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Phase Advance Control to Reduce Torque Ripple of Brush-less DC Motor According to Winding Connection, Wye and Delta

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Abstract – In this research, the characteristics of Brush-less DC (BLDC) motor in accordance with winding connection method, both Y-connection and Δ-connection, has been identified with design methodology simply. BLDC motor has been designed for both winding connections, and their torque analysis has been performed considering ideal current source analysis and voltage source analysis with 6-step control. In addition, to reduce torque ripple of BLDC motor, caused by coil inductance, on voltage source analysis with 6-step control, we have proposed suitable control method which is Phase Advance Control. It is verified that the torque ripple has been decreased by virtue of phase advance control, advancing and widening conduction angle of switching, via performance analysis by Finite Element Analysis.

Keywords: Brush-less DC motor, Winding connection method, Current source analysis, Voltage source analysis, Phase advance control, Finite element analysis

1. Introduction

Brush-less DC (BLDC) motor guarantees extraordinary performances of efficiency, power density, and various speed range capability [1]. Owing to these characteristics and reasonable cost, BLDC motor is applied in various industrial fields such as appliances, communications, tractions, and even servomotor with assistance of simple operating system.

Since BLDC motor is controlled by semiconductor switching device instead of brush and commutator, it has distinctive structure of stator with armature winding and rotor with permanent magnets (PMs) compared to the general DC motor [2-4]. As a result, it has advantages on giving variations to the structure. Thus, it is possible to optimize the structure of BLDC motor for various purposes such as size minimization, flattening, and etc. [4]. BLDC motor has a decided advantage over speed variance because of smaller inertia than general DC motor. Moreover, BLDC motor can operate at high speed region owing to the absence of a commutator and brush which can cause a problem on mechanical friction or commutation, etc. Also, it is easy to protect against heat since winding is located at stator, not rotor. It leads to have an advantage on producing maximum output torque of BLDC motor compared with one of conventional DC motor which has an armature current limit due to avoiding demagnetization of PMs. In addition, it generates higher power density about 15% than Permanent Magnet Synchronous Motor (PMSM). The reason for this is Root Mean Square (RMS) value of BLDC Back-Electro Motive Force (BEMF), trapezoidal waveform, is larger than one of PMSM BEMF, sinusoidal waveform [5].

To implement an electric rectification, it is essential to adopt semiconductors on actuation circuit for switching phase currents. For this reason, the research on topology of actuation circuit for BLDC motor is being carried out [3, 6].

In this paper, the design of BLDC motor has been performed according to winding connection, “Y-connection, 2-phase excitation system” and “Δ-connection, 3-phase excitation system”, respectively. In addition, it is accomplished that ideal current source analysis and voltage source analysis via designed models considering both winding connections, mentioned above, and their torque analysis by Finite Element Analysis (FEA). Finally, the control method, phase advance control, has been introduced for reduction of torque ripple caused by coil inductance in real driving circumstance.

2. BLDC Motor and Control Method

2.1 Governing equation for BLDC motor

For reference, the conventional BLDC 3-phase voltage equation can be represented as follow:

$$V_{abc} = R_s i_{abc} + L_s \frac{di_{abc}}{dt} + e_{abc} \tag{1}$$

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where, R_s is phase resistance, L_s is inductance, and e_{abc} denotes BEMF of each phase.

The output power equation is given by:

$$P_e = e_a i_a + e_b i_b + e_c i_c \tag{2}$$

where, i_a, i_b, i_c represent the current of each phase, respectively.

The torque equation of 3-phase BLDC motor can be formulated from output power, P_e, and angular frequency of rotor, ω_m, as following Eq. (3):

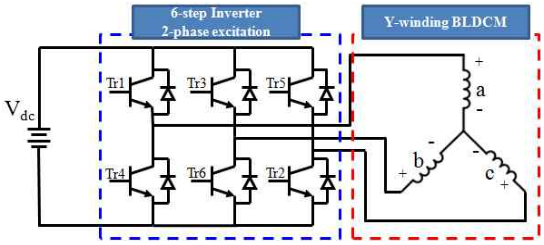
$$T^e = \frac{P_e}{\omega_m} = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_m} \tag{3}$$

