Development of Interior Permanent Magnet Motors for Underwater Propulsions

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Abstract — This paper presents different IPMs developed for underwater propulsion, and discusses the technical aspects such as the increase in power factor, power density and the reduction of losses. Load characteristics and motor design requirements are analyzed. Comparisons are made between different designs in order to examine the effect of critical design parameters and materials. Finite element method (FEM) is used to verify the designs. Practical high power density IPMs with different design parameters and materials are designed, which fulfill the applications and reduce the mass and volume effectively.

I. Introduction

Nowadays, the use of electrical motor drives for underwater propulsion is drawing considerable attention because of great advantages offered with respect to conventional thermo-chemical power systems, such as more silent, less technology complexity, step-less speed control and low life-cycle cost [1]-[2]. For electrical motor of underwater propulsions, the interior permanent magnet motors (IPM) are mostly taken into consideration due to their power density, efficiency, and excellent acoustic characteristics.

Due to the submerged environments, IPMs used in underwater propulsion have some special characteristics compared with those in other applications such as electrical vehicles. The design criteria of high power factor, high power density IPMs for underwater vehicle propulsions are valuable to be examined in details.

This paper presents different electrical motors developed for underwater propulsion, and discusses the technical aspects of the drive motor such as the increase in power factor, power weight ratio and the reduction of losses.

II. Design and Development of the Motors

A. Design Requirements

For underwater propulsion, the drive motor should fulfill specific requirements as described as follows.

a). Constant torque requirement.

Typical propeller load characteristic in submerged environments shows that the variation of propulsion torque T_L with speed n is to a first approximation a square relationship. It is obvious that field-weakening is almost unnecessary. The maximum speed occurs when output torque reaches its' peak value. Thus the designed maximum speed should be located near the turning point of the torque characteristics curve, then the IPM would have the capability to output a constant torque which can speed up the accelerate process at whole speed range.

b). Downsizing and weight reduction.

Underwater applications are always limited with respect to internal space and reduced equipment volumes have direct benefits in providing capacity for additional cargo and voyage, therefore propulsion motors have both low volume and mass as desirable characteristics.

The most effective way to increase the power density is increasing the rated speed of IPM and adding a gear reduction to fulfill the load torque requirements. However in most applications, the motor's operating speed should be over 8000rpm in order to overcome the influence of additional mass of the gear reduction. Hence, the special design attention to rotor mechanical strength for higher centrifugal force must be paid.

c). High efficiency.

As a result of downsizing, the cooling of IPM becomes very important and a high efficiency is preferred, which is necessary for the heat reduction. Special attentions must be paid not only to the stator loss but also to the rotor core loss and magnet eddy current loss [3]. There are several origins that cause losses in the rotor and magnets, such as the stator slot harmonics and carrier harmonics of PWM inverters. When using concentrated windings, the harmonic components of stator MMF can also end with great eddy currents in the rotor and magnets. As a result the thermal demagnetization of the magnet by the eddy current loss is one of the major problems in the high power density IPMs. Loss analysis is an indispensable task in the system developed in this paper.

d). High power factor.

The need for compact and efficient equipment applies equally to the power electronic converters that are used to drive the propulsion motors and the motors itself. Capacitors and power electronic devices such as IGBTs hold most of the inner space of converters, and their volume increase with the output apparent power. The motor's power factor affects the active power to volume ratio of power electronic converters greatly.

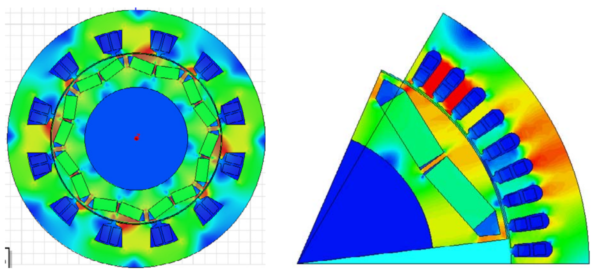
In addition to the design requirements mentioned above, there are many others such as noise and vibration, high reliability and low cost. Accordingly, this development has to be accomplished with well-balanced.

B. Design Approach

The basic design features of two 80kW prototypes are visible in the finite element model shown in Fig. 1. The motor is water cooled. Some design parameters are listed in Table I.

