Stator-Teeth Design of Direct-Drive Large-Torque Transverse Flux-Type Motor with High Power Factor for Electric Ship Propulsion

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***Abstract*—Electric propulsion (EP) system has been one of the attractive solutions for energy saving and reducing maintenance costs in marine application. Transverse flux-type machine (TFM) with permanent magnets (PMs) has been developed as a direct-drive propulsion motor called for high torque at low speed and high reliability without gearbox simultaneously. This manuscript describes a design method of the TFM with large torque and high power factor (PF) by simple modeling focused on basic magnetic-circuit structure as a pre-process of parameter search to conduct detailed design process using numerical study efficiently. Besides, the detailed design, especially materials and structure, is mainly discussed to create a prototype model. Torque density defined as torque to total motor volume ratio and PF of the proposed model are improved 109% and 44% better than those of the previous one through the numerical computation and experiments.**

***Index Terms*—Permanent magnet synchronous motor, PMSM, transverse flux machine, TFM, torque density, finite element method, FEM, power factor (PF), motor design, ship propulsion**

I. Introduction

Marine transportation system has been acknowledged as fuel-efficient energy-saving conveyance, but due to growing concern for environmental problem, especially CO_2 emission, and increasing fuel cost, International Maritime Organization (IMO) has determined energy efficiency design index (EEDI) for new vessels as a regulation including the emission and fuel efficiency and will start mandatory of EEDI in January, 2013 [1]. Consequently, advance of electric propulsion (EP) system for ships as a solution is required more than ever.

In order to fulfill particular demands in marine application, transverse flux-type motors (TFMs), one of the axial flux-type motors (AFMs), have been given high attention due to suitable for short pole-pitch and high-torque characteristics, but TFMs are plagued by low power factor (PF) [2].

In this manuscript, as a post process of the proposed design method, simple modeling focused on one pair of armature core tooth and field permanent magnet (PM) [3], core-tooth design for large torque and high PF without failing to ensure the easy creation is carried out. The fitness between design requirement and specification of a prototype machine is also verified based on finite element analysis (FEA) and fundamental experiments.

II. Concept and Basic Strategy for New Motor Design

TFMs have a 3-D flux path to generate torque and are less subjective to trade-off between electrical or magnetic loading than conventional machines. The prototype machines taking advantage of TFM's structure have been made. The problems of cogging torque and eddy current loss on the rotor have been resolved by idea of pole-slot combination and high-resistivity carbon fiber reinforced plastic (C-FRP) with high strength in the earlier machine. On the other hand, high torque was not achieved due to its sparse stator structure as shown in Fig. 1 and restriction of armature current. Moreover, the problem of low PF makes an obstacle against this kind of motor attaining high real power to volume ratio due to the converters of large capacity for drive [4].

Consequently, the goals in the design of a new machine are decided to fulfill high torque density of more than 10kNm/m^3 as well as high PF of more than 0.80. AFMs have dense stator structure using trapezoidal teeth and PMs [5,6]. Therefore, the same structure is determined to apply to our new motor design for high torque density as shown in Fig. 1. Furthermore, flat-type windings are adapted to supply large load current, reduce whole volume and decrease inductance. A modification on the number of poles is also conducted considering rated speed.

III. Simple Method for Systematic Motor Design

3-D numerical analysis is essential to design TFMs due to TFMs' peculiar magnetic-circuit structure. Therefore, it takes long time to optimize design and it is not easy to confirm the validity of the simulation results. In order to design efficiently and systematically, a design method using a simple modeling focused on structure of basic magnetic circuit and permeance method has been proposed [3]. The simple method is used for parameter survey as a pre-process of detailed design using numerical study in accordance the process as shown in Fig. 2.

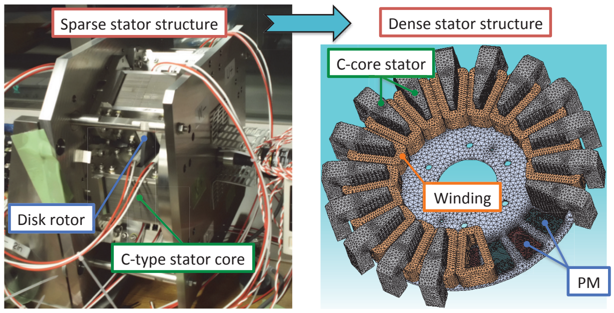


Fig. 1. Previous machine (left) and configuration of the proposed motor and 3-D element mesh for FEA (right, 886,736 elements, 238,128 nodes)