2.2 Characteristics of BLDC motor according to winding connection

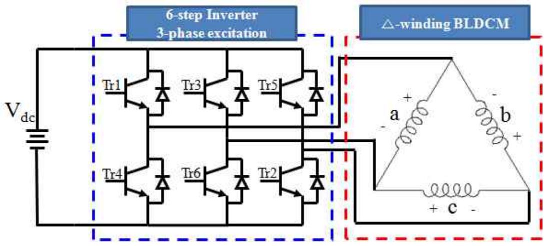
BLDC motor requires a trapezoidal waveform of BEMF, and it can be obtained in concentrated winding, normally. This characteristic differs markedly from BLAC motor with sinusoidal BEMF waveform. The torque is occurred by product of BEMF and phase current, expressed as Eq. (3). Therefore, input current should be a square wave analogous to BEMF, so we call a BLDC motor as square-wave drive motor. A major difference between Y-connection and Δ-connection is a requisite flat-top width of phase BEMF, 120° for Y-connection and 60° for Δ-connection, besides winding method. This flat-top width of BEMF is not an automatic consequence of only connecting the winding in Y or Δ differently. Therefore, the winding pitch and/or the pole-arc must be designed to satisfy each model BEMF condition. It is important to avoid triplen-harmonics, defined as the odd multiples of the 3^{rd} harmonics, in the phase BEMF, otherwise there will be a circulating current in the Δ-connection. In addition, saliency, ratio of inductance in d-axis and q-axis, is undesirable with square-wave drive, because it produces a reluctance torque, causing a vibration and noise, that varies as the rotor rotates. For this reason, the most common square-wave motors have surface-mounted magnets [7].

Fig. 1 shows the equivalent circuit of BLDC motor in accordance with winding connection method; (a) is for Y-connection and (b) is for Δ-connection. The Y-connection and Δ-connection have a same circuit and switching till input terminal of motor, represented as the blue dotted line. However, as the red dotted line marks, the flow sequence of phase current is different in the two cases.

By way of example, Fig. 2 indicates the flow of input current from DC supply to motor at a particular step in 6-step inverter control. In case of Y-connection, when two switches out of six switches are ‘on’, only two phases are excited, which is noted “Y-connection, 2-phase excitation system”. On the other hand, all of three phases are excited at same condition in Δ-connection, called “Δ-connection, 3-phase excitation system”.

