Permanent Magnet Motor Design for Turret Applications with Large Diameter

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***Abstract*—This paper deals with a design approach for an initial design to development a permanent magnet motor for a turret application with a large diameter. The proposed design techniques are introduced as three stages; the first is selection of a pole-slot combination, the second is selection of the rotor topology, and the last is decision of the outermost dimensions. In the every stage, a useful technique is described considering effective fabrication as well as the motor performances, and magnetic field computation is performed using the finite element method.**

***Index Terms*—Design methodology, finite element methods, permanent magnet machines.**

I. Introduction

For electric motor designs, these days many researchers have introduced the design examples using variable optimum algorithms [1]-[2]. However, the optimum design process using an optimum algorithm is usually used when there is a prototype already, which has performances almost satisfying the requirements. To simply improve the performances such as efficiency and torque ripple a little more, the optimum design processes are usefully used, and the design variables are limited to detail dimensions such as magnet and tooth shapes. If the optimum design processes are used from an initial design, which starts to select inner and outer dimensions and number of poles and slots for examples, design variables are too many and the process is probably time-consuming.

This paper presents a design approach for an initial design to develop a permanent magnet (PM) motor for a turret application with a large diameter. In other words, the optimum design has been already introduced in [2], and this paper is about the previous work. The proposed design techniques are introduced as three stages; the first is selection of a pole –slot combination, and the second is selection of the rotor topology, and the last is decision of the outermost dimensions. After introducing the specifications for the machine design, the three stages are explained in detail. In the last section, the design results are discussed with analysis and experimental results.

II. Design Specifications

Table I shows the design specifications of a PM motor design for a turret application. The constraint of dimensions is only the max outer diameter, and the required motor performance during a typical operating cycle is shown in Fig. 1. Even though the max torque in Fig. 1 is under 5000Nm, the required max torque for design is 6000Nm because of considering starting torque, which is required more than running torque. With these specification, the motor should be designed as compact as possible.

TABLE I
MOTOR DESIGN SPECIFICATIONS

Max output power	9 kW
Max current	28.3Arms
Max Torque	6000 Nm
Torque ripple	Under 3 %
Max speed	14.3 rpm
Max outer diameter	2 m (including housing)
Cooling	Natural cooling (enclosed condition)

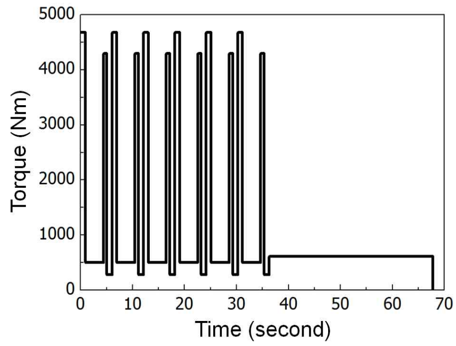

Fig. 1. Required motor performance during a typical operating cycle.

III. Selection of Pole-Slot Combinations

In the motor design process, it is very important to select the pole and slot number combinations that can achieve the highest machine performance [3]. In the several literature surveys [3]-[4], the lowest common multiple (LCM), the fundamental winding factor, k_w, and an unbalanced magnetic pull (UMP) have been considered as the selection criteria. This paper was also considered them, and eight combinations were chosen at this design stage.

However, in order to select one during the several pole and slot number combinations, different methods are suggested in each of [3]-[4]. In the proposed approach, the output power is calculated by finite element analysis (FEA), and the so-called marking score techniques are used to meet the requirements for the target application.

For this initial research, the surface mounted PM (SPM) rotor as the basic rotor topology is used. In order to fairly compare between the models, some constraints have to be given, as listed in the following.

1) The inner and outer diameters and axial length are fixed because of the required volume limit

2) The slot open width is fixed.

3) The maximum flux density is kept below 1.8 T.

TABLE II
THE DESIGN RESULTS AND THE SCORES ACCORDING TO POLE-SLOT COMBINATIONS

PSR	2:3		4:3		5:6			8:9
Model	128P 192S	150P 225S	200P 150S	240P 180S	120P 144S	**150P 180S**	200P 240S	200P 225S
LCM	384	450	600	720	720	**900**	1200	1800
kw	0.866				**0.933**			0.945
Torque (kNm)	5.9	5.7	6.2	5.9	6.1	**5.7**	5.9	5.8
Current(A)	23.2	22.4	35.7	34.4	24.7	**21.4**	24.9	24.7
T_ripple (%)	9.2 [0.7]	7.7 [0.8]	7.1 [0.8]	7.9 [0.8]	1.8 [3.3]	**0.9 [6.7]**	0.6 [10]	1.4 [4.3]
T_const (kNm/A)	254 [9.5]	254 [9.6]	173 [6.5]	171 [6.4]	247 [9.3]	**266 [10]**	237 [8.9]	235 [8.8]
Efficiency (%)	61.2 [9.4]	62.6 [9.6]	57.6 [8.8]	56.1 [8.6]	57.5 [8.8]	**65.4 [10]**	65.0 [9.9]	65.3 [10]
Score_sum	85.8	86.8	68.7	67.3	84.9	**96.7**	94.2	88.3
Rank-1	5	4	7	8	6	**1**	2	3
Rank-2	4	6	3	5	1	**2**	8	7
Overall - Rank	**3**	**4**	**4**	**8**	**2**	**1**	**4**	**4**