TABLE I
DESIGN PARAMETERS OF PROTOTYPES

Design Parameters	IPM A	IPM B
Soft Magnetic Material	Si-Fe	Co-Fe
Permanent Magnet Material	Nd-Fe-B	Sm-Co
Winding Type	Concentrated	Distributed
Poles Number	8	6
Rated Speed (rpm)	10000	10000
Rated Power Factor	0.94	0.9
Maxim efficiency	90%	96%
Power Density (kW/kg)	3.0	3.2



(a) (b)
Fig. 1. Flux density plots at full load. (a). IPM A. (b). IPM B.

According to the requirements that have to be fulfilled mentioned above, the major points of design approach are:

a). In these designs, 6 and 8 poles rotor configuration has been selected from the viewpoints of balance between iron loss reduction and rotor mechanical strength.

b). The optimal bridge and rib designs are examined by using electromagnetic field and mechanical FEA software, as shown in Fig. 1 and 2, taking the restrictions on reluctance torque, magnet opening angle, mechanical strength and flux leakage of magnets into considerations.

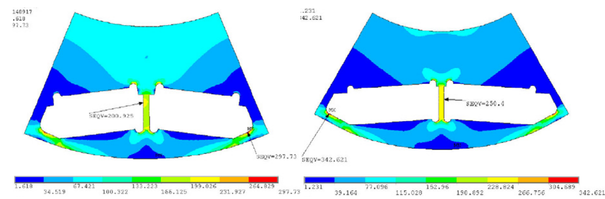
c). The shape and dimensions of magnet segments has been designed from the viewpoints of balance between magnet eddy current loss and high stability against demagnetizing fields [4]-[5]. The loss reduction effects by the magnet segmentations are analyzed by FEM.

d). Both Sm-Co alloy and Nd-Fe-B magnets have been examined in details. It shows that the air-gap flux density produced by Sm-Co alloy is acceptable although it has a lower maximum energy product. It’s because that the motor’s iron loss must be designed to be proportional to the copper loss in order to achieve high efficiency, and stronger air-gap flux density is not necessary. For a compact design, the maxim operating temperature of stator windings is limited to 180°C and the thermal demagnetization of magnets is consider to be one of the major problems, therefore the Sm-Co alloy is very appropriate to be used in the underwater propulsion motors for its temperature stability.

e). The normalized d-axis inductance can be roughly predicted based on the magnet thickness, the magnet flux-linkage and conductors per slot. In underwater applications, strong magnet and light specific loading are needed in order to reduce the normalized d-axis inductance and increase the power factor.

f). Higher power density can be achieved using materials with higher saturation magnetization, such as soft magnetic cobalt-iron alloys. However, the cost is much higher than using typical silicon steels.

More Details will be given in the full paper.



(a) (b)
Fig. 2. Mechanical stress analysis result at 12000 rpm. (a). IPM A. (b). IPM B.

III. Testing Results

This section provides information about the performance and efficiency evaluations of the manufactured IPM B. Fig. 3 shows the no-load phase induce voltage measured at 10000rpm. Fig. 4 shows the efficiency map. More results will be given in the full paper.

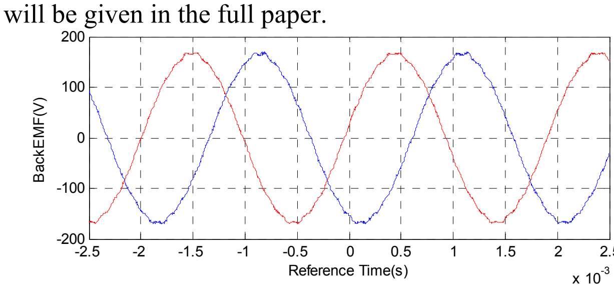


Fig. 3. Measured no-load phase induce voltage at 10000 rpm.

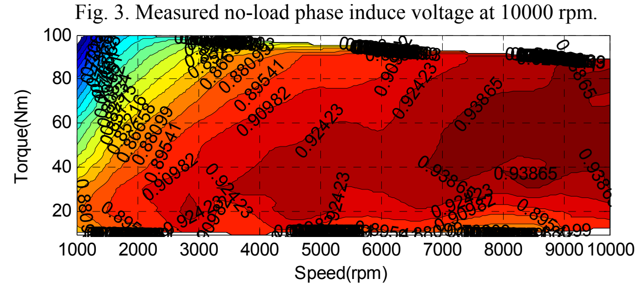


Fig. 4. Measured efficiency map of IPM B.

IV. References

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