Optimal Design of a Two-phase BLDC Motor Considering Efficiency and Torque Ripple

Jae-Beom Kim*, Yong-Min You**, Sun-Il Kang*** and Byung-il Kwon†

Abstract – This paper introduces novel a two-phase permanent magnet BLDC (PMBLDC) motor with both an asymmetric tooth and an auxiliary tooth in order to improve the dead point, efficiency and torque ripple. To calculate the merits of introducing each of the asymmetric tooth and the auxiliary tooth, characteristic analysis is performed respectively using finite element method (FEM). To maximize performance, we propose a novel model which combines the asymmetric tooth and the auxiliary tooth. To maximize the efficiency of the novel model, an optimal design is processed using the Kriging method and a genetic algorithm. Finally, an experiment is used to confirm the initial and optimal design results.

Keywords: Two-phase PMBLDC motor, Asymmetric tooth, Auxiliary tooth

1. Introduction

Permanent magnet brushless DC (PMBLDC) motors have been used in various applications of electro-mechanical systems because of their high efficiency and good controllability over a wide range of speeds. PMBLDC motors also have several advantages over DC motors such as a longer lifespan, faster response, and high speed drive capability. Two-phase PMBLDC motors have a competitive price compared to three-phase motors and have been used extensively in small power applications such as pumps and cooling fans [1-2]. However, two-phase PMBLDC motors have a dead point where the developed torque is zero. When the motor carries a frictional load, it may possibly stop at the dead point and be unable to start again [3-4]. Until recently, many structural designs which have unequal air gap have been commonly used such as tapered, asymmetric, or stepped air gaps. Furthermore, slotted teeth for overcoming the dead point have been developed and researched [5-6]. Earlier studies have focused on overcoming the dead point without regard for other important characteristics [7-11], such as the efficiency and torque ripple. Therefore, further research considering the overall characteristics of two-phase PMBLDC motors is needed.

In this paper, we present a novel model that uses both asymmetry and auxiliary teeth in order to overcome the dead point and improve the efficiency and torque ripple.

Then, we use an optimal design process in order to maximize the efficiency of a two-phase PMBLDC motor. The optimization is performed by the Kriging method based on Latin hypercube sampling (LHS) and genetic algorithms (GA). Finally, we experimentally verify the improved performance of the optimal model.

2. Novel Two-phase PMBLDC Motor

The structure of an initial model for a two-phase PMBLDC motor is shown in Fig. 1 (a). The air-gap length is 1 mm, and the rotor has bonded NdFeB magnets with a radial thickness of 5 mm. The coil is made up of two windings in each slot. The double winding increases the rate of slot performance. In addition, the external drive circuit, which has a basic inverter consisting of two switches and two diodes, supports the drive of the machine as shown in Fig. 1 (b). This two-phase PMBLDC is applied to a hair dryer, taking advantage of its high efficiency and long-life compared to direct-current (DC) motors. Table 1 shows the specifications of a two-phase PMBLDC motor. The performance of the initial model will be discussed later.
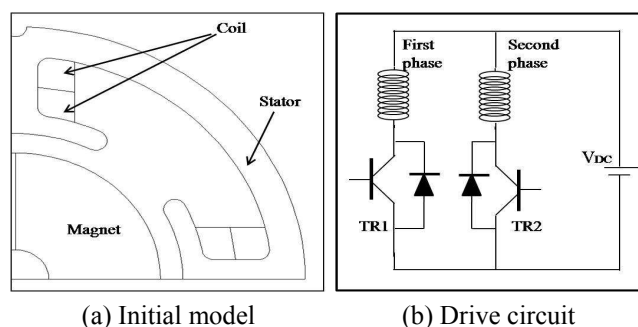

(a) Initial model   (b) Drive circuit

Fig. 1. Drawings of an initial model and drive circuit

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Table 1. Specification of the initial model

