ERJ
Engineering Research Journal
Faculty of Engineering
Minoufiya University

PERFORMANCE IMPROVEMENT OF BRUSHLESS DC MOTOR THROUGH SWITCH-ON ANGLE CONTROL

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ABSTRACT

This paper presents a method for improving the performance of Brushless DC motor drive. This method depends on the varying of switch-on angle of motor phase current. The phase current and torque for proposed method are discussed. The operation of motor drive at different switch-on angle for same speed is studied and discussed. The results of this studying report an investigation into the motor characteristics of such method according to torque, efficiency and torque ripples factor. Computer simulation result had shown a noticeable improvement in motor performance.

يقدم هذا البحث طريقة لتحسين أداء محرك التيار المستمر عديم الفرش للحصول على خواص أفضل، تعتمد هذه الطريقة على تغيير زاوية توصيل كل وجه بالمنبع. وقد تم تحليل ومناقشة الشكل الموجي لتيار الوجه وعزم المحرك للطريقة المقترحة . وتم دراسة تأثير تقديم زاوية توصيل كل وجه بالمنبع لنفس السرعة ووجد أن هذا التقديم يؤدى إلى زيادة عزم المحرك وخفض تذبذبات هذا العزم - وزيادة قدرة خرج المحرك وتحسين كفاءته. و قد أظهرت النتائج تحسنا ملحوظا. حيث تم الحصول على قيم تقديم زاوية التوصيل المثالية للحصول على أعلي عزم، أعلى كفاءة وأقل تذبذبات في العزم.

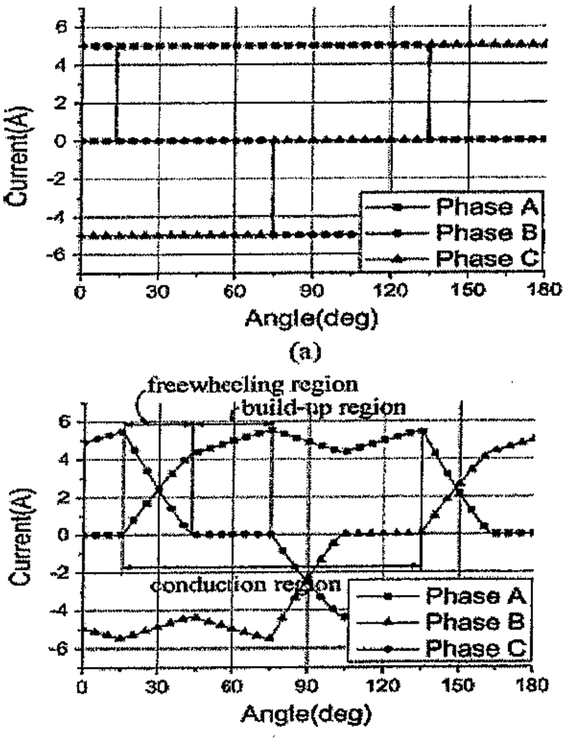
Keywords: Brushless DC motor drive, Performance improvement, Switch-on angle

1. INTRODUCTION

The brushless direct current (BLDC) motor has high torque, compact size, and high efficiency. Therefore, the BLDC motor is widely used in computers, household and industrial products, and automobiles. However, the BLDC motor has a disadvantage of high cost compared with the direct current (DC) motor because it is necessary to use an inverter and controller to remove a brush of DC motor [1], [2]. In the ideal BLDC motor, it has trapezoidal back-electromotive force (EMF) and constant source voltage inputted. Therefore, the current made by source voltage instantly rise to steady state limited by a resistance as Fig. 1(a) and the torque is produced without torque ripples.

However, the current characteristic of the actual BLDC motor is different from the ideal case. Because the current is influenced by the inductance and resistance, the current has a time constant and cannot rise or fall to the steady state instantly as Fig. 1(b).

Therefore, the current ripples are produced by influence of the motor phase inductance. And the torque ripples is affected by current ripples directly when the back-EMF has the trapezoidal waveform [3], [4].



(a)

(b)

Fig. 1. Current waveform of the BLDC motor.
(a) Ideal case. (b) Actual case.

To get improved operation must produce smooth torque profile - reduced torque ripples -, which can be put into two categories, the first category is focused on improving the magnetic design of the motor. The second category is focused on the control of phase currents. Our method falls into the second category.

