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MTPA Control Concept of BLDC Motor Using 2-step Voltage Level for High Efficiency

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BLDC motor has the high efficiency, high power density, low acoustic noise, and low maintenance cost due to the removal of the mechanical commutators and brushes. In the general design and driving control technology about BLDC motor, the square waveform phase current has been known as the ideal current waveform to get high torque production and high efficiency driving characteristics. But in here, the kinematic vector characteristics of magnetic force between stator and rotor pole is not considered. Conventionally recommended square wave current has no consideration about this vector angular feature of magnetic force. This paper studied about this vector potential separation of magnetic force during torque production to generate maximum torque per ampere (MTPA). The modified current waveform for MTPA is suggested by this study. In addition, this paper also suggests 2-step voltage control method for MTPA and high efficiency driving. The optimal voltage control condition is derived by DOE (Design of Experiments) and RS (Response Surface). This suggested control method is validified by finite element analysis (FEA) using voltage source operation to simulate real driving condition. As a result, the suggested control method can be a good driving control technology to maximize the output torque per ampere and improve the driving efficiency.

Keywords : BLDC motor, MTPA, 2-step voltage control, high efficiency

1. Introduction

BLDC motors have been popular with industrial fields, because it has the high efficiency, high power density, low acoustic noise, and low maintenance cost due to the removal of the mechanical commutators and brushes [1-4].

It is known that BLDC motor is operated ideally, when a rectangular shape phase current is injected at the flat part of back-EMF (BEMF) waveform. However, practically, phase current is not achieved to rated current level instantaneously due to the inductance component of stator windings [5-7].

Assuming that the field flux of rotor and armature current of stator are constant, it has been argued that the output torque of the ideal BLDC motor is constant. But in here, the kinematic vector characteristics of mechanical force caused by magnetic force between stator and rotor pole is not considered.

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From the conventional torque production theory, the generated torque is proportional to vector product of stator and rotor flux axis. This theory is basically correct. But, in the real torque production mechanism of BLDCM, the concept of the magnetic force operating points between the pole face of stator and rotor pole are not included in this theory. The stator's magnetic force to pull the rotor pole face can be divided as the tangential direction force and the radial force. This tangential force could be contributed to torque. When some stator poles are excited, the tangential and radial vector potentials of magnetic force between stator and rotor flux are changed according to rotor pole position. Conventionally recommended square wave current has no consideration about this vector angular feature of magnetic force. This paper studied about this vector potential separation of magnetic force during torque production to generate maximum torque per ampere (MTPA).

The modified current waveform for MTPA is suggested by this study. In addition, this paper also suggests 2-step voltage control method for MTPA and high efficiency driving. The more delicate multi-step control of voltage or current would be better if it is possible considering the hardware performance of controller.

The optimal voltage control condition is derived by DOE (Design of Experiments) and RS (Response Surface). This suggested control method is validified by finite element analysis (FEA) using voltage source operation to simulate real driving condition.

As a result, the suggested control method can maximize the output torque per ampere and improve the driving efficiency.

2. Output Torque Analysis of BLDC Motor

In the ideal switching control pattern, BLDC motor has assumed that the rotor and stator fluxes are always orthogonal. Therefore, the BLDC motor is assumed as operated ideally, when the square waveform phase current is injected at the flat part of BEMF waveform as shown in Fig. 1. However, current is not achieved to rated current level instantaneously due to current delay time by the inductance of stator windings.

However, the stator and rotor flux of BLDC motor are not always orthogonal due to the two-phase conduction mode operation. In the two-phase conduction mode, there are six combinations of the stator excitation in one cycle. Each combination lasts for 60 electrical degrees, which is called normal conduction period. In the normal conduction period, only two phases are conducted. Due to this, the stator flux is stopped and only the rotor flux is rotated. This fact has not been considered before, and this paper takes this into account by calculating the force according to the change in the angle between magnetic fluxes in an arbitrary conduction section.

