

Speed Control of an Eleven-Phase Brushless DC Motor

Morteza Azadi and Ahmad Darabi

Abstract—In this paper, an eleven-phase permanent magnet brushless DC motor fed by an eleven-leg two-level inverter is modeled and simulated. In order to produce trapezoidal back electromotive force waveforms by permanent magnet rotor, the motor has concentrated stator windings. The motor speed is controlled by Mamdani-type fuzzy incremental controller. The hysteresis modulation is used for switching operation. The simulation is carried out by Matlab/Simulink.

Index Terms—Fuzzy incremental controller, hysteresis band, permanent magnet brushless DC motor, voltage source inverter.

I. INTRODUCTION

There are two types of permanent magnet AC motors; permanent magnet synchronous motors (PMSMs) which have sinusoidal current waveforms and permanent magnet brushless DC motors (PMBLDCMs) which have quasi-rectangular current waveforms. Stator windings of PMSM are distributed as sinusoidal forms; so, their back electromotive force (BEMF) waveforms are sinusoidal, whereas in PMBLDCM, we require the concentrated stator windings to produce trapezoidal BEMF waveforms [1]. The PMBLDCMs are employed in variety applications such as computer disk drives, robots, actuators, electrical vehicles and bodybuilding equipments as motorized treadmill [2], [3]. Nowadays, American and European researchers have proceeded to investigate PMBLDCMs because they have been employed for warship propulsion [3], [4]. Application of this motor due to high efficiency, loss free field excitation [5], ease of their control, simple structure, loss free mechanical commutator and low maintenance costs are growing increasingly.

Multiphase PMBLDCMs have some advantages in compare with traditional three-phase PMBLDCMs that have been listed in the following [1], [6]:

- low amplitude of torque pulsations
- high frequency of torque pulsations
- high torque per ampere ratio in comparison with a similar machine volume
- low phase current of stator without increasing phase voltage
- high reliability
- high power density

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Nevertheless, it is not so clear why most of researchers investigate on traditional three-phase PMBLDCMs [7], [8].

In this paper, an eleven-phase four-pole, Y-connected stator winding, 20 Hz, 8.5 kW and 600 rpm permanent magnet brushless DC motor is simulated and the rotor speed is controlled by fuzzy incremental controller as well as hysteresis current controller is used for firing switches of an inverter.

II. MODELING OF A PMBLDCM IN THE "ABC" FRAME

Generally, PMBLDCMs are designed so that can neglect from effect saliency of rotor poles [9]. For modeling a permanent magnet brushless DC motor, like other electrical machines, the following simplifier assumptions are considered:

- Saturation effects on parameter of motor were negligible.
- The saliencies of poles were neglected.
- Demagnetization of PM material was neglected.
- All of the self inductances, mutual inductance and resistances of stator windings are equal.

$$L_{self} = L_{aa} = L_{bb} = L_{cc} = L_{dd} = L_{ee} = L_{ff} = L_{gg} = L_{hh} = L_{ii} = L_{jj} = L_{kk} \quad (H) \quad (1)$$

$$M = L_{pq} \quad (H) \quad (2)$$

$$p = a, b, \dots, k, \quad q = a, b, \dots, k, \quad p \neq q \quad (3)$$

$$r_s = r_{as} = r_{bs} = r_{cs} = r_{ds} = r_{es} = r_{fs} = r_{gs} = r_{hs} = r_{is} = r_{js} = r_{ks} \quad (\Omega) \quad (4)$$

The phase voltage equations of the machine in the frame "ABC" are as follows:

$$[v] = [r][i] + \frac{d[\lambda]}{dt} \quad (V) \quad (5)$$

$$\frac{d[\lambda]}{dt} = [L] \frac{d[i]}{dt} + [e] \quad (V) \quad (6)$$

$$[v] = [v_{as} \ v_{bs} \ v_{cs} \ v_{ds} \ v_{es} \ v_{fs} \ v_{gs} \ \dots \ v_{hs} \ v_{is} \ v_{js} \ v_{ks}]^T \quad (V) \quad (7)$$