In this paper, the method to simply reduce the torque ripples and improve motor operation is proposed by varying the switching-on angle for motor phase current.

2. PROPOSED METHOD

For the BLDC motor and the corresponding winding connection shown in Fig.2, Motor phases are supplied consequently; any phase is connected to the supply after the previous phase is disconnected with certain arrangement according to excitation technique type to keep the rotor rotation. A switch-on point occur every 60° and the conduction period of any phase is equal to 120°.

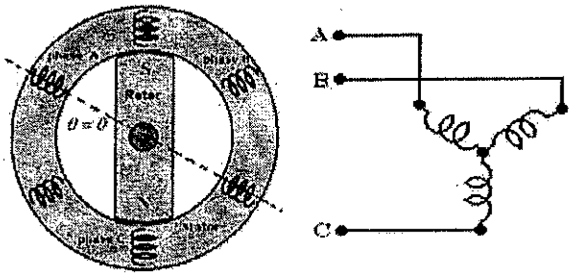


Fig. 2 A cross-sectional sketch of 3-phase BLDC motor and corresponding winding connection.

The effects of advancing the switch-on angle (α) of the current on motor characteristics are investigated. In Fig. 3(a) and Table 1(a) normal motor operation is illustrated, but by advancing the switch-on angle (α) of the current; the motor operation will be changed as illustrated in Fig. 3(b) and Table 2(b).

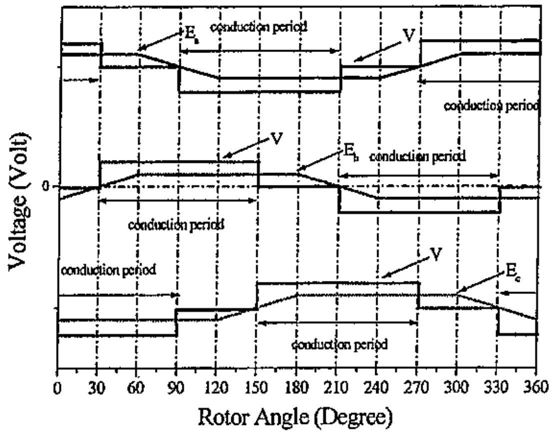


Fig. 3(a) without advancing of switch-on angle.

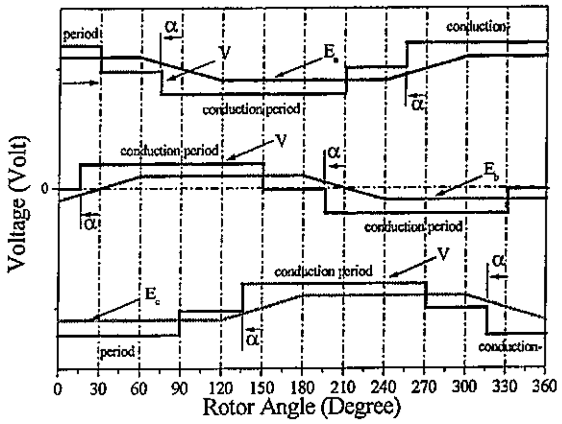


Fig. 3(b) with advancing of switch-on angle

Fig. 3 Supply voltage and Back emf waveform of the BLDC motor.

Table 1 Phase feeding sequence of Two Phase Excitation technique

(a) without advancing of switch-on angle				(b) with advancing of switch-on angle			
	Phase (A)	**Phase (B)**	**Phase (C)**		**Phase (A)**	**Phase (B)**	**Phase (C)**
1	•	+	-	1	0	+	-
				2	-	+	-
2	-	+	•	3	-	+	0
				4	-	+	+
3	-	•	+	5	-	0	+
				6	-	-	+
4	•	-	+	7	0	-	+
				8	+	-	+
5	+	-	•	9	+	-	0
				10	+	-	-
6	+	•	-	11	+	0	-
				12	+	+	-

Where:

+ Phase connected to positive terminal of source
- Phase connected to negative terminal of source
0 Phase open circuit

The disconnection angle will be reduced 60°. So the phase conduction period to the supply is increased over than 120°. During the advancing of the switch-on angle, the supplied phase will be in parallel with the last supplied phase.

3. PROPOSED MODEL

3.1. Phase Current Waveform

The motor phases are supplied sequentially whenever the rotor is rotated by an angle according to the type of excitation technique as follow [4], [5].