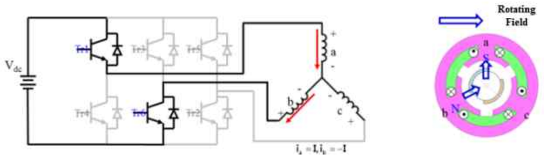


(a) Y-connection, 2-phase excitation system

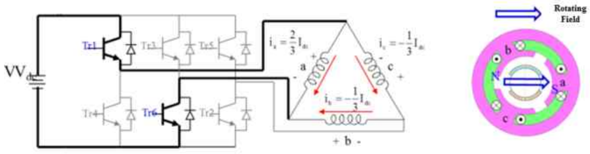


(b) Δ-connection, 3-phase excitation system

Fig. 1. Equivalent circuit of BLDC motor according to winding connection



(a) Y-connection, 2-phase excitation system

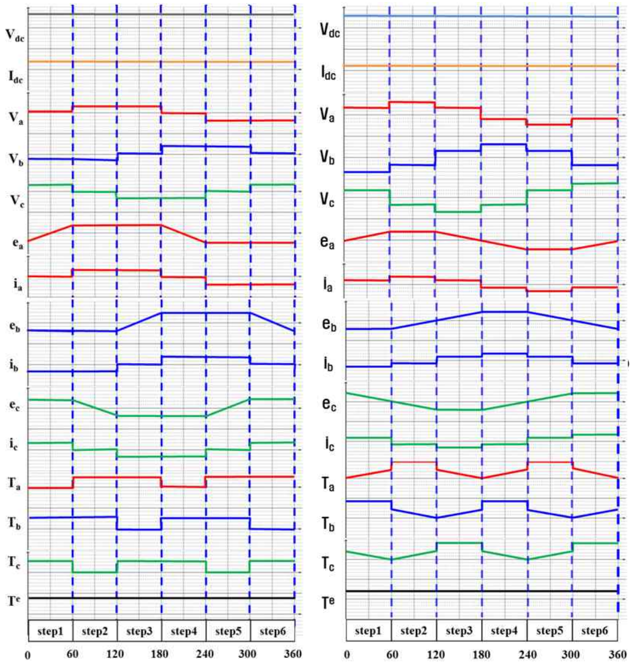


(b) Δ-connection, 3-phase excitation system

Fig. 2. Current flow example at one of 6-step control

Theoretically, Δ-connection is appropriate for high speed, but it has low efficiency at low speed operating region. Meanwhile, Y-connection manifests its superiority on efficiency when it operates at high torque under low speed operating region. The lower efficiency and lower torque at low speed region compared with Y-connection are regarded as the major drawback in Δ-connection.

Fig. 3(a) shows the ideal basic 6-step control for “Y-connection, 2-phase excitation system”. The input current, flows in each phase, has to be maintained as flat-top for 120° in electrical angle, and 2-phase out of 3-phase are excited at the same time in every step. That is, BLDC motor design must necessarily take BEMF of each phase into account in order that it manifests a trapezoidal waveform with 120° flat-top corresponding to that of input current, since torque of each phase is product of input current and BEMF. Then, torque of each phase can be obtained from flat-top of current and BEMF, and synthesized torque of 3-phase torque, which are shifted



(a) Y-connection, 2-phase excitation system

(b) Δ-connection, 3-phase excitation system

Fig. 3. Ideal basic 6-step control

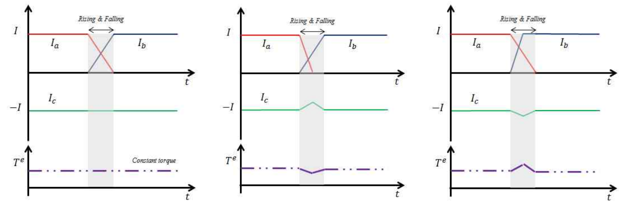
120° each other, remains consistent by compensation, totally [6, 8, 9].

Analogous to Y-connection, the ideal basic 6-step control for "Δ-connection, 3-phase excitation system" is presented in Fig. 3(b). As mentioned, current flows in all 3-phases in every step, changing its direction and magnitude. Hence, BEMF has to be a trapezoidal waveform with flat-top during 60° not 120° in electrical angle. Also, current and BEMF in every step contribute to torque production, different from Y-connection case. Therefore, these should be considered into BLDC motor design.

2.3 Phase advance control

The basic 6-step control according to winding connection has been identified in previous chapter. However, when BLDC motor operate practically, current lags behind input voltage, fed by inverter, owing to inductance of stator winding [10]. In other words, current cannot reach to objective value instantaneously. For this reason, it is impracticable to apply current as square-waveform, and the discrepancy between current and BEMF, which were supposed to be consistent, is major factor of increasing torque ripple.

As shown in Fig. 4(a), if the rate of increase and decrease of phase current is same, there is no torque ripple because non-changing current, I_c in this example, remains consistent. In most cases, however, the rate is different and it gives rise to torque ripple such as Figs. 4(b) and (c). The difference between phase current increase rate and decrease rate is proceeding from a time constant of coil, voltage difference of DC link and BEMF, and etc. Thus, proper control method is essential to compensate for lagging current [11, 12].



(a) constant torque (b) torque decrease (c) torque increase

Fig. 4. Torque ripple variation caused by current

This paper introduces the control method, which is "phase advance control", to compensate for lagging current by increasing conduction angle fed by inverter.

The available voltage to drive current into the phase winding, ΔV, is the voltage difference between DC link, V_s, and BEMF, e_{LL}, and is expressed as Eq. (4):

$$\Delta \mathrm{V} = V_s - e_{LL} \tag{4}$$

This available voltage would be decreased to zero when the motor is at high speed operation owing to BEMF increase. The principle of proposed method in this paper is advancing the turn-on angle to an earlier point on the BEMF waveform, where ΔV is greater, as shown in Fig. 5. By means of proposed method, *di/dt* component would increase at the start of the conduction interval. There exists the most appropriate phase advance control angle which maximizes torque or minimizes torque ripple when any speed and torque level is given. A hazardous problem can arise in consequence of applying phase advance control,