$$[\lambda] = [\lambda_{as} \ \lambda_{bs} \ \lambda_{cs} \ \lambda_{ds} \ \lambda_{es} \ \lambda_{fs} \ \lambda_{gs} \ \dots \ \lambda_{hs} \ \lambda_{is} \ \lambda_{js} \ \lambda_{ks}]^T \quad (V.s) \quad (8)$$

$$[e] = [e_{as} \ e_{bs} \ e_{cs} \ e_{ds} \ e_{es} \ e_{fs} \ e_{gs} \ \dots \ e_{hs} \ e_{is} \ e_{js} \ e_{ks}]^T \quad (V) \quad (9)$$

$$[r] = \text{diag}[r_s]_{11 \times 11} = r_s \times I_{11 \times 11} \quad (\Omega) \quad (10)$$

I is the 11-by-11 square Identity matrix.

$$[L] = \begin{bmatrix} L_{self} & M & M & \dots & M & M \\ M & L_{self} & M & \dots & M & M \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ M & M & M & \dots & L_{self} & M \\ M & M & M & \dots & M & L_{self} \end{bmatrix}_{11 \times 11} \quad (H) \quad (11)$$

$$[i] = [i_{as} \ i_{bs} \ i_{cs} \ i_{ds} \ i_{es} \ i_{fs} \ i_{gs} \ \dots \ i_{hs} \ i_{is} \ i_{js} \ i_{ks}]^T \quad (A) \quad (12)$$

Since sum of the phase currents is zero; so, we can write (6) as the following:

$$\frac{d[\lambda]}{dt} = L_s \frac{d[i]}{dt} + [e] \quad (V) \quad (13)$$

$$L_s = L_{self} - M \quad (H) \quad (14)$$

where $[v]$, $[\lambda]$, $[i]$ and $[e]$ are motor phase voltages matrix, flux linkages matrix, input phase currents matrix into the motor and BEMFs matrix, respectively. The BEMF is directly proportional with magnetic flux produced by permanent magnet rotor and angular speed of rotor. Since produced magnetic flux is constant, the BEMF is direct proportion with the rotor position only. Therefore BEMF is written as the following:

$$e = \frac{2}{P} \times K_e \omega_r \quad (V) \quad (15)$$

where K_e , ω_r and P are BEMF constant in $(\frac{V.s}{rad})$, electrical angular speed of the rotor in $(\frac{rad}{sec})$ and number of poles, respectively.

The electromagnetic torque can be calculated by:

$$T_e = \frac{P}{2} \times \frac{[i]^T e}{\omega_r} \quad (16)$$

Basic equation of the rotor dynamic is written as:

$$T_e = J \left(\frac{2}{P} \right) \frac{d\omega_r}{dt} + B_m \left(\frac{2}{P} \right) \omega_r + T_l \quad (17)$$

where J , B_m and T_l are the total inertia of the rotor and load in $(kg.m^2)$, damping coefficient of the rotating system in $(\frac{N.m.s}{rad})$ and constant load torque in $(N.m)$, respectively.

III. SPEED CONTROLLER

The difference between the reference speed and the real speed is error signal. For reducing steady state error, we require integrator block. On the other hand, fuzzy PI controller is not used because of integrator windup problem. There are some methods to solve this trouble. One of the best methods is to configure the controller as a fuzzy incremental

controller (FInC). A partial of Fig. 1 shows a schematic of FInC [10-12]. Coefficients of error and change of error signals are the inputs of rule base. Diagram of FInC is similar to fuzzy PD controller and the only difference is the integrator on the output of the rule base and Go gain.

Stator windings of PMBLDCM are supplied by a two-level inverter. During rotor acceleration, frequency of the fundamental component voltage generated by voltage source inverter (VSI) must be increased gradually from zero to a desired value according to the frequency of the rotor speed. Modulation techniques of VSI are base on hysteresis modulation or space vector pulse width modulation. In this paper, hysteresis modulation has been employed. In this modulation technique, the motor currents track the rectangular reference current within hysteresis band. If the current crosses the upper (lower) limit of the hysteresis band, the upper (lower) switch of the inverter leg is turned off; so the currents start to decay (rise). Thus, the real currents stay into the hysteresis band. Fig. 1 shows a schematic of speed control of the eleven-phase of PMBLDCM.