In the proposed method, the currents I_A, I_B and I_C according to the first sequence shown in Table 1(b) are determined as follow;

$$I_A=\frac{V-E_A-E_B}{2R}\left(1-e^{-(t_{caif}/\tau_{cai})}\right)\times e^{-(t_{ad}/\tau_{ad})} \qquad (1)$$

$$I_B=\frac{V-E_B-E_C}{2R}\left(1-e^{-(t_{bc}/\tau_{bc})}\right) \qquad (2)$$

$$I_C=\frac{V-E_B-E_C}{2R}\left(1-e^{-(t_{bci}/\tau_{bci})}\right)$$
$$+\frac{V-E_A-E_C}{2R}\left(1-e^{-(t_{caif}/\tau_{cai})}\right)\times e^{-(t_{cd}/\tau_{cd})} \qquad (3)$$

The currents I_A, I_B and I_C according to the second sequence shown in Table 1(b) are determined as follow;

$$I_A=\frac{V-E_A-E_B}{2R}\left(1-e^{-(t_{abif}/\tau_{abi})}\right)+I_{Ao}\times e^{-(t_{ad}/\tau_{ad})} \qquad (4)$$

$$I_C=\frac{V-E_B-E_C}{2R}\left(1-e^{-(t_{bcif}/\tau_{bci})}\right)+I_{Co}\times e^{-(t_{cd}/\tau_{cd})} \qquad (5)$$

$$I_B=(I_A+I_C)+(I_{Ao}+I_{Co})\times e^{-(t_{bd}/\tau_{bd})} \qquad (6)$$

Where:

I_{Ao} : equal to I_A given in equation (1)
I_{Co} : equal to I_C given in equation (3)
V : the voltage of DC source.
E_A , E_B and E_C: the back EMF of phase A ,B and C.
R : the resistance of phase winding.
t_{ai}, t_{bi} and t_{ci}: the time from the moment of phase connection.
t_{aif}, t_{bif} and t_{cif} : the time at the moment of phase disconnection.
τ_{ai}, τ_{bi} and τ_{ci} : the electrical time constant of phase during connection.
t_{ad}, t_{bd} and t_{cd} : the time starting from the moment of phase disconnection.
τ_{ad}, τ_{bd} and τ_{cd} : the electrical time constant of phase during disconnection
t_{abi}, t_{bci} and t_{cai} : the time starting from the moment of two phase connection.
t_{abif}, t_{bcif} and t_{caif} : the time at the moment of two phase disconnection.
τ_{abi}, τ_{bci} and τ_{cai} : the electrical time constant of two phase during connection.

3.2. Motor Torque Waveform

The electromagnetic torque can be expressed in terms of co energy W_{co} variation as follows [6]:

$$T=\frac{\partial W_{co}}{\partial \theta}\bigg|_{i\ const} \qquad (7)$$

It can be noted that the self and mutual inductance coefficients of the armature windings are dependent on the rotor angular position θ. Thus, the electromagnetic torque can be expressed as

$$T=\sum_{i=1}^{z} F_m\, i_i \frac{d\,M_{im}(\theta)}{d\,\theta}+\frac{1}{2}F_m^2\frac{d\,P_m}{d\,\theta} \qquad (8)$$

Where:

Z : is the number of phases.
F_m : is the equivalent *MMF* of the magnets.
P_m : is the magnetic circuit permeance of the magnets.
i : is the stator winding current .
M_{im} : is the mutual inductance between a stator winding and the one turn equivalent circuit of the magnets.

The *EMF* of a stator winding e_i is related to the magnet flux by

$$e_i=-\frac{d\,\varphi_{im}}{d\,t}=-\omega_m\,F_m\frac{d\,M_{im}(\theta)}{d\,\theta} \qquad (9)$$

Where:

ϕ_{im} : is the magnetic flux produced by the magnets.

From (8) and (9) it follows:

$$T=-\sum_{i=1}^{z}\frac{e_i\,i_i}{\omega_m}+\frac{1}{2}F_m^2\frac{d\,P_m}{d\,\theta} \qquad (10)$$

The first term in (10) represents the permanent magnet torque which produced due to the amount of magnetic flux in permanent magnet [7], while the second term represents the reluctance torque which produced due to the saliency in rotor.