Figure 2 shows the flux and magnetic force contributed

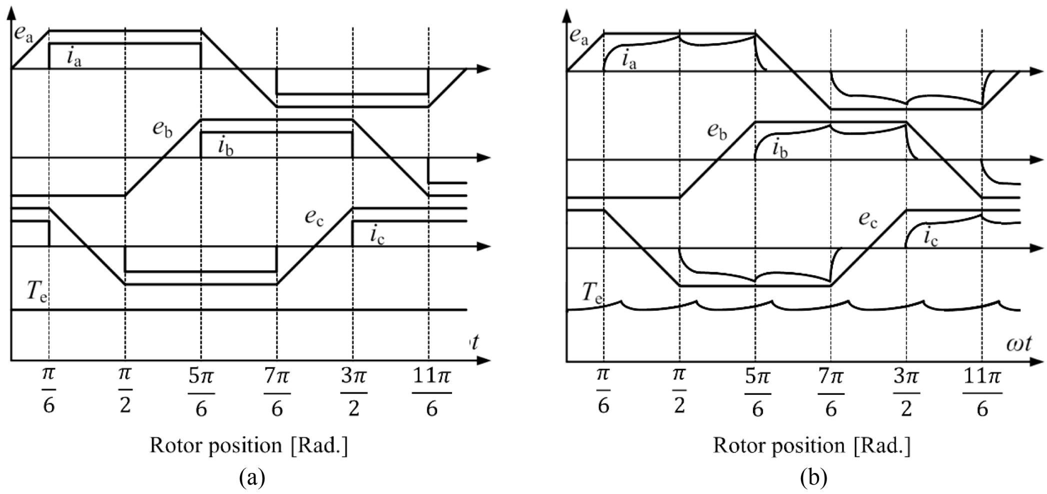

Fig. 1. BEMF and current waveform of ideal and real BLDC motor (a) ideal current waveform, (b) real current waveform.

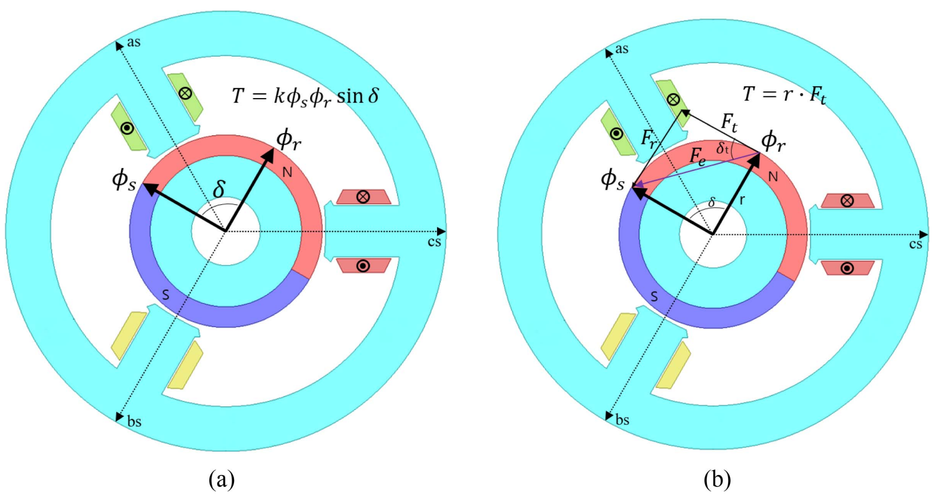

Fig. 2. (Color online) Magnetic flux and force vector of BLDC motor (a) Conventional torque concept, (b) suggested torque concept considering magnetic force vector.

to torque during rotor position θ is located π/2~5π/6 in Fig. 1. From the conventional torque production theory, the generated torque is proportional to vector product of stator and rotor flux axis as shown in Fig. 2(a). But, in the real torque production mechanism of BLDCM, the kinematic concept of the magnetic force operating points between the pole face of stator and rotor pole are not considered in this theory.

As in Fig. 2(b), the stator's magnetic force to pull the rotor pole face can be divided as the tangential direction force and the radial force. This tangential force is important, and it could be contributed to torque.

The generated torque can be expressed as in Eq. (1) as the multiply of rotor outer radius and tangential direction force of force operating point.

$$T = r \cdot F_t \tag{1}$$

Where, T is torque, r is radius of rotor, F_t is tangential force on the rotor surface, respectively. When the shape of the rotor is cylindrical, the output torque is determined according to the magnitude of the tangential force of the rotor, and the output torque of motor according to the position of rotor can be analyzed by calculating the magnitude of tangential force. The magnitude of the electromagnetic force induced by the field and the armature can be expressed by the relationship between the rotor flux and the armature current as shown in Eq. (2).

$$F_e = \frac{N_p}{2} \cdot l_{stk} \cdot B_r \cdot i_s \cdot \sin\delta \tag{2}$$

Where, F_e is electromagnetic force, N_p is number of poles, l_{stk} is stack length of motor, B_r is flux density of rotor, i_s is armature current, δ is angle between the rotor flux and armature current, respectively. If the flux density of rotor and armature current in Eq. (2) are expressed as a rotor flux ϕ_r and stator flux ϕ_s, it can be expressed as Eq. (3).

$$F_e = \frac{N_p}{2} \cdot l_{stk} \cdot \frac{\phi_r}{A_g} \cdot \frac{N_t}{L_s}\phi_s \cdot \sin\delta \tag{3}$$

In Eq. (3), A_g is the air-gap side area of permanent magnet, N_t is the number of conductors of the armature winding, and L_s is the inductance of armature winding.