Item	Unit	Value
Pole/slot	-	4/4
Voltage	V	24
Rated current	A	0.72
Rated speed	rpm	11,500
Number of turns per phase	-	150
Outer diameter of stator	mm	56
Outer diameter of rotor	mm	26
Inner diameter of rotor	mm	15
Stack length	mm	24

2.2 The novel model using both asymmetric and auxiliary teeth

The two-phase PMBLDC motor, which uses one hall element, has a dead point. The dead point is the range where the torque is zero or negative, so it has negative influence on the motor performance at the starting and rating operation [12]. Our novel model, which has both an asymmetric tooth and an auxiliary tooth, is proposed to overcome the dead point and improve the average torque, efficiency, and torque ripple in the initial model.

2.2.1. Asymmetric tooth

In the initial model, a high cogging torque is generated by slot opening, giving it a high negative torque and torque ripple. The high negative toque generates the dead point, and the direction of rotation is indeterminate. To improve the negative torque and provide the preferred direction of rotation, the asymmetric tooth is absolutely necessary. The asymmetric tooth also has the advantage of improving the average torque at the rated speed due to reducing negative torque. Fig. 2 shows the asymmetric tooth and the degrees from the center of the tooth to the end of it.

To analyze the two-phase PMBLDC using FEM, JMAG-studio ver. 10 is utilized, which uses the nodal force method to estimate the torque. Fig. 3 (a) shows the torque curve based on an increasing degree of the asymmetric tooth from mechanical angle 0° to 43° at the starting operation. Although the starting torque has a positive value at mechanical angle 0 [°], the dead point is formed from mechanical angle 37 [°] to 43 [°]. As the degree of the
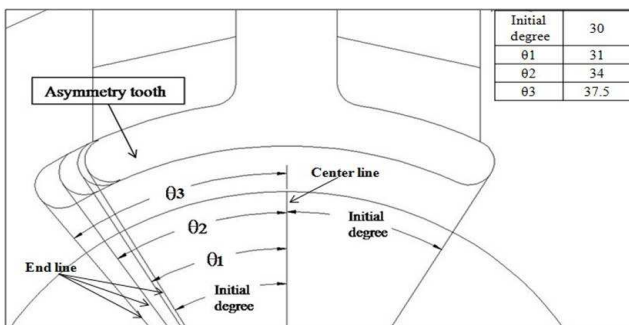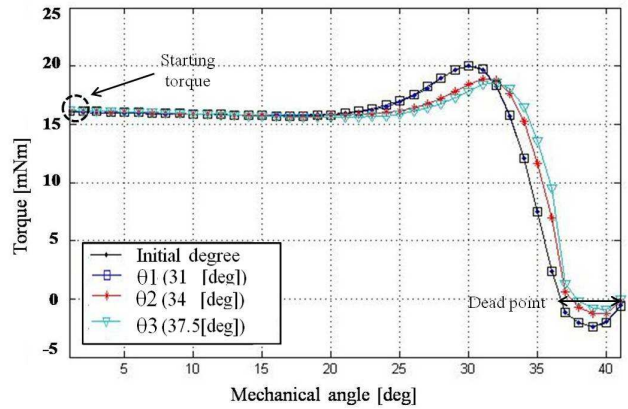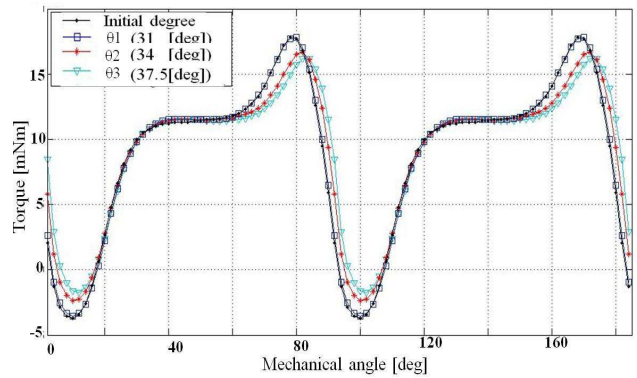

