ERJ
Engineering Research Journal
Faculty of Engineering
Minoufiya University

EXCITATION TECHNIQUES FOR PERMANENT MAGNET BRUSHLESS DC MOTOR DRIVE

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ABSTRACT

This paper presents four excitation techniques for Permanent Magnet Brushless DC motor drive. These techniques are single phase excitation technique, two phase excitation technique, three phase excitation technique and single phase / two phase excitation technique. Waveforms of phase current and torque for all excitation techniques are analyzed and discussed. The operation of the motor drive at different excitation techniques for same load is studied and discussed. The results of this studying reports an investigation into the characteristics of such techniques according to torque, no load speed, efficiency, supply current and control circuit. Computer simulation result had shown a noticeable difference between four excitation techniques

يقدم هذا البحث أربع تقنيات مختلفة لتغذية محرك التيار المستمر عديم الفرش، التقنية الأولى تغذية وجه واحد والثانية تغذية وجهين معا والثالثة تغذية الثلاثة أوجه معا والرابعة تغذية وجه ثم وجهين.وتم تحليل ومناقشة الشكل الموجي لتيار الوجه و عزم المحرك للتقنيات الأربعة. وقد تم تشغيل المحرك عند نفس الحمل للأربع تقنيات ، وتم تعين قيم العزم وسرعة اللاحمل والكفاءة وتيار المغذي في كل حالة. و قد أظهرت النتائج فروقا ملحوظة.

Keywords: Brushless DC motor drive, excitation technique

1. INTRODUCTION

Permanent machines have been used for many years in applications where simplicity of structure was of primary importance. The availability of low cost power electronic control devices and the improved permanent magnet characteristics have paved the way for the applications of these machines to more demanding industrial fields [1]. The combination of high - energy permanent magnets and solid state power semiconductors resulted in relatively new class of machines known as "Brushless DC machines" (BLDC) [2-4]. This machine has many advantages like less weight and smaller size favour the application of these machines in electric vehicles also [5]. The function of the solid-state power semiconductors is to switch the suitable current into the suitable stator coil at suitable time and in right sequence by taking information supplied by sensors [6]. Phase motor winding are excited by DC source with many kinds of excitation techniques that depend on the number of motor phases always excited and time of phase conduction.

2. PROPOSED EXCITATION TECHNIQUES

For the BLDC motor and the corresponding winding connection shown in Fig. 1, there are many phase feeding sequences according to the following proposed excitation techniques:

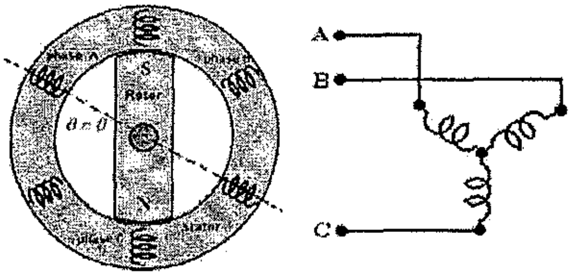


Fig. 1 A cross-sectional sketch of 3-phase BLDC motor and corresponding winding connection.

1. Single Phase Excitation technique:

In this method, always one phase is excited and time of phase conduction is 60 ° electrical, as shown in Table 1.

2. Two Phase Excitation technique:

In this method, always two phases is excited and time of phase conduction is 120 ° electrical, as shown in Table 2.

3. Three Phase Excitation technique:

In this method, always three phases is excited and time of phase conduction is 180 ° electrical, as shown in Table 3.

4. Single Phase/Two Phase Excitation technique:

In this method, always one phase/two phases are excited sequentially and time of phase conduction is 90° electrical, as shown in Table 4.

Table 1. Phase feeding sequence of Single Phase Excitation technique

Interval	Phase (A)	Phase (B)	Phase (C)	Neutral
1	0	0	-	+
2	0	+	0	-
3	-	0	0	+
4	0	0	+	-
5	0	-	0	+
6	+	0	0	-

Table 2 Phase feeding sequence of Two Phase Excitation technique

Interval	Phase (A)	Phase (B)	Phase (C)	Neutral
1	0	+	-	0
2	-	+	0	0
3	-	0	+	0
4	0	-	+	0
5	+	-	0	0
6	+	0	-	0

Table 3 Phase feeding sequence of Three Phase Excitation technique

Interval	Phase (A)	Phase (B)	Phase (C)	Neutral
1	+	+	-	0
2	-	+	-	0
3	-	+	+	0
4	-	-	+	0
5	+	-	+	0
6	+	-	-	0