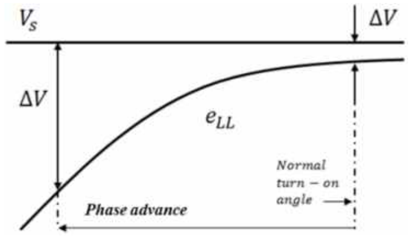


Fig. 5. Voltage available with phase advance control

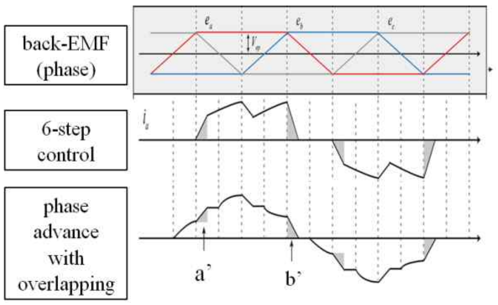


Fig. 6. BEMF waveform and comparison of current waveform according to 6-step and phase advance control

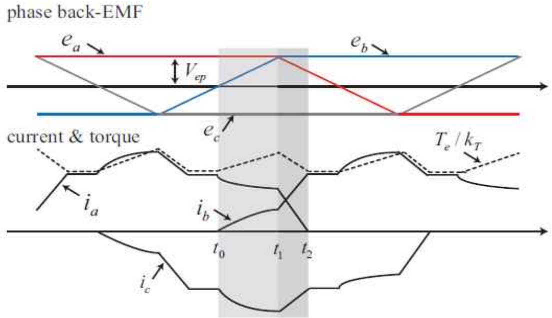


Fig. 7. Phase current and synthesized torque waveforms applying phase advance control

if the drive to the transistors shown in Fig. 1 is suddenly lost when e_{LL} is considerably higher than V_s. In that case, there will be uncontrolled rectification through the freewheel diodes [7].

In Fig. 6, waveform of BEMF, that of input current applied basic 6-step control, and that of input current applied proposed phase advance control, are presented in sequence. Through this proposed method, each phase current flows at earlier point than normal point applying 6-step control by switching. In the waveform of input current, it is represented as shaded regions that have influence on increasing torque ripple. As shown in Fig. 6, it is observed that shaded region, a' and b', of proposed control method has decreased compared with one of basic 6-step control.

In Fig. 7, the effectiveness of change conduction angle on torque ripple is shown. In section, $t_1 \sim t_2$, shaded as dark gray, it is shown that synthesized torque is getting decreased due to influence of lagging current. Nevertheless, torque ripple of synthesized torque can be reduced overall, since torque from each phase mutually compensates for the lagging current effect in $t_0 \sim t_1$ section by applying proposed phase advance control [13].

3. Simulation Result

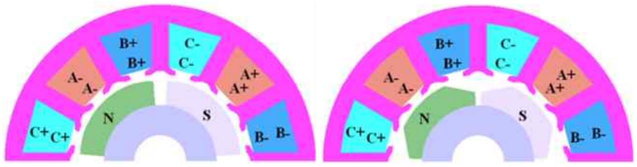
3.1 Design and comparison results according to winding connection

By using theory associated with winding connection, BLDC motors for both Y-connection and Δ-connection, having same performing specification, have been designed. The design specifications of BLDC motor for sunroof discussed in this paper are summarized in Table 1.

In Fig. 8, drawings of both BLDC motors are shown, where (a) is for Y-connection and (b) is for Δ-connection. Both models have same stator configuration with distributed winding for the purpose of reducing torque ripple, and notch has been additionally chosen on teeth for reduction of cogging torque. Furthermore, Surface mounted Permanent Magnet (SPM) type has been sorted out for rotor with bread shaped PMs. To satisfy flat-top of BEMF in both models, a PM configuration has to be optimized and adopted. For example, in the case of Δ-connection, 60° flat-top of BEMF has been implemented through cut-off edge of PMs mounted on rotor surface and considered in design.