(a) Torque curve from mechanical angle 0 [°] to 43 [°] at starting operation

(b) Torque curve at the rated speed (11,500 [rpm])

Fig. 3. Torque curves by degree of the asymmetric tooth

asymmetric tooth increases, the negative torque on the dead point is reduced. Although the maximum value of the torque is decreased in a positive area, both the positive area and the negative area widen, which affect the dead point at starting. At the rated speed, the dead point is also improved by increasing the degree of the asymmetric tooth as shown in Fig. 3(b). As applied to the asymmetric tooth with 37.5 [°], the negative area is reduced 64 [%], and so the average torque is increased, compared to the initial degree. As the degree of the asymmetric tooth increases, the torque ripple is reduced by a little at the rated speed. As a result, the dead point and average torque are improved using the asymmetric tooth.

2.2.2 . Auxiliary tooth

Fewer fluxes are generated in a normal two-phase BLDC motor when the rotor poles align with the stator slot openings than in other positions. This causes a dead point and high torque ripple. Fig. 4 (a) shows a two-phase BLDC motor with an auxiliary tooth. The fluxes are increased when the rotor poles align with the auxiliary tooth as shown in Fig. 4 (b). Therefore, the auxiliary tooth can restrain the dead point and improve the torque ripple.
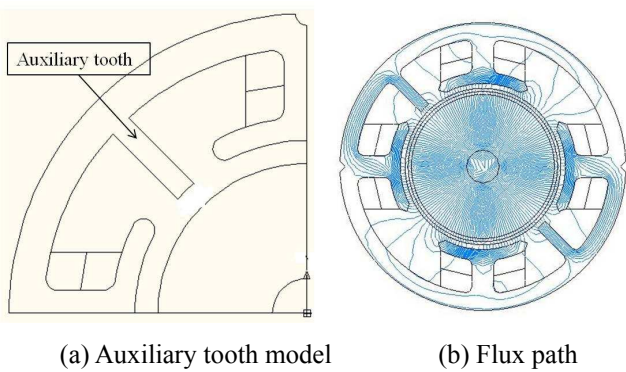

Fig. 2. Asymmetric tooth model

(a) Auxiliary tooth model (b) Flux path

Fig. 4. Auxiliary tooth model and the flux path when the rotor poles align with the auxiliary tooth

(a) Initial model (b) Novel model

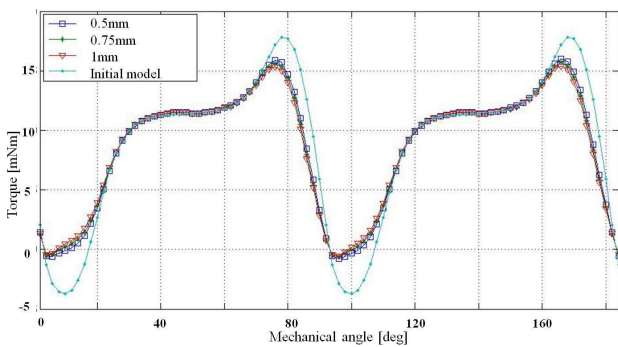**Fig. 6.** The shape of the initial and novel models

Fig. 5. Torque curve in different width of the auxiliary tooth at the rated speed (11,500 [rpm])

Fig. 7. Torque curves of the initial model and novel model at the rated speed (11,500 [rpm])

Fig. 5 shows a torque curve at the rated speed. The auxiliary tooth has width such as 0.5 [mm], 0.75 [mm], and 1 [mm]. With an auxiliary tooth of width of 1 [mm], the torque ripple is reduced by 26 [%] compared to the initial model. The dead point is also improved due to decreasing the minimum torque peak from 3.74 [mNm] to 0.54 [mNm]. Although the auxiliary tooth is applied, the average torque is almost the same as the initial model due to the reduction of both the maximum and minimum torque peaks. As a result, the auxiliary tooth is effective in improving the dead point and torque ripple by increasing its width.