From Eq. (3), if the remaining terms excluding ϕ_r, ϕ_s and sin δ are substituted with K_f, it is expressed simply as in Eq. (4). In Eq. (4), δ varies from 2π/3 to π/3 depending on the rotor position.

$$F_e = K_f \cdot \phi_r \cdot \phi_s \cdot \sin\delta \tag{4}$$

Figure 2(b) shows the F_e generated by the magnetic flux when the phase A and B is conducted. The radial force component F_r is a component that does not affect the angular momentum of the rotor, and the tangential force component F_t acts in the tangential direction of the rotor to change the angular momentum.

Where, δ_t is angle between the F_e and F_r. The relationship between F_e and each component shown in Fig. 2(b) can be expressed as Eq. (5). The δ_t calculation formula according to the rotor position can be derived as shown in Eq. (6).

$$\begin{aligned} F_r &= F_e \cdot \sin\delta_t \\ F_t &= F_e \cdot \cos\delta_t \end{aligned} \tag{5}$$

$$\delta_t = \tan^{-1}\left(\frac{\phi_r + \phi_s \sin\left(\delta - \frac{\pi}{2}\right)}{\phi_s \cos\left(\delta - \frac{\pi}{2}\right)} \right) \tag{6}$$

By substituting Eq. (4) and Eq. (6) into Eq. (5), the F_r and F_t can be expressed as a function of the ϕ_r, ϕ_s and δ as shown in Eq. (7) and (8).

$$F_r = K_f \phi_r \phi_s \sin\delta \sin\left\{ \tan^{-1}\left[\frac{\phi_r + \phi_s \sin\left(\delta - \frac{\pi}{2}\right)}{\phi_s \cos\left(\delta - \frac{\pi}{2}\right)} \right] \right\} \tag{7}$$

$$F_t = K_f \phi_r \phi_s \sin\delta \cos\left\{ \tan^{-1}\left[\frac{\phi_r + \phi_s \sin\left(\delta - \frac{\pi}{2}\right)}{\phi_s \cos\left(\delta - \frac{\pi}{2}\right)} \right] \right\} \tag{8}$$

ϕ_r and ϕ_s of an ideal BLDC motor can be assumed to be

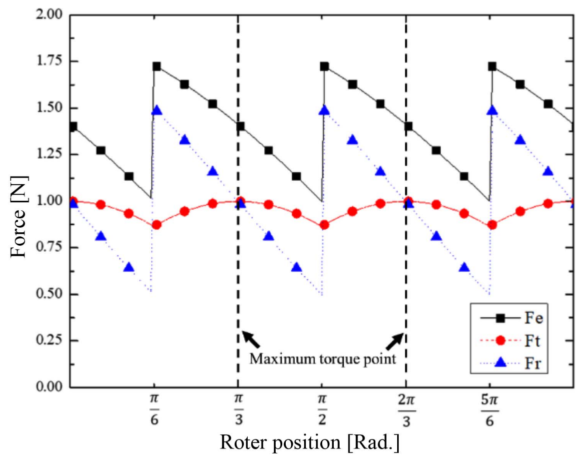

Fig. 3. (Color online) Calculation result of tangential force and radial force according to rotor position.

