Integrated Motor Propulsor Magnet Design with Hybrid Halbach Array for Torque Ripple Reduction

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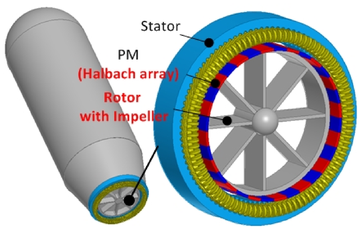
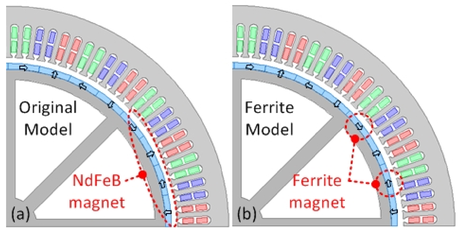
Background

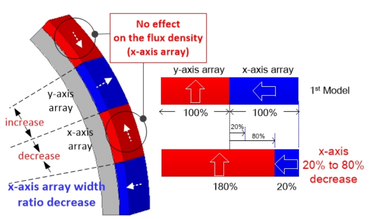
This paper presents a magnet design using a Halbach array to reduce torque ripple based on the width ratio, and deals with the influence of the material of a radial array permanent magnet (PM) for a 22.5-kW 1500-rpm-class unmanned submarine. This paper is divided into two main parts: a comparison of the characteristics of a hybrid Halbach array integrated motor/propulsor (IMP) with *x*-axis magnets replaced by ferrite magnets, and an analysis of PM optimization of the Halbach array in terms of torque ripple reduction based on the width ratio of the *x*-axis array magnet. Results show that the size of the rare-earth magnet, volume of the IMP, and torque ripple were reduced by 25%, 25%, and 75%, respectively, when a ferrite magnet was substituted for the *x*-axis array magnet and the PM width was optimized for magnetization in the *x*-axis direction of the Halbach array.

Objectives

- ✓ This paper presents a comparison of the characteristics of a hybrid Halbach array IMP with *x*-axis magnets replaced by ferrite magnets, and considers the PM optimization of the Halbach array in terms of torque ripple reduction based on the width ratio of the *x*-axis array magnet.
- ✓ This paper presents the design and analysis of an IMP for a 22.5-kW 1500-rpm-class unmanned submarine.
- ✓ First, the replacement of the rare-earth magnet for magnetization in the *x*-axis direction is discussed.
- ✓ Second, the focus shifts to the PM width ratio; a downscaled PM was used to compensate for the torque pulsation.



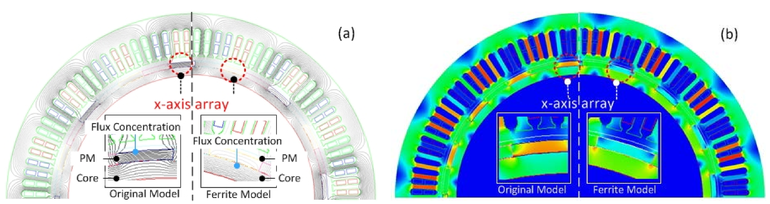




Substitution of rare-earth magnet

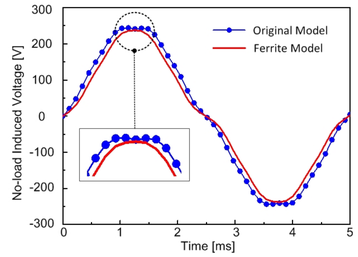
TABLE I
Design parameters

Parameter	Value
Stator outer diameter	300 mm
Stator inner diameter	230 mm
Rotor outer diameter	214 mm
Rotor inner diameter	200 mm
PM thickness	4 mm
Stack	85 mm
Poles	16
Slots	72



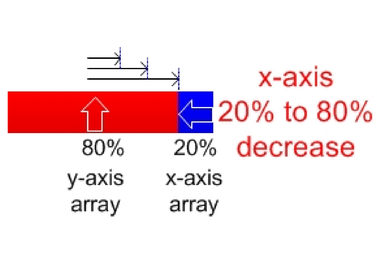
- ✓ the magnetic flux line distribution for the rare-earth magnet; much of the magnetic flux flowed through the PM. However, the flow of the magnetic flux was confirmed to be small in the PM when a ferrite magnet was used for the *x*-axis array magnet, and much of the magnetic flux flowed through the rotor.
- ✓ if a rare-earth magnet is used, the *x*-axis array magnet is saturated; the *x*-axis magnet is not saturated when a ferrite magnet is used.

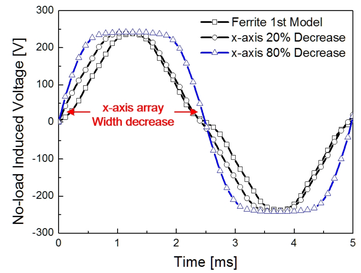
Comparison of no-load induced voltage

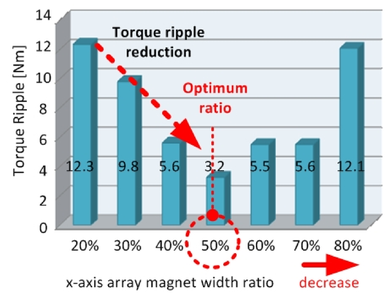


- ✓ The peak back-EMF value of the ferrite model decreased because of the reduced concentration of the magnetic flux.
- ✓ However, despite the volume of rare-earth magnets being reduced by half, the back-EMF shows similar values, and both models exhibited comparable waveforms.
- ✓ The ferrite model represents the sinusoidal of the maximum values, but the original model shows a non-sinusoidal shape near the maximum value because of the saturation of the *x*-axis array magnet.

Results & conclution

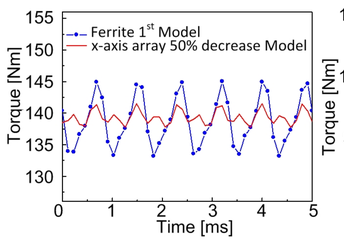


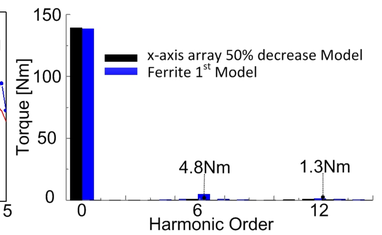




Concept of x-axis array magnet decrease and torque ripple result according to PM width ratio

- ✓ A model with a 20% reduction in the width ratio of the *x*-axis magnetization magnet and a model with 80% reduction.
- ✓ As the *y*-axis magnetization increases (the *x*-axis magnetization decreases), the back electromotive force waveform becomes closer to a square wave; the torque ripple is affected by the change in the back-EMF waveform.





- ✓ **The volume of rare-earth magnets was reduced by 25%; by changing the width of the magnet, the torque ripple was reduced by 75%.**