2.2.3. Novel model

We have have previously previously touched mentioned the effect that an asymmetric tooth can have in improving the dead point and average torque, and that the auxiliary tooth can also improve the dead point and torque ripple. If either of them is applied, there will be a little improvement in performance. To maximize each effect, the asymmetry tooth and the auxiliary tooth have to be merged as a novel model. Fig. 6 shows a difference between the shapes of the initial model and the novel model. The novel model has an asymmetric tooth which is one and a quarter times larger than the initial degree, and also has an auxiliary tooth which has 1 [mm] thickness, as shown in Fig. 6 (b).
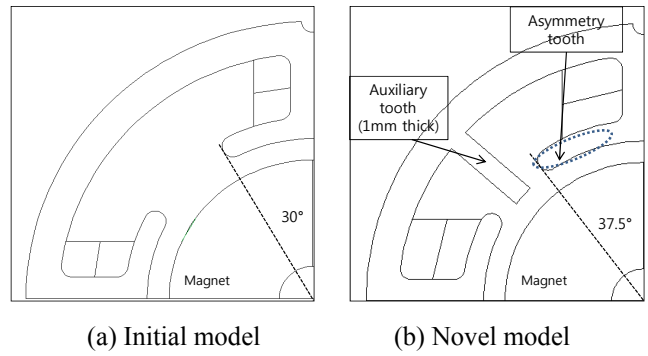
Table 2. Analysis results comparing the initial model and novel model

Item	Unit	Initial model	Novel model
Torque ripple	mNm	22.5	13
Average torque	mNm	8.6	9.3
Efficiency	%	42	45.8

7 and Table 2 show analysis results of the initial model and novel model at the rated speed. During the FEM analysis, the rated current is 0.72 [A] and phase shifting between the armature current and open circuit flux linkage is zero. Also, the resistive winding losses and core losses of 50H1300 in a laminated iron core are calculated. For the core loss calculation, an iron loss calculation tool in JMAG-studio is used. Additional AC joule loss by the skin effect and eddy current loss in magnet are not considered. The dead point, torque ripple, average torque, and efficiency of the novel model are improved. Particularly, the dead point is improved because of the reduction of the negative torque. The torque ripple is reduced by 42 [%] due to the reduction in both the maximum and minimum torque peaks. The average torque and efficiency are also increased by 7.6 [%] and 3.8 [%], respectively.

3. Optimal design

To improve the efficiency, we optimize the novel model. The optimal design variables are selected, which have an influence on the efficiency, torque ripple and average torque to overcome the dead point. Then, we determine the optimal design with the objective function and constraint functions. In considering the nonlinearity of these optimal design variables, the LHS, Kriging model, and GA are used, as shown in Fig. 8.
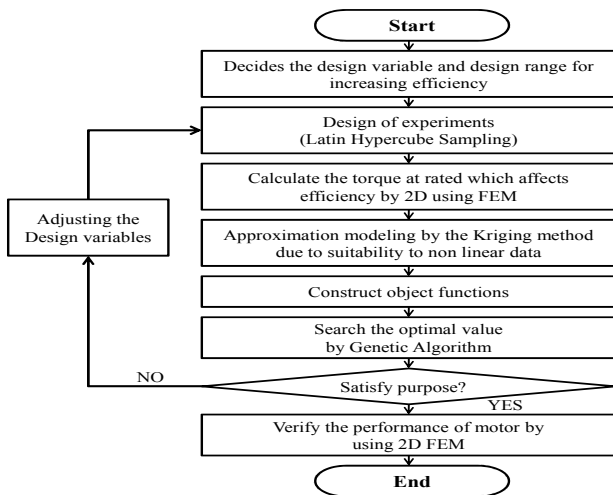

Fig. 8. Optimal design process.