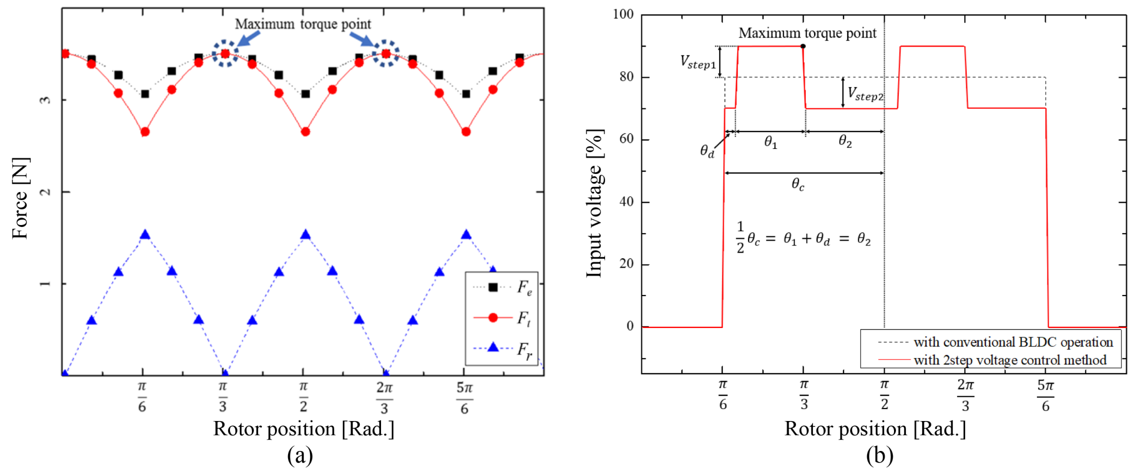

Fig. 4. (Color online) Maximum torque point (a) and phase voltage switching pattern of conventional and proposed method (b).

constants that do not change depending on the rotor position, and Fig. 3 shows the calculation result of Eq. (7) and (8) based on the ideal back electromotive force and constant armature current.

When some stator poles are excited, the tangential and radial vector potentials of magnetic force between stator and rotor flux are changed according to rotor pole position.

Figure 3 shows the calculation result of tangential force and radial force according to rotor position. According to the result in Fig. 3, since F_t changes according to the rotor position, it can be inferred that the efficiency of the BLDC motor can be improved by controlling the phase current to be maximized at the nearby of maximum torque point.

Figure 4 shows the maximum torque point and the phase voltage switching control pattern to use usefully this point to improve torque production per same average current. Conventionally recommended square wave current has no consideration about this vector angular feature of magnetic force. This paper suggested 2-step voltage level control method to generate maximum torque per ampere (MTPA).

The proposed 2-step voltage control method is able to control the current through a changing of input voltage according to rotor position as described in Fig. 4(b).

Where, the V_{step1} and V_{step2} are amplitude of voltage variation, θ_c is conduction period, θ_d is lagging angle of θ_1, θ_1 and θ_2 is conduction section before and after the maximum torque point, respectively.

The proposed method is aims to control the amplitude of current by increasing the voltage by V_{step1} during section θ_1 before the maximum torque generation point and lowering the voltage by V_{step2} in subsequent section θ_d and θ_2. The reason for controlling the voltage based on the maximum torque point is due to the change of current

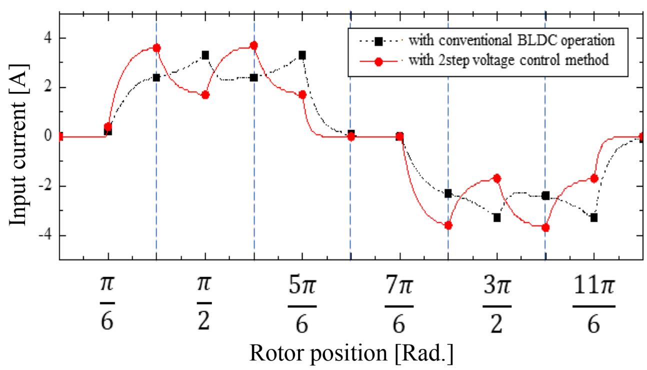

Fig. 5. (Color online) Comparison of current waveform according to operation method.

is delayed by the inductance of the stator winding. Because of the increased input voltage during θ_1 before the maximum torque point, the current can be achieved to higher than conventional BLDC operation method at the maximum torque point as shown in Fig. 5. This change helps the increase of torque per ampere of motor.

3. Modeling and Results

To verify the proposed 2-step voltage control method, finite element analysis, DOE and response optimization was performed. FEA model and circuit diagram of voltage source inverter drive is applied to simulate the instantaneous driving characteristics considering control methods is shown in Fig. 6.

Table 1 shows the specification of target motor. The range of the input voltage was based on the rated input voltage of target motor, and the maximum value of V_{step1} and V_{step2} was selected not to exceed the DC link voltage.

