performance of Miniaturized Prototype Testing

○Scale down limitations - Size of SMC materials

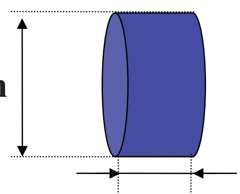
Excitation pole SMC core **Excitation pole SMC core**

Universal SMC cylindrical material (Material from Mistubishi PMGMBS318)



Full scale
ϕ264 mm

ϕ100 mm



L=50 mm

Outer circumference of SMC stator core

Scaling ratio k=100/264=0.378… approx. the same scale of dimensions
－Radial air gap 0.8×k=0.303≒0.3 mm
－Excitation gap 0.5×k=0.189≒0.2 mm ⇒ 0.5 mm expanded (gap management)

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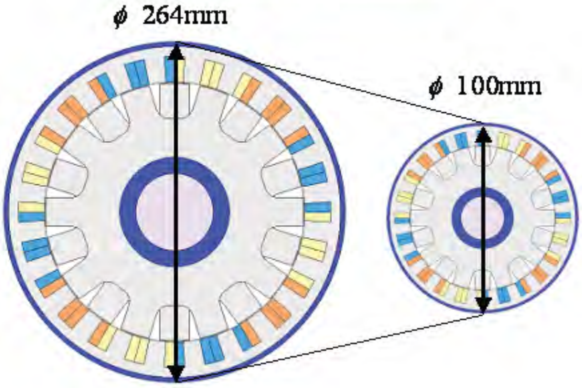
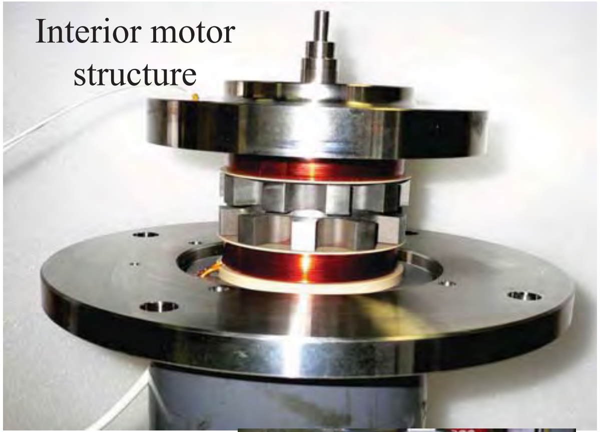
7. Evaluating the Performance of Miniaturized Prototype Testing

$$\text{Scale} = \frac{\phi 100}{\phi 264} \approx 0.379$$




Interior motor structure


Rotor


Excitation pole


Excitation pole + excitation winding


Stator

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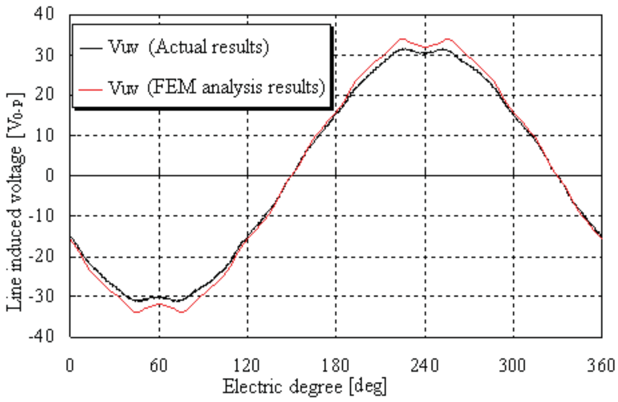
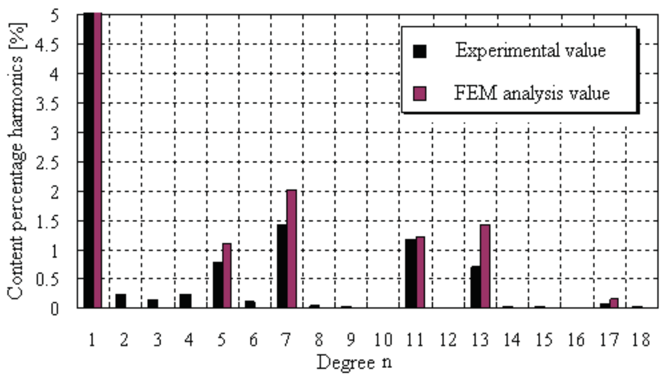
7. Evaluating the Performance of Miniaturized Prototype Testing