3.1. Optimization techniques

3.1.1. Kriging model

The optimization process is applied for the two-phase BLDC motor to increase its efficiency by using the Kriging method based on LHS. Generally, in the response surface method (RSM), a 2nd polynomial regression (PR) model, is used for fitting the data. However this model is not adequate to approximate a nonlinear function such as inductance parameters, cogging torque and torque ripple estimated because of the low-order PR of RSM. To reduce these drawbacks, for global optimization, a Kriging model using stochastic processes could be applied to the optimal design of two-phase BLDC motor. [13]

The Kriging method is an interpolation method [13] composed of the global model and the localized deviation

$$y(x) = f(x) + Z(x) \tag{1}$$

where, $y(x)$ is the unknown function, $f(x)$ is the known approximation (usually polynomial) function in the region of the design parameter and $Z(x)$ is the realization of a stochastic process with average zero, variance and nonzero covariance. $y(x)$ is the interpolated point via Kriging corresponding to the true function $f(x)$ with $Z(x)$ denoting

the error deviation of the predicted value $y(x)$ from the true function $f(x)$. $Z(x)$ presents the localized deviation from the global model $f(x)$.

3.1.2. Latin hypercube sampling

Latin hypercube sampling was found to be more accurate than either random sampling or stratified sampling for estimating the means, deviations and distribution functions of an output. Moreover, it ensures that each of the input variables has all portions of its range represented [14-15].

3.2. Objective function, constraints and design variables

The objective function is the maximization of the efficiency and the constraint functions are the average torque and torque ripple as in (2) and (3).

Maximize	*Efficiency*	(2)
Constraints	*Average torque* > 9.3 [mNm]	(3)
	Torque ripple < 13 [mNm]	

Several optimal design variables are selected: the asymmetry tooth length [A], tooth thickness [B], tooth neck angle [C], and auxiliary tooth thickness [D] considering the torque ripple, average torque, leakage and concentration of flux in the optimization process, as shown in Fig. 9. The range of the optimal design variables [A] and [D] are based on the slot-opening length, as shown in Table 3.
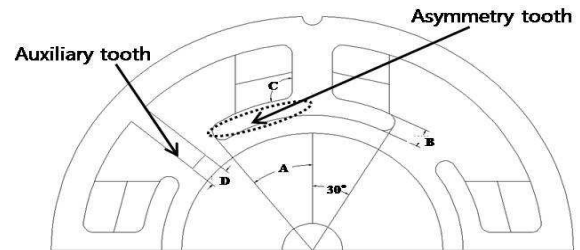

Fig. 9. Topology of the novel model and design variables

Table 3. Range of the optimal design variables

Optimal design variable	Unit	Range	
		min	max
A	degree	31	40
B	mm	1	1.2
C	degree	116	140
D	mm	0.7	1

3.3. Optimal design results

The convergence progresses for obtaining the optimal points are conducted by using GA, as shown in Fig. 10. The optimal design variables converge well during 200 iterations. The value of design variables of the optimal model are compared with the novel model, as listed in

Table 4.

The dead points of the novel model and the optimal model are better than that of the initial model due to the reduction of the negative torque, as shown in Fig. 11. Fig. 12 and Table 5 show the analysis results of the initial,
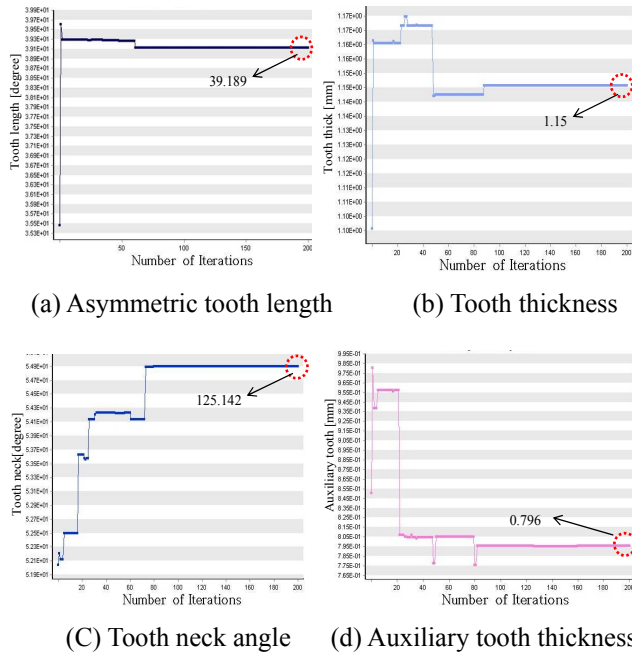
novel and optimal model at the rated current to 0.72[A]. And the phase shifting condition between the armature current and open circuit flux linkage is zero. As compared to the novel model, the optimal model had reduced torque ripple of 6.2 [%], and increased average torque of 4.3 [%] and efficiency of 0.4 [%].