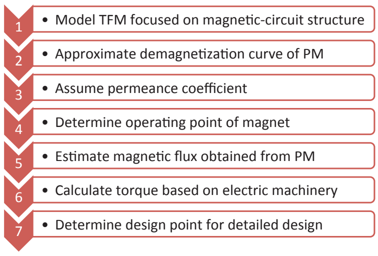
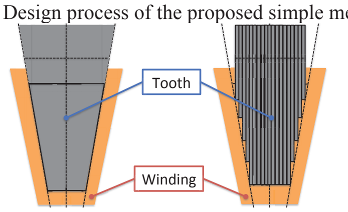


Fig. 2. Design process of the proposed simple method



(a) Bulk-core type (Type I) (b) Laminated-steel type (Type II)
Fig. 3. Stator-core-tooth design for large torque and easy creation

IV. Determination of Detailed Stator-Core Design

A. Stator Design for Large Torque and Easy Fabrication

Considering the fabrication of prototype model, trapezoid-stator teeth can be a big problem in view of easy fabrication and material. Hence, a design modification through detailed studies on the stator core by FEA is essential. The production process and determination of materials are closely connected. Therefore, it is necessary to inspect specification by change of constituent materials in the cores. Bulk-type core, laminated steels and soft magnetic composite (SMC) are applicable as a material, but SMC is excluded from the study due to its high cost, low permeability and saturation flux density. In the bulk core, trapezoid-type core teeth can be shaped easily, but an eddy current loss is expected to occur, especially at high drive frequency. On the other hand, the flexibility of shaping form in the laminated cores is not high in spite of desirable material property. In order to apply them, the design modification by quasi-trapezoid stepped teeth as shown in Fig. 3 is essential to conduct. For that reason, torque density, cogging torque and eddy current loss are inspected to choose the material logically.

B. Determination of Core Design to Create New Prototype

Numerical electromagnetic field computation is carried out to inquire details by JMAG, commercial software [7]. There are not much differences of specification between bulk-type core (type I) and quasi-trapezoid-type stepped laminated steels (type II) are shown in Table I. The torque density of type I is 7% higher than that of type II with low peak-to-peak cogging torque to output torque ratio of less than 3%, while the criteria on eddy current loss of type I as shown in Fig. 4 is 38% higher than that of type II at rated frequency of 35Hz. Thus, type II is determined to apply to the new prototype machine.

C. Quantitative Verification of Specification in New Motor

After design modification, the consistency of initial targets is verified as shown in Table II by FEA and tests using new prototype model as shown in Fig. 5. The new prototype model is clarified to achieve torque density of 11.4kNm/m^3 and high PF of 0.976 simultaneously compared to the previous machine due to dense stator structure as shown in Fig. 1 and reduction of armature resistance and inductance by high coil space factor.

V. Conclusion

This manuscript has introduced stator-teeth design process of determination of structure and material taken consideration into creation and design requirements. In the final design, the new prototype machine is demonstrated to achieve high torque density as well as high PF to fulfill initial design requirements. The proposed TFM with high torque density and high PF can be a key solution for EEDI and contributes to reducing volume of whole motor drive system, main components of EP system.

TABLE I
SPECIFICATION IN BULK AND STEPPED LAMINATED STEELS

Item	Type I	Type II	Theory [3]
Cogging to Rated Torque Ratio [%]	2.4	2.3	–
Torque Density [kNm/m^3]	12.3	11.5	10.3

TABLE II
COMPARISON OF SPECIFICATION IN THE PROTOTYPE MODELS

Item	Previous	Proposed	Tested
Armature Resistance [Ω]	8.06	2.16	2.12
Synchronous Inductance [mH]	99.5	17.5	15.3
Rated Torque Density [kNm/m^3]	5.50	11.5	11.4
Rated Power Factor	0.678	0.975	0.981

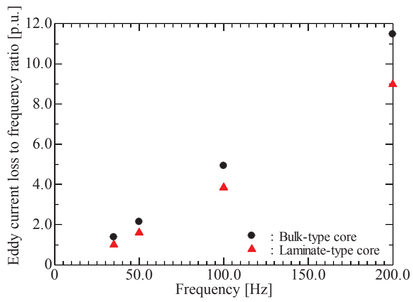


Fig. 4. Eddy current loss of iron loss at rated frequency of 35Hz

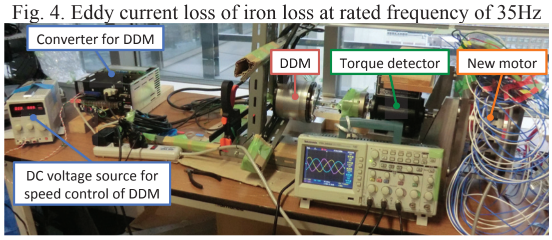


Fig. 5. Experimental setup for new prototype machine

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