<Back EMF waveform between wires (at 3,000 r/min)>



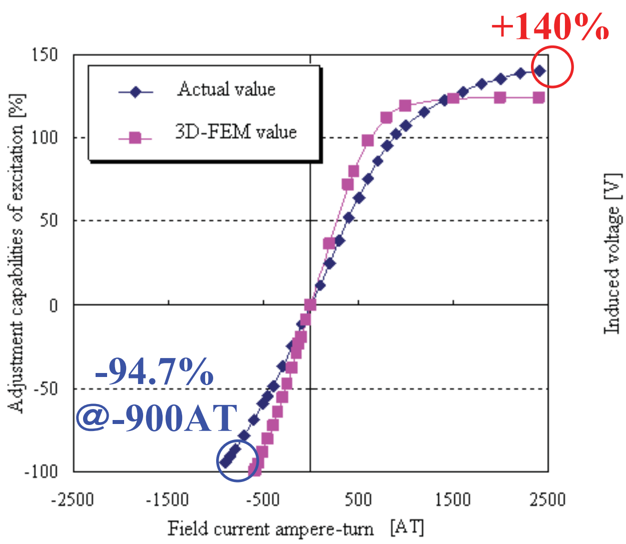
<Rate including harmonic components>



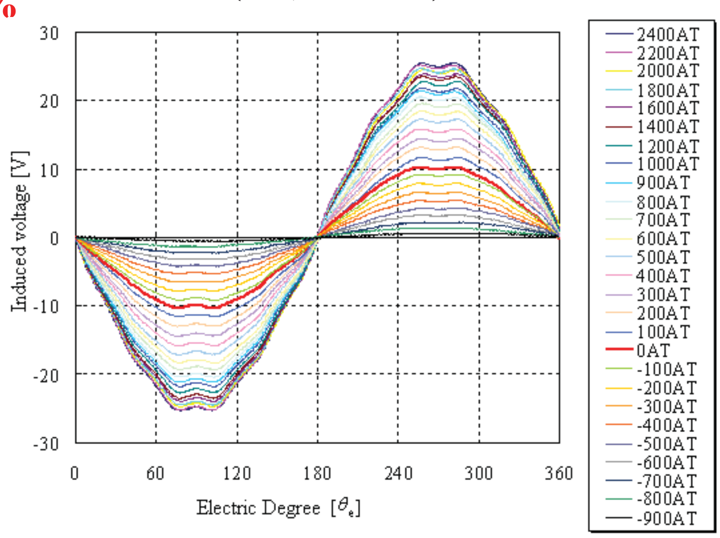
The error between the actual results and FEM analysis results is **- 6.6%**(at 3,000 r/min)
The harmonic components of the back EMF waveform match well

7. Evaluating the Performance of Miniaturized Prototype Testing

<Adjustment capabilities of excitation>

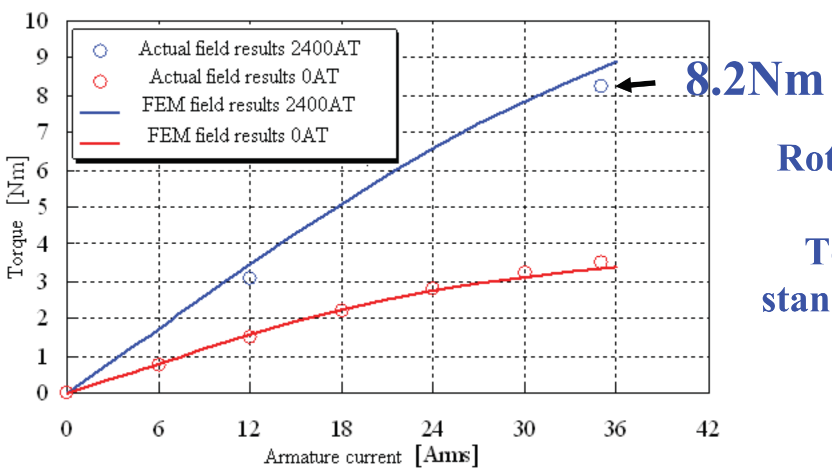


<Back EMF waveform between wires (at 1,000 r/min)>



7. Evaluating the Performance of Miniaturized Prototype Testing

<Rotor current - Torque characteristics (at 1,000 r/min)>



Rotor torque density
68.8 Nm/L
Testing an 82.3%
standard of 83.6 Nm/L

Actual maximum torque	8.2 Nm	Estimated error -7%
Estimated FEMtorque	8.8 Nm	

Accuracy of evaluating performance by 3D-FEM○ ⇒ Realizing full scale features High

8. Conclusion

- Uses Neodymium magnets : Compared to conventional technology: 50 [%] －500 [g] approximately
- Torque mass density : Equal to conventional technology－6 [Nm/kg]
- Output mass density : Equal to conventional technology－More than 3.5 [kg/kW] (Note: Water cooled type motor)
- Maximum speed : 20,000 r/min（Compatible to conventional maximum torque of a 4:1 gear)

Achieved in the full scale design（JMAG estimiate from full 3D-FEA calculation)

Desired performance	Desired value	Design results	Achievement
Amount of magnetic material used	Approx. 500 [g]	517 [g]（NEOMAX38AH）	OK
Maximum speed	20,000 [r/min]	Voltage limitations and mechanical intensity cleared	OK
Max torque	More than 210 [Nm]	183 [Nm]	87%
Output @ 6-7 kr/min	More than 123 [kW]	124 [kW] @ 6.5kr/min	101%
Desired torque density	More than 6 [Nm/kg]	4.9[Nm/kg]	81.6%
Desired output density	More than 3.5 [kW/kg]	3.35 [kW/kg]	97.1 [%]