Then, coil specifications are decided for each model to get the highest efficiency under the max speed, and the characteristics of designed results are listed in Table II. The meanings of terms expressed with abbreviation in this table are as follows: PSR is the ratio of pole and slot numbers, T_ripple is torque ripple, and T_const is torque constant defined as the ratio of torque and current. The models are named the numbers of pole and slot (a letter 'P' after the number of the pole, and a letter 'S' after the number of the slot).

For the three parameters, T_ripple, T_const, and efficiency, the relative score is marked in square brackets to choose one model considering the required characteristics. Each value is converted to a relative score out of 10 points. When the values of T_ripple are converted, the reciprocal number of the value is considered. So this value has a high score when its value is low. On the contrary, the values of T_constant and Efficiency have a high score when its value is high.

Score_sum is the sum of the score of the three parameters considering weighting factor, which is different depending on the importance of the parameter. The weighting factors for T_ripple, T_const, and Efficiency are 1, 5, and 4 respectively. The rank is arranged in order of high score of Score_sum in Rank-1. The rank in Rank-2 is arranged in order of effective fabrication. It has the higher score if the model has the fewer numbers of poles and slots, and the simpler winding pattern.

Overall-rank is the average of Rank-1 and Rank-2, and the model 150P180S hold first rank.

IV. Selection of Rotor Topology

When field-weakening performance is not considered, SPM rotor has higher torque than any kinds of interior PM (IPM) rotor [5]. If only consider the torque density, SPM rotor is proper to this turret application. However, considering a possible external impact of the motor system, protecting PM is required. As shown in Fig. 2, both conventional and spoke type IPM rotors are investigated, and spoke type IPM rotor is selected since big reluctance torque can compensate the reduced PM torque, and it is more effective in the view point of manufacturing.

V. Decision of Outermost Dimensions

In Fig. 3 and Fig. 4 analysis results and FEA model are shown. These are to selection outermost dimensions such as motor inner and outer diameter, and axial length. In the extended paper, more analysis and test results will be explained in detail.

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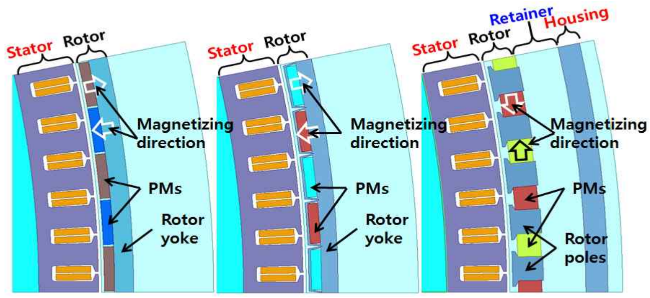

(a) SPM rotor (b) Conventional IPM rotor (c) Spoke type IPM rotor
Fig. 2. Three rotor topologies for 150P180S

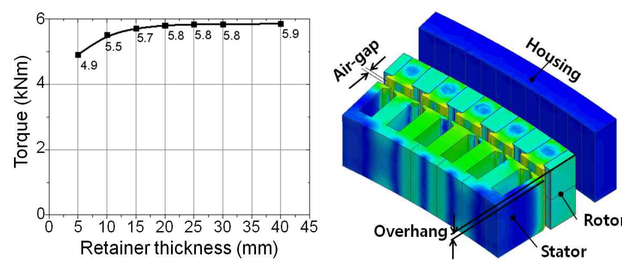

Fig. 3. Analysis result to select outer diameter (left), and FEA model to select axial length (right).

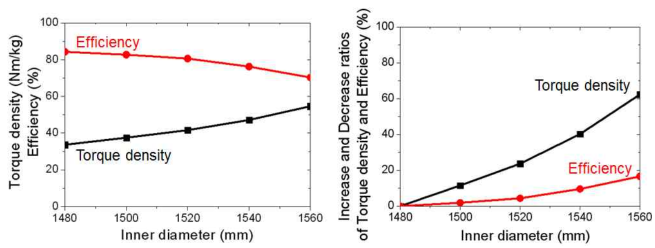

Fig. 4. Analysis results to select inner diameter