Table 1. Design specifications of BLDC motor

	Parameters	Spec.	Unit
Performance	Torque	0.0655	[Nm]
	Speed	2500	[r/m]
General	No. of pole and slot	4 / 12	
	No. of phase	3	
	Air-gap	0.5	[mm]
Stator	Outer diameter	36	[mm]
Rotor	PM property	Ferrite-9D	



(a) Y-connection (b) Δ-connection

Fig. 8. Comparison of BLDC motor configuration with Y-connection and Δ-connection

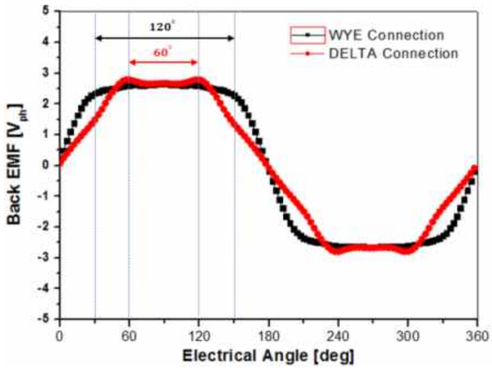
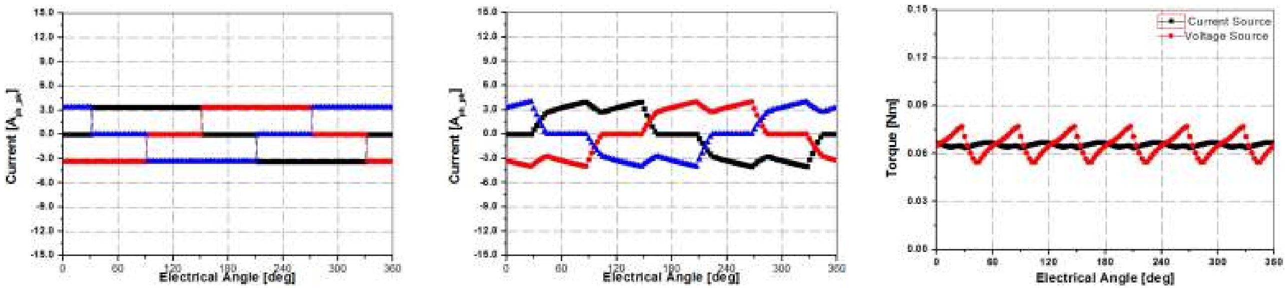


Fig. 9. Comparison results of BEMF waveform according to winding connection

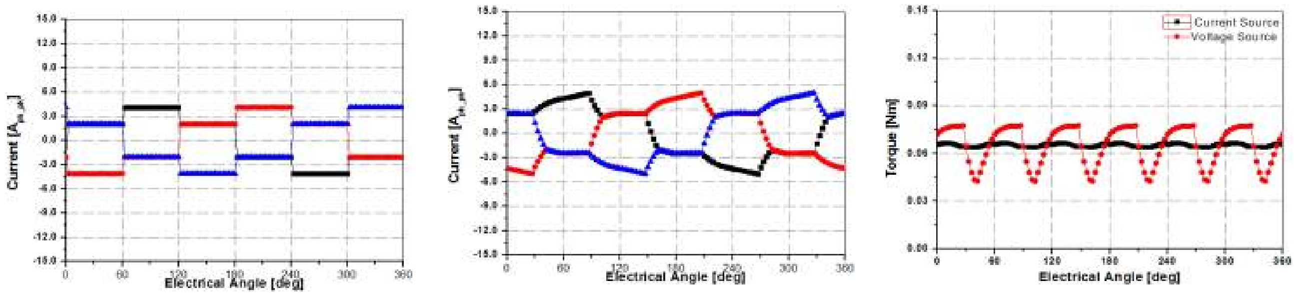
Fig. 9 represents BEMF waveforms according to Y-connection and Δ-connection. As mentioned above, flat-top of BEMF waveform is maintained for 120° for Y-connection, 60° for Δ-connection, not ideally but as possible.

Fig. 10 shows the phase current flowing into each phase of Y-connection and Δ-connection, and torque waveform analyzed via FEA with both current source and voltage source, respectively. In the voltage source analysis, Figs. 10(b) and (e), it is identified that the phase current increases slowly because of coil inductance unlike case of current source analysis one, Figs. 10(a) and (d). In Table 2, the FEA results have been compared under normal 6-step control condition.