Figs. 13 and 14 show the Back EMF and the cogging torque wave forms of the initial, novel and optimal model at the rated speed. The Back EMF of the optimal model is increased by 16 [%] and the cogging torque is reduced 65.7 [%] compared to the initial model as shown in Figs. 13 and 14. In additionally, self-inductance is 2.541 [mH] when the rated current is 0.72 [A]. It is calculated by the inductance calculation tool of JMAG-studio.

(a) Asymmetric tooth length   (b) Tooth thickness

(C) Tooth neck angle   (d) Auxiliary tooth thickness

Fig. 10. Convergence progress of optimal design variables by GA

Table 4. Comparison of the value of design variables between the novel model and the optimal model

Design variable	Unit	Novel model	Optimal model
A	degree	37.5	39.189
B	mm	1	1.150
C	degree	-	125.142
D	mm	1	0.796
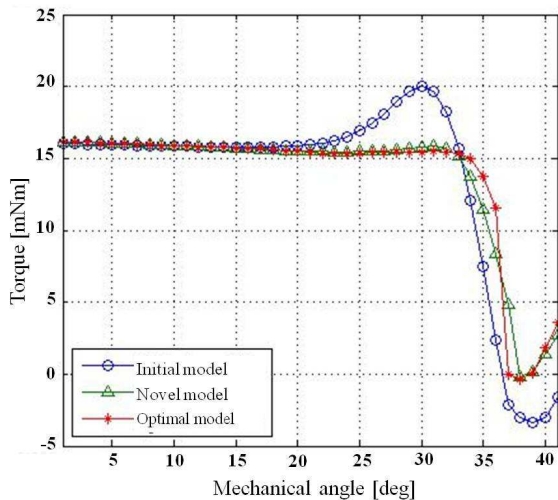
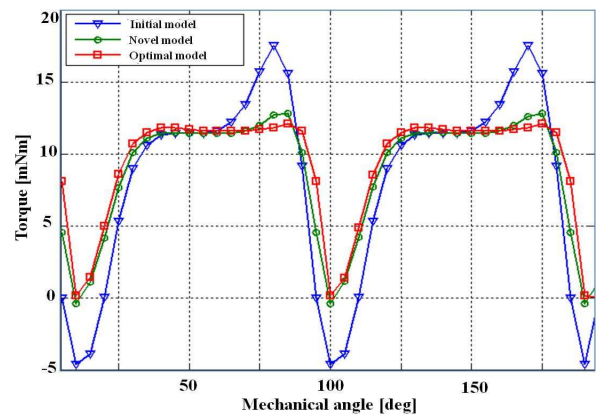**Fig. 11.** Torque curves of the initial model, novel model and optimal model at starting operation

Fig. 12. Torque curves of the initial model, novel model and optimal model at the rated speed (11,500 [rpm])