Table 4 Phase feeding sequence of Single Phase / Two Phase Excitation technique

Interval	Phase (A)	Phase (B)	Phase (C)	Neutral
1	0	0	-	+
2	0	+	-	0
3	0	+	0	-
4	-	+	0	0
5	-	0	0	+
6	-	0	+	0
7	0	0	+	-
8	0	-	+	0
9	0	-	0	+
10	+	-	0	0
11	+	0	0	-
12	+	0	-	0

Where:

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

2. PROPOSED MODEL

A. 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 [7], [8]:

1. Currents of Single Phase Excitation technique:

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

$$I_A = \frac{V - E_A}{R}(1 - e^{-(t_{aif}/\tau_{ai})}) \times e^{-(t_{ad}/\tau_{ad})} \qquad (1)$$

$$I_B = \frac{-V - E_B}{R}(1 - e^{-(t_{bif}/\tau_{bi})}) \times e^{-(t_{bd}/\tau_{bd})} \qquad (2)$$

$$I_C = \frac{-V - E_C}{R}(1 - e^{-(t_{ci}/\tau_{ci})}) \qquad (3)$$

Where:

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

2. Currents of Two Phase Excitation technique:

In this method, the currents I_A, I_B and I_C according to the first sequence shown in Table 2 are determined as follow;

$$I_A = \frac{V - E_A - E_B}{2R}(1 - e^{-(t_{caif}/\tau_{cai})}) \times e^{-(t_{ad}/\tau_{ad}} \qquad (4)$$

$$I_B = \frac{V - E_B - E_C}{2R}(1 - e^{-(t_{bc}/\tau_{bc})}) \qquad (5)$$

$$I_C = -\frac{V - E_B - E_C}{2R}(1 - e^{-(t_{bci}/\tau_{bci})})$$

$$-\frac{V-E_A-E_C}{2R}(1-e^{-(t_{caif}/\tau_{cai})})\times e^{-(t_{cd}/\tau_{cd})} \quad (6)$$

Where:

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. Currents of Three Phase Excitation technique:

In this method, the currents I_A, I_B and I_C according to the first sequence shown in Table 3 are determined as follow;

$$I_A=\frac{V-E_A-E_C}{2R}(1-e^{-(t_{caif}/\tau_{cai})})+I_{Ao}\times e^{-(t_{ad}/\tau_{ad})} \quad (7)$$

$$I_B=\frac{V-E_B-E_C}{2R}(1-e^{-(t_{bcif}/\tau_{bci})})+I_{Bo}\times e^{-(t_{bd}/\tau_{bd})} \quad (8)$$

$$I_c = -(I_A+I_B)+I_{Co}\times e^{-(t_{cd}/\tau_{cd})} \quad (9)$$

Where:

$$I_{Co} = -\frac{V-E_A-E_C}{2R}(1-e^{-(t_{caif}/\tau_{cai})}) \quad (10)$$

$$I_{Bo} = -\frac{V-E_A-E_B}{2R}(1-e^{-(t_{abif}/\tau_{abi})}) \quad (11)$$

$$I_{Ao} = -(I_{Bo}+I_{Co}) \quad (12)$$

4. Currents of Single Phase/Two phase Excitation technique:

In this method, the currents I_A, I_B and I_C according to the first and second sequences shown in Table 4 are determined from the equations (1) to(3)and from (4) to (6) respectively.

B. Motor Torque Waveform

The electromagnetic torque can be expressed in terms of co energy W_{co} variation as follows [9]:

$$T=\frac{\partial W_{co}}{\partial\theta}\Big|_{i\ const} \quad (13)$$

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

$$T=\sum_{i=1}^{z}F_m\,i_i\frac{d\,M_{im}(\theta)}{d\theta}+\frac{1}{2}F_m^2\frac{d\,P_m}{d\theta} \quad (14)$$

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

$$e_i=-\frac{d\,\varphi_{im}}{d\,t}=-\omega_m\,F_m\frac{d\,M_{im}(\theta)}{d\theta} \quad (15)$$

Where:

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

From (14) and (15) it follows:

$$T=-\sum_{i=1}^{z}\frac{e_i\,i_i}{\omega_m}+\frac{1}{2}F_m^2\frac{d\,P_m}{d\theta} \quad (16)$$

The first term in (16) represents the permanent magnet torque which produced due to the amount of magnetic flux in permanent magnet [10], while the second term represents the reluctance torque which produced due to the saliency in rotor. The current and torque waveforms of all excitation techniques are shown in Fig. 2.