As mentioned, it is clear that torque ripple of voltage source analysis is higher than one of current source analysis remarkably in both winding method due to lagging current by coil inductance. For reference, the reason why input voltage of Δ-connection is lower compared with one of Y-connection is voltage available difference. In other



(a) phase current with current source : Y-connection
(b) phase current with voltage source : Y-connection
(c) torque for (a)&(b)



(d) phase current with current source : Δ-connection
(e) phase current with voltage source : Δ-connection
(f) torque for (d)&(e)

Fig. 10. Comparison of input current and torque waveform

Table 2. Comparison results of motor performance between Y- and Δ-connection models

	Y-connection	Δ -connection	Unit
Input current (current source)	3.35	4.1	[A_{ph_max}]
Input voltage (voltage source)	8.0	4.25	[V_{dc}]
Average torque	0.0655		[Nm]
Torque ripple (current source)	5.1	3.9	[%]
Torque ripple (voltage source)	34.1	53.3	[%]

words, even if the magnitude of phase BEMF is similar in both winding, there is a magnitude difference from a line-to-line BEMF point. In case of Δ-connection, enough voltage available owing to lower line-to-line BEMF value makes higher current flow into phase winding than Y-connection.

3.2 Comparison results applying phase advance control

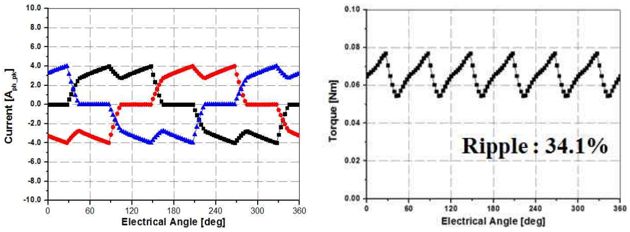
It is verified that phase advance control, applied to BLDC motor, has influence on reduction of torque ripple in theory. When phase advance control is applied to BLDC motor aimed for torque ripple reduction, there are two ways; one is advancing both the start of the commutation interval and the end of one, the other is advancing only the start of one maintaining end point. Based on these methods, we have selected second one; advancing only the start angle of commutation interval in this research.

Table 3. Torque ripple comparison in Y-connection and Δ-connection according to change of conduction angle

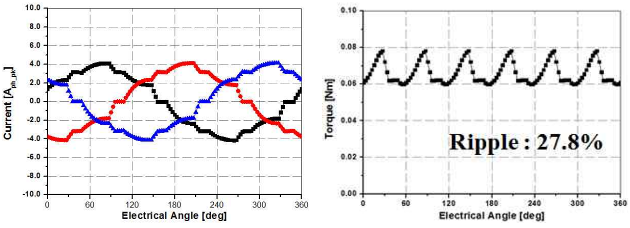
	Conduction angle	120	130	140	150	160	170
Y	Input voltage [V_{dc}]	8.0	7.7	7.4	6.8	***6.4***	6.0
	Torque ripple[%]	34.1	34.3	32.7	29.5	***27.8***	33.4
Δ	Input voltage[V_{dc}]	4.3	3.9	3.6	3.3	3.1	***3.1***
	Torque ripple[%]	53.3	47.4	43.7	44.2	32.4	***15.7***

Table 3 shows results of performance analysis of Y-connection and Δ-connection each, for BLDC motor, by increasing conduction angle of line current from 120° to 170° in tens when phase advance control applied. The wider conduction angle, the more current can be available into motor winding. For this reason, the average torque would increase if input voltage is maintained. In this research, thus, the input voltage has been controlled in each conduction angle case to satisfy required torque condition equally, and the results have been compared. As a result, if the current flowing into winding is in allowable range, the input voltage as well as torque ripple could be reduced. The minimum torque ripple is obtained at 160° conduction angle for Y-connection and 170° conduction angle for Δ-connection each. As mentioned earlier, depending on the target performance and the motor type, it is regarded as requisite to identify proper conduction angle for optimal control.