3.3. Motor Torque Ripples factor

The value of motor torque ripples at certain speed *TR* is determined by the following equation [8]:

$$TR=\frac{\sum_{i=1}^{i=360}(T_i-T_{av})/360}{T_{av}} \qquad (11)$$

Where

T_i : instantaneous motor torque at i rotor angle
T_{av} : average motor torque at certain speed

The phase current and motor torque waveforms at different values of advancing the switch-on angle are shown in Fig. 4 and Fig. 5 respectively

4. SIMULATION RESULTS

4.1. Motor Performance at Different Switch-on Angle

In this section, the effect of advancing the switch-on angle (α) of the current on the motor performance is studied. The simulation program is developed to give the average phase current, total motor torque, efficiency and torque ripples with the variation of motor speed at different values of advancing the switch-on angle and fixing back EMF constant.

Fig. 6 shows the variation of the average phase current with speed at different values of advancing the switch-on angle. It is clear that the phase current is reduced with the increase in speed. And also the average value of the phase current increases with the increase in advancing the switch-on angle at any speed.

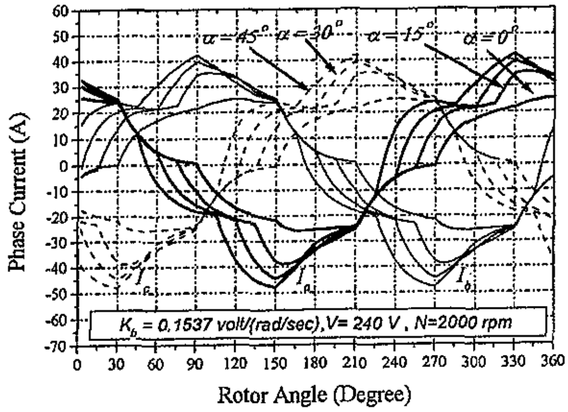


Fig. 4 Variation of phases current with rotor angle at different values of advancing the switch-on angle.

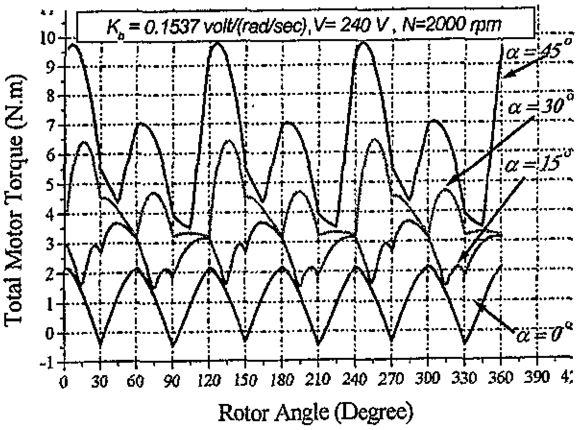


Fig. 5 Variation of motor torque with rotor angle at different values of advancing the switch-on angle.

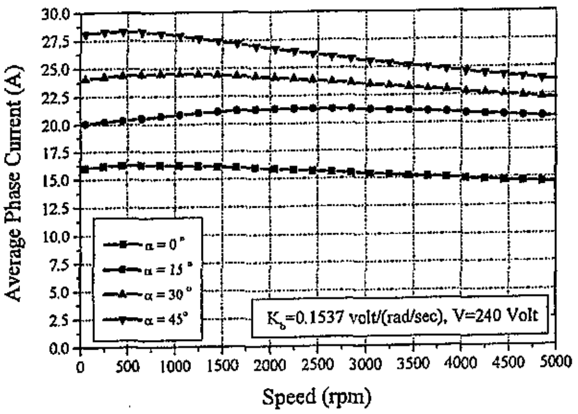


Fig. 6 Variation of phase current with speed at different values of advancing the switch-on angle.

The BLDC motor torque variation with speed is similar to that of the series motor as shown in Fig. 7. It is noticed that, when the motor applied voltage equals 240 V and advancing the switch-on angle equals zero, the motor torque reduces with the increase in speed. And this torque reaches zero at speed approximately equals 3250 rpm.

The Increase in advancing the switch-on angle at the same voltage leads to an increase in motor torque. Therefore, the motor availability to rotate with load by a speed higher than 3250 rpm will be achieved by increasing advancing the switch-on angle as shown.