In the main effects plot shown on the left side of Fig. 6,

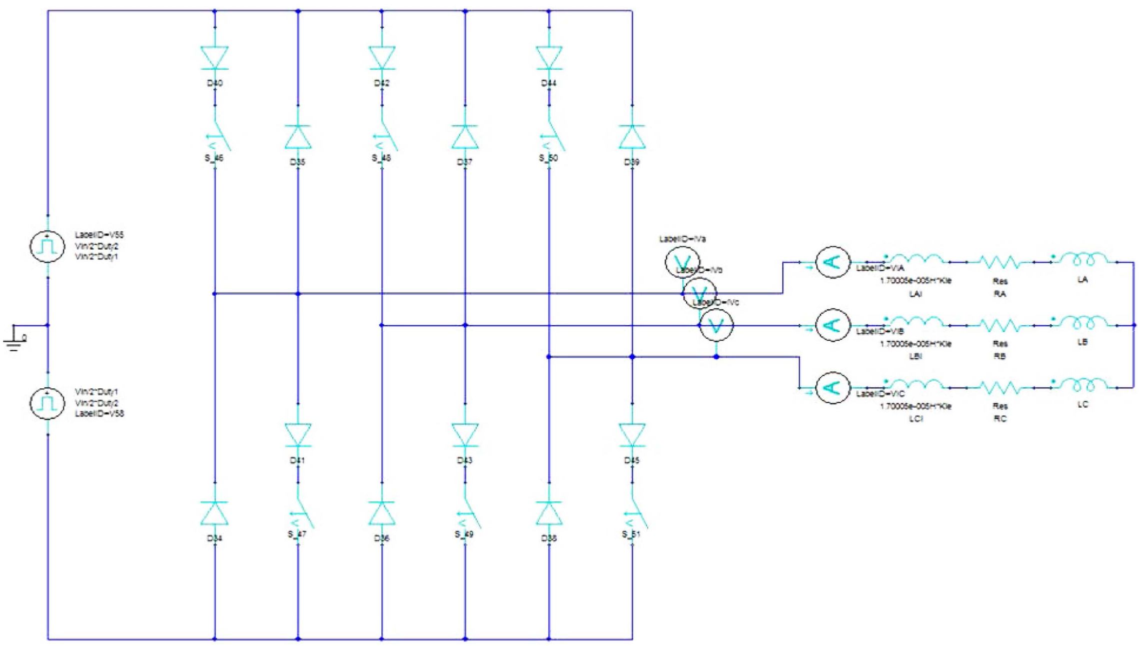

Fig. 6. (Color online) Model and circuit diagram for implementing the proposed voltage control method.

Table 1. The Specifications of target motor.

Parameter	Unit	Value
Rated output power	kW	2.5
Rated speed	rpm	3,000
Rated torque	Nm	8.2
Rated input voltage	V	310
Outer diameter of stator	mm	118
Radius of rotor	mm	63
Axial length	mm	70
Magnet grade	-	NdFeB 40UH
Core material	-	30PNF1600

the effect of θ_d, V_{step1} and V_{step2} is analyzed based on the median value of the remaining two factors to analyze the correlation between the factors. Based on the results of analyzing the influence between each factor, the optimal value of each factor can be derived through response optimization as shown in the right side of Fig. 7.

As shown in Fig. 7, θ_d was expected to have only a small change compared to other factors, and V_{step1} expected to have a tendency to gradually decrease the amount of change. Unlike other factors, V_{step2} showed a different tendency before and after based on the median value. The