The phase current, also line current, of Y-connection is presented when conduction angle is 120°, normal control, and 160°, phase advance control, with torque waveform in

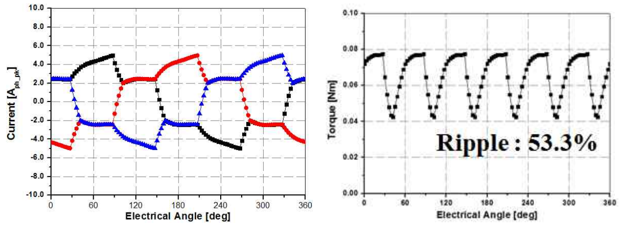


(a) 120° phase current (b) 120° torque

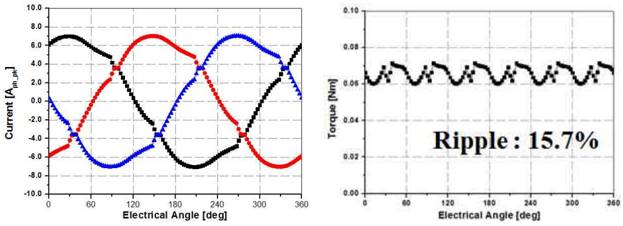


(c) 160° phase current (d) 160° torque

Fig. 11. Input current and torque waveforms in Y-connection according to change of conduction angle

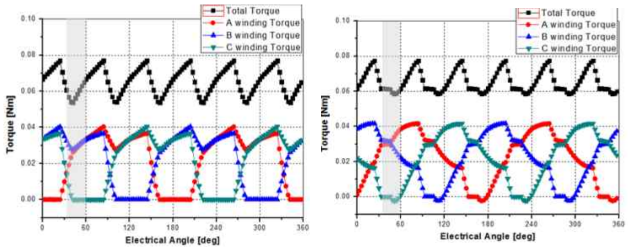


(a) 120° phase current (b) 120° torque

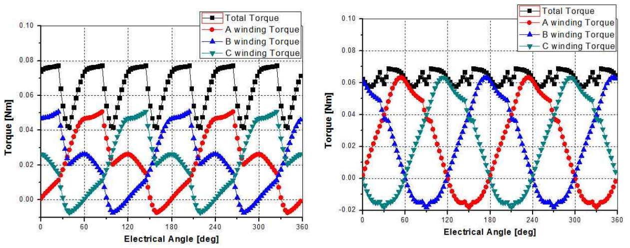


(c) 170° phase current (d) 170° torque

Fig. 12. Input current and torque waveforms in Δ-connection according to change of conduction angle



(a) 120° torque analysis : Y-connection (b) 160° torque analysis : Y-connection



(c) 120° torque analysis : Δ-connection (d) 170° torque analysis : Δ-connection

Fig. 13. Torque analysis: phase torque & synthesized torque

Fig. 11. This torque waveform manifests that the minimum value point of torque is getting increased higher as conduction angle increased, and it leads to a torque ripple reduction.

Analogously to the previous result, Fig. 12 shows characteristics of input phase current and torque waveform for Δ-connection when the conduction angle 120° and 170° are applied. In case the conduction angle is 170°, it is identified that phase current has been varied dramatically compared with one of 120° conduction angle due to extended switching pulse width.

By changing of conduction angle, the comparison results of torque characteristic including each phase torque occurred by product of phase current and BEMF are shown in Fig. 13. Analogous to the previous figures, shaded areas of Figs. 13(a) and (b), in Y-connection case, manifest the torque compensation region by overlapping each phase current and compensation region occurs periodically. However, in Δ-connection Figs. 13(c) and (d), this compensation region is not seen because of the changed input current. Nevertheless, from these results, it is proved that 6-step phase advance control is compatible with both Y-connection and Δ-connection in terms of torque ripple reduction by adjusting conduction angle.

4. Conclusion

This paper has researched a design and control methodology of BLDC motor in order to reduce torque ripple considering winding connection, Wye and Delta. The validation of the proposed design methodology in accordance with winding connection is verified by performance analysis according to ideal current source analysis and voltage source analysis with 6-step control. Furthermore, the proposed method, phase advance control, is applied to designed model aimed for torque ripple reduction and its effectiveness has been investigated via FEA. As a result, the conduction angles 160° for Y-connection and 170° for Δ-connection are optimal angle in order to reduce torque ripple maintaining average torque under BLDC model considered in this paper.

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