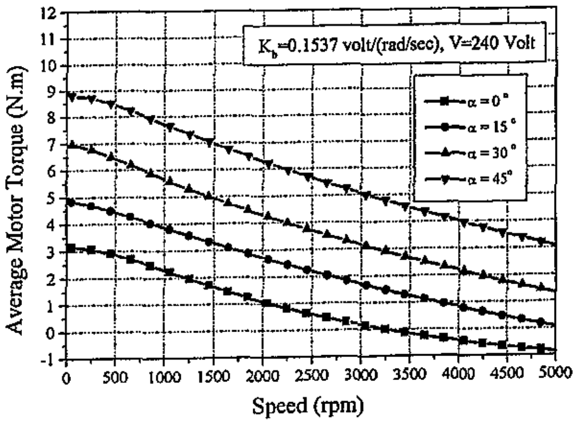


Fig. 7 Variation of average motor torque with speed at different values of advancing the switch-on angle

Fig. 8 shows the variation of efficiency with speed. It is clear that the efficiency curve increases with the increase in advancing the switch-on angle through all speeds. The motor efficiency has high values at low speeds, and it is decreased with increasing the speed.

Fig. 9 shows the variation of motor torque ripples with speed. It is clear that torque ripples decreases with the increase in advancing the switch-on angle through all speeds. The motor torque ripples is high during high speed

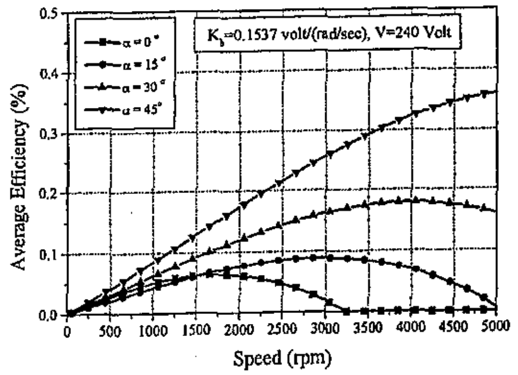


Fig. 8 Variation of average efficiency with speed at different values of advancing the switch-on angle.

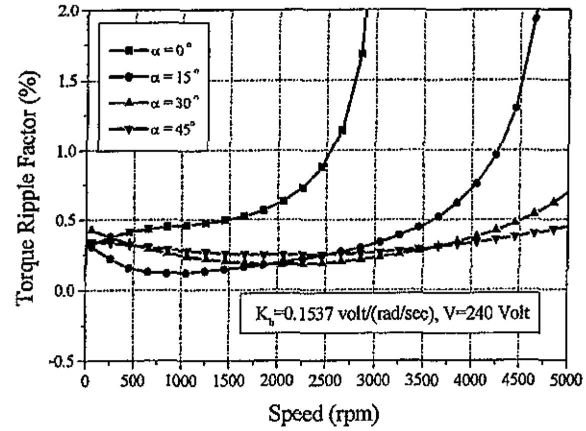


Fig. 9 Variation of torque ripples factor with speed at different values of advancing the switch-on angle.

4.2. Motor Performance at Optimum Switch-on Angle

In this section, fixing the motor speed with any value, the advance angle (α) can be controlled to give the motor characteristics to be suitable for the load case and give improved operation.

The simulation program is developed to give the total motor torque, efficiency and torque ripples with the variation of advancing the switch-on angle and fixing speed and back EMF constant.

Variation of motor torque is illustrated in Fig. 10 Increasing advancing the switch-on angle always increases the motor torque at any speed. If the load torque is constant with speed variation, advancing the switch-on angle must be increased to increase the load speed although the supply voltage is constant. So, it can be found that the control of motor speed is efficient when the advancing the switch-on angle is controlled.

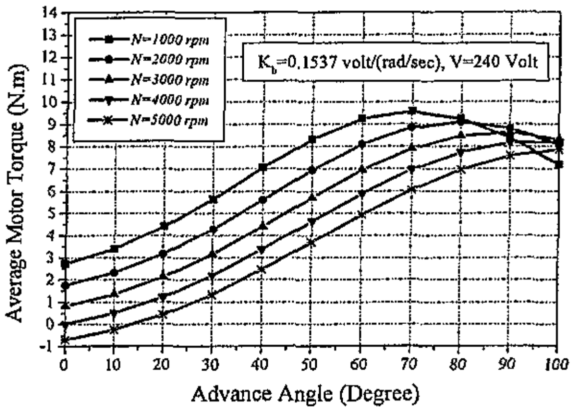


Fig. 10 Variation of average motor torque with advancing switch-on angle at different speed.