Table 5. Analysis results of the initial model, novel model, and optimal model

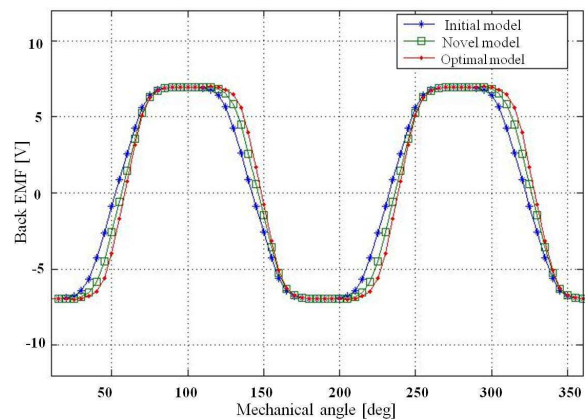| Item	Unit	Initial model	Novel model	Optimal model
Torque ripple	mNm	22.5	13	12.2
Average torque	mNm	8.6	9.3	9.7
Efficiency	%	42	45.8	46.2

Fig. 13. Back EMF of the initial model, novel model and optimal model at the rated speed (11,500 [rpm])
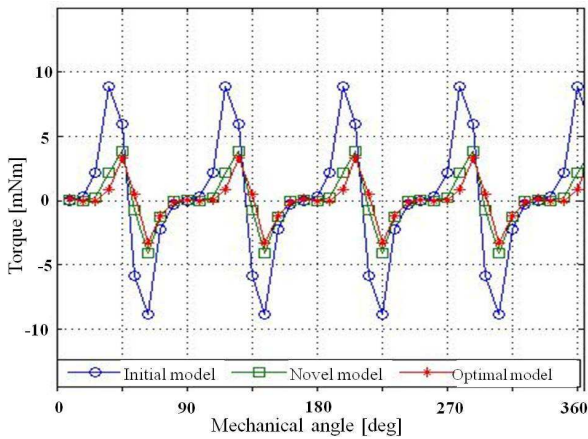
Fig. 14. Cogging torque waveforms of the initial model, novel model and optimal model at the rated speed (11,500 [rpm])

4. Experiment

The initial model and optimal model of the two-phase PMBLDC motor were manufactured in order to verify the analysis results. A prototype of the optimal model and a motor drive are illustrated in Fig. 15 (a). The input and output power, efficiency and torque were measured by a power meter and torque meter, as shown in Fig. 15 (b).
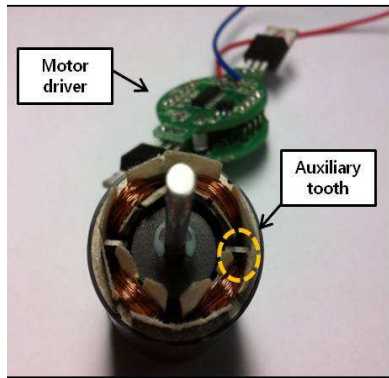
(a) Prototype and motor drive
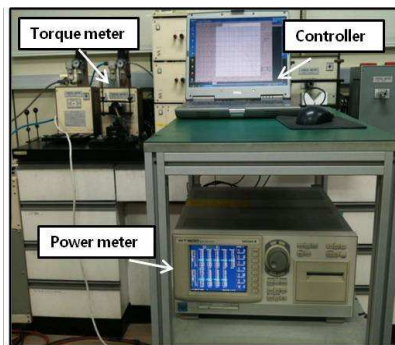
(b) Measurement set-up

Fig. 15. Prototype and measurement set-up

Table 6. FEM analysis results and experiment results of the initial model and optimal model

Item	Unit	Initial		Optimal	
		FEM	Exp.	FEM	Exp.
Efficiency	%	42	42.29	46.2	46.63

Table 6 showed the FEM results and experimental results of the efficiency of the initial model and optimal model at the rated speed. The experimental results of the efficiency of the initial model and optimal model were in close agreement with the FEM results.

5. Conclusion

Based on the FEM results, the asymmetry tooth can improve the dead point and average torque by reducing the negative torque. The auxiliary tooth can also improve the dead point and torque ripple through forming a flux path. To improve the characteristics of a two-phase PMBLDC, we have introduced a novel model combining the asymmetric tooth and the auxiliary tooth. This novel model can maximize the advantages of the asymmetric tooth and the auxiliary tooth. To improve performance of the novel model, an optimal design was applied, and its usefulness was verified by the experimental results.

Acknowledgements

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