C. Motor Torque Ripples factor

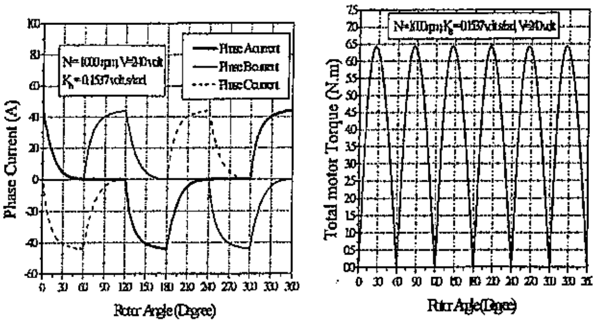
The value of motor torque ripples at certain speed *TR* is determined by the following equation [11-13]:

$$TR=\frac{\sum_{i=1}^{i=360}(T_i-T_{av})/360}{T_{av}} \quad (17)$$

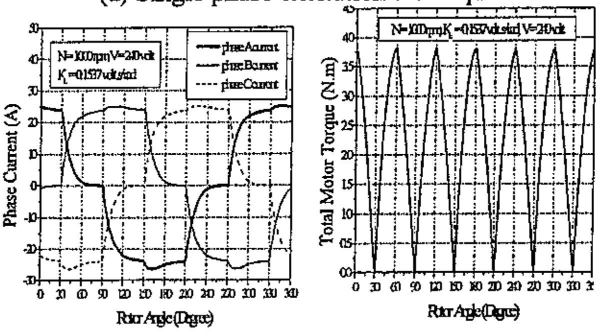
Where

T_i : instantaneous motor torque at i rotor angle

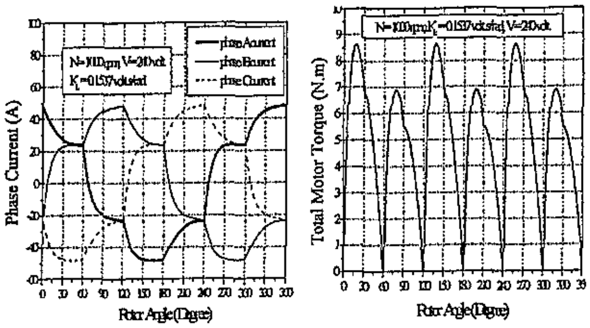
T_{av} : average motor torque at certain speed



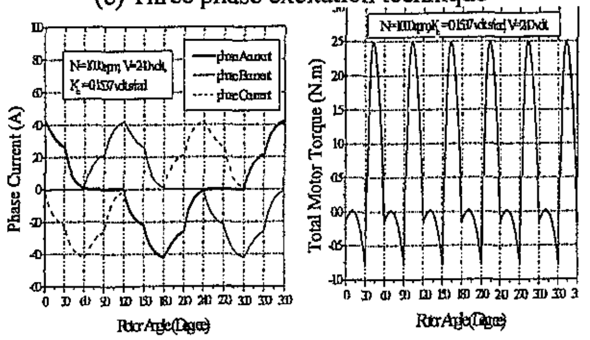
(a) Single phase excitation technique



(b) Two phase excitation technique.



(c) Three phase excitation technique



(d) Single phase /Two phase excitation technique

Fig. 2 Variation of phase current and total torque with rotor angle

3. SIMULATION RESULTS

To get the difference between the four excitation techniques, Constant load operation is carried out for the proposed techniques. The average value of supply current in all proposed techniques is shown in Fig. 3. It is noticed that single phase excitation technique has the highest no load supply current which equal two times of that of two phase excitation technique, and the rate of increase of supply current with speed change is higher for single phase excitation technique than other techniques. Fig. 4 shows the total motor torque in all proposed techniques. It is clarified that single phase, two phase and three phase excitation techniques have approximately the same no load speed which equal more than two times of that of single phase / two phase excitation technique, and the rate of increase of torque with speed change is higher for single phase excitation technique than all excitation techniques. The average value of efficiency in all proposed techniques is shown in Fig. 5. Three phase excitation technique has the highest efficiency, while single phase / two phase excitation technique has the lowest efficiency. Two phase excitation technique has higher efficiency than single phase excitation technique. Fig. 6 shows the motor torque ripples in all proposed techniques. It is noticed that single phase excitation technique has the lowest torque ripples factor, while single phase/two phase excitation technique has the highest one. Two phase excitation technique has lower torque ripples factor than single phase excitation technique. Table 5 summarizes the difference between all types of proposed excitation techniques.