Fig. 11 shows the variation of the efficiency with advancing the switch-on angle at different speeds. It is clear that the efficiency increases at any speed by the increase in advancing the switch-on angle until it reaches its maximum value, and then it begins reducing. It is noticed also that the value of advancing the switch-on angle; which gives the maximum efficiency increases by the increase in the motor speed. Therefore, its value depends on the motor speed. And also the maximum efficiency is increased by speed increasing.

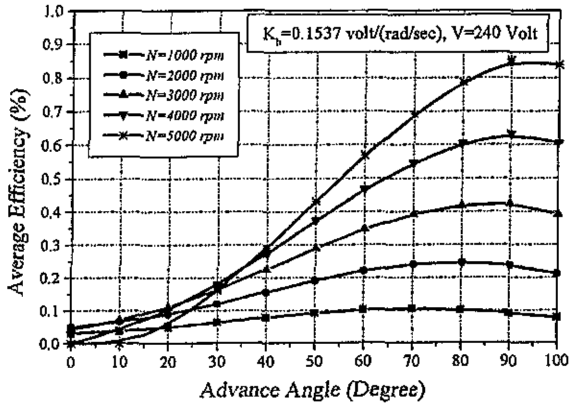


Fig. 11 Variation of average efficiency with advancing switch-on angle at different speed.

Fig. 12 shows the variation of motor torque ripples with advancing the switch-on angle at different speeds. It is clear that torque ripples decreases with the increase in advancing the switch-on angle through all speeds. The motor torque ripples is high during high speed.

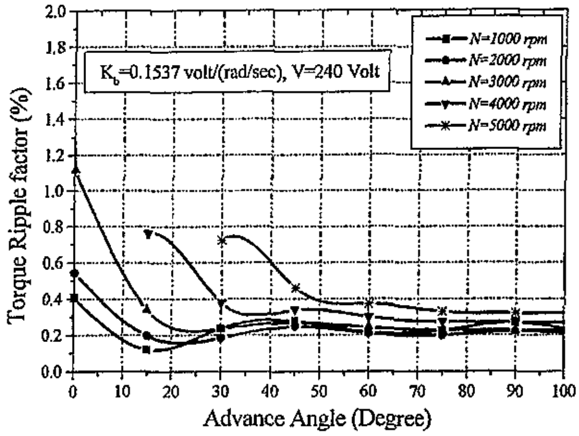


Fig. 12 Variation of motor torque ripples with advancing switch-on angle at different speed.

From the pervious results, the variation of the optimum advancing of the switch-on angle; maximum motor torque, maximum efficiency, and minimum torque ripples at different speeds with the speed can be deduced as shown in Fig. 10. It is clear also that the value of optimum advancing the switch-on angle increases by the increase in motor speed.

So Fig. 13 presents the optimum value of switch-on angle to get the improved motor operation.

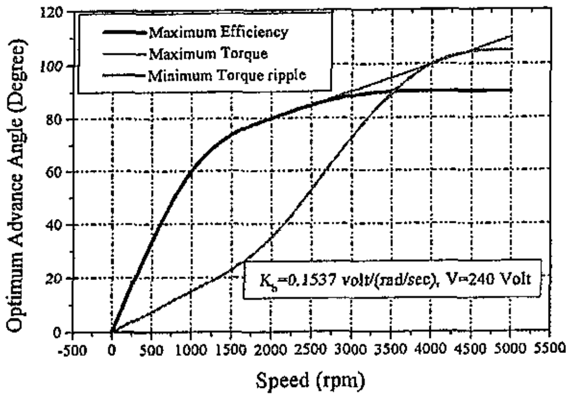


Fig.13 Variation of optimum advancing of switch-on angle with speed.

5. CONCLUSION

Advancing of switch-on angle had been proposed here. From simulation results, the differences between operation with and without switch-on angle advancing are noticed, and can easily deduced that Increasing advance angle (α) leads to lower phase current, higher motor torque, lower torque ripples, higher no load speed and higher efficiency comparing with normal operation. Advance angle (α) can be controlled to give the motor characteristics to be suitable for the load case and give improved operation.

6. APPENDIX

The parameters of BLDC motor used in simulation are:

DC supply voltage (V) = *240 V*
Phase resistance (R) = 5 Ω
Stator phase inductance at aligned position = *0.012 H*
Stator phase inductance at unaligned position= *0.007 H*
Number of rotor poles (P) = *2 pole*
Number of stator phases = *3 phases*
Back EMF constant (K_b) = *0.1537 volt.s/rad*

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