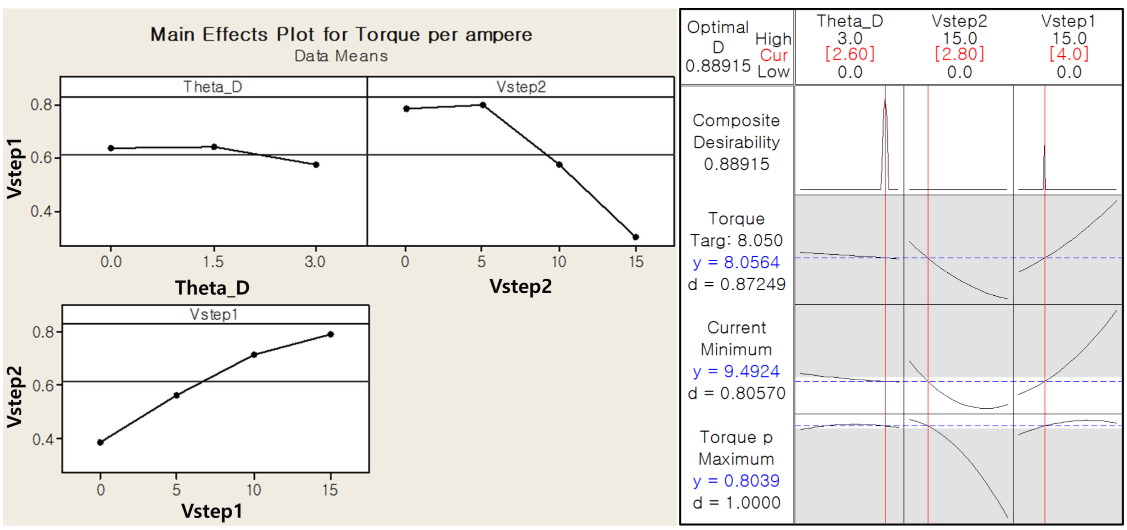

Fig. 7. (Color online) Main effects plot and response optimization result.

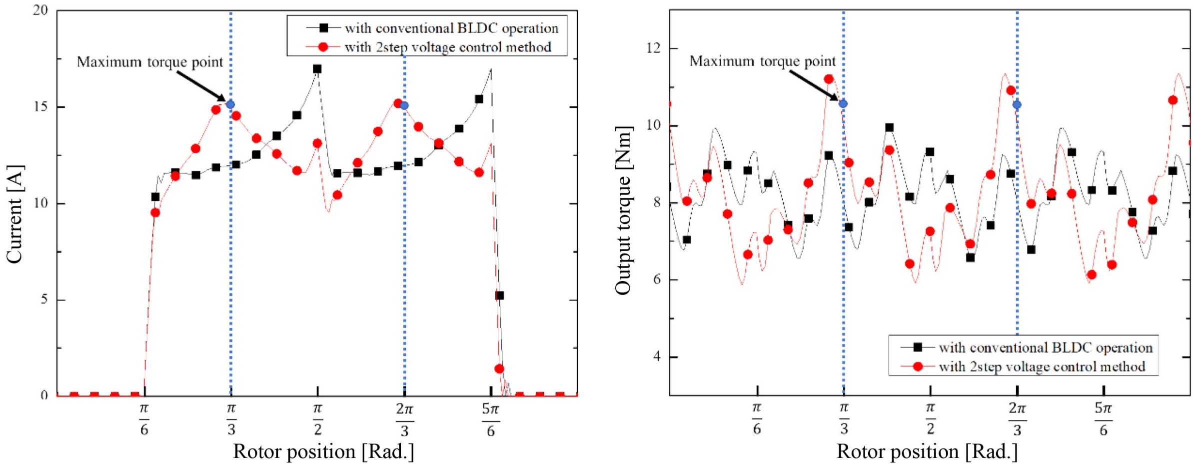

Fig. 8. (Color online) Input current and output torque analysis result according to drive method.

Table 2. Output characteristics analysis result according to operation method.

Parameter	Conventional	Proposed
Output torque [Nm]	8.05	8.05
Input current [A_{rms}]	10.3	9.3
Core loss [W]	38.9	38.8
Copper loss [W]	158.8	129.7
Input power [W]	2726.3	2699.3
Output power [W]	2528.6	2530.8
Efficiency [%]	92.8	93.7
Torque per ampere [Nm/A]	0.78	0.87

increase of V_{step2} in the section before the median value does not have a big effect on the torque per current, but V_{step2} becomes the factor that has the greatest influence in the section after the median value.

The optimum combination of each design factor was determined to maximize the efficiency of the target motor by using the response optimization. The response optimization was performed based on an objective function that maximizes efficiency and torque per current and minimizes current while maintaining the same output torque.

Based on these analysis results, an optimum value of V_{step1}, V_{step2} and θ_d that improves efficiency while having the same output as initial model was derived as shown in Fig. 8. By applying the proposed driving method, it can be confirmed that the current and torque are increased near the maximum torque point.

In the Table 2, the output and loss characteristics are compared according to the driving method applied to the target motor. The input current is decreased by about 11 % with same output torque. On the loss side, the core loss is the same, and only the change of copper loss according to the decreased input current was confirmed. Due to the reduced copper loss, the efficiency of target motor is improved by about 1 %.

4. Conclusion

In this paper, 2-step voltage control method was proposed based on the result of analyzing the output torque according to the rotor position of BLDC motor.

The maximum output torque point of the BLDC motor was derived through the correlation of stator and rotor flux, and based on this, a voltage control method for improving the efficiency was presented. According to optimization result based on FEA result, it is verified that due to the decreased input current by applying the proposed method, the efficiency was improved by about 1 % compared to the conventional method.

Acknowledgement

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