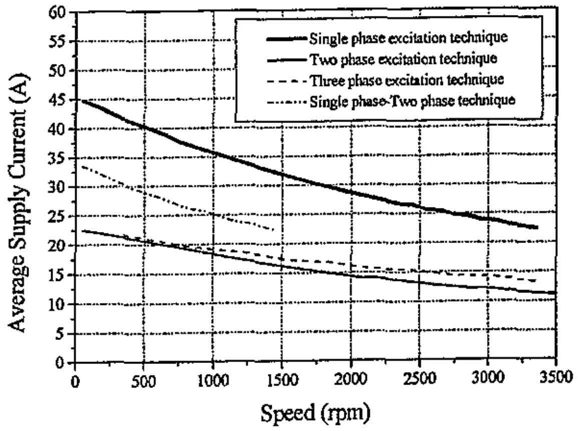


Fig. 3 Variation of average supply current with speed in all excitation techniques at constant load

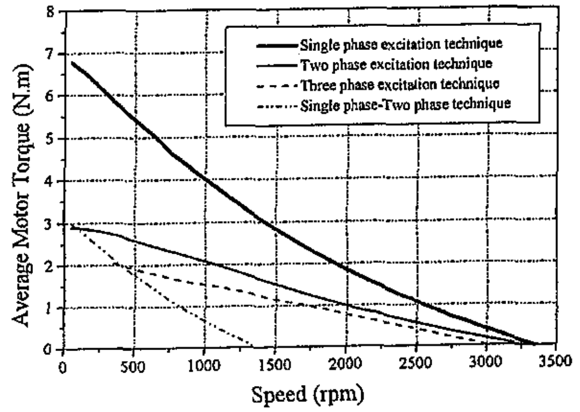


Fig. 4 Variation of average motor torque with speed in all excitation techniques at constant load

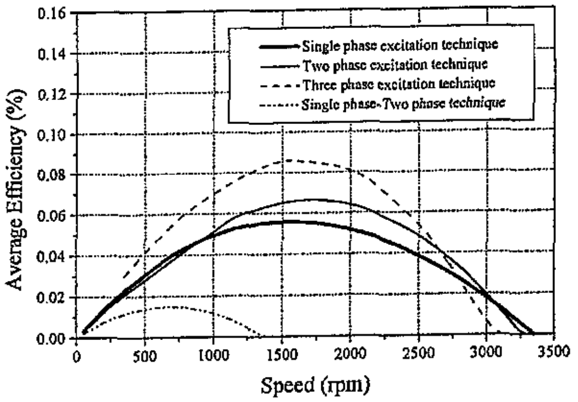


Fig. 5 Variation of average efficiency with speed in all excitation techniques at constant load

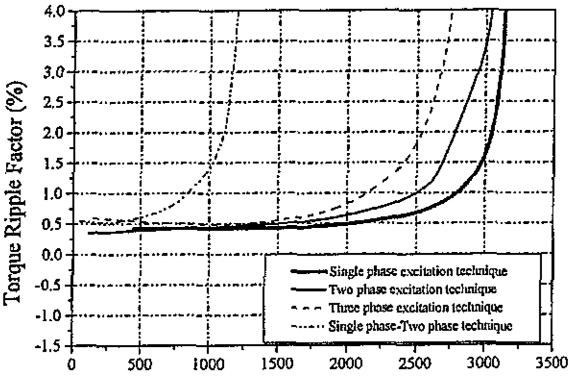


Fig. 6 Variation of torque ripples factor with speed in all excitation techniques at constant load.

Table 5 Summary of simulation results

	Single Phase Excitation technique	Two Phase Excitation technique	Three phase Excitation technique	Single/two phase Excitation technique
Motor torque	High	Moderate	Low	Moderate (low N) lowest (*high* N)
Supply current	Higher	Moderate	Moderate	High
Motor efficiency	Moderate	Moderate	High	Low
Torque ripples	Lowest	Low	Lower	High
No load speed	Higher	Higher	High	Low
Control circuit	Complex	ordinary	ordinary	More complex

4. CONCLUSION

Several excitation techniques had been proposed here. From simulation results, the differences between four proposed types of excitation techniques are noticed, and can easily deduced that the single phase excitation technique has highest motor torque, lowest torque ripples, higher no load speed and moderate efficiency comparing with other excitation techniques. The main disadvantages are highest supply current and more complex control circuit, but the advantages of improved performance and power electronics development can make the complex structure of circuit less important. So the single phase excitation technique is better.

The conventional control circuit of two phase excitation technique is the main reason of widely using of it in researches.

5. 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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