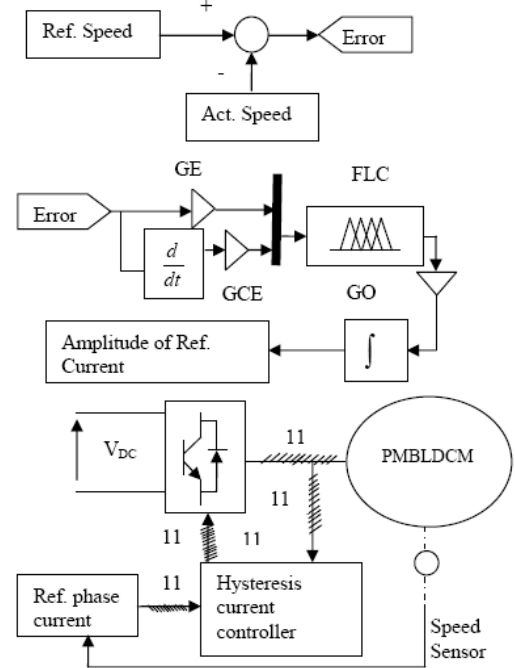


Fig. 1. Schematic of speed control of the eleven-phase PMBLDCM

TABLE I: PARAMETERS OF THE MOTOR

BEMF Constant	$K_e = 0.763 \left(\frac{V.s}{rad} \right)$
Self inductance of stator	$L_{aa} = 0.0218 \text{ (H)}$
Mutual inductance between stator windings	$M = 0.0018 \text{ (H)}$
Resistance of each phase of stator windings	$r_s = 1 \ \Omega$
Total inertia of rotor and load	$J = 0.005 \text{ (kg.m}^2\text{)}$
Number of poles	$P = 4$
DC voltage source	$V_{DC} = 220 \text{ (V)}$
Friction coefficient	$B_m = 1 \left(\frac{N.m.sec}{rad} \right)$
Hysteresis band	$HB = 0.005$
Initial constant load	$T_l = 50 \text{ (N.m)}$
Final constant load	$T_l = 70 \text{ (N.m)}$

IV. SIMULATION RESULTS

Table I shows the main parameters of the machine. The motor runs its friction load and a 50 N.m constant mechanical load from standstill. After 0.5 second, constant load of motor has been increased to 70(N.m). In order to control motor speed, we use fuzzy incremental controller. We have three triangular membership functions for error and also three triangular membership functions for change of error. So, we have nine triangular membership functions for output of rule base. Using the membership functions the following control rules are established for the FInC.

- (R1) if (e is N) and (de is N) then (output is NL)
- (R2) if (e is N) and (de is Z) then (output is NS)
- (R3) if (e is N) and (de is P) then (output is Z)
- (R4) if (e is Z) and (de is N) then (output is NS)
- (R5) if (e is Z) and (de is Z) then (output is Z)
- (R6) if (e is Z) and (de is P) then (output is PS)
- (R7) if (e is P) and (de is N) then (output is Z)
- (R8) if (e is P) and (de is Z) then (output is PS)
- (R9) if (e is P) and (de is P) then (output is PL)

Fig. 2 shows the surface viewer of FInC which is a three-dimensional curve that represents the mapping from error and change of error to amplitude of reference phase current. In Fig. 1, the gain value of GE, GCE and GO are 1, 0.007 and 20, respectively.

TABLE II: PHASE CURRENT FLOWS ACCORDING TO THE OPERATING MODES

	ia	ib	ic	id	ie	if	ig	ih	ii	ij	ik
1	+	-	-	-	-	-	0	+	+	+	+
2	+	0	-	-	-	-	-	+	+	+	+
3	+	+	-	-	-	-	-	0	+	+	+
4	+	+	0	-	-	-	-	-	+	+	+
5	+	+	+	-	-	-	-	-	0	+	+
6	+	+	+	0	-	-	-	-	-	+	+
7	+	+	+	+	-	-	-	-	-	0	+
8	+	+	+	+	0	-	-	-	-	-	+
9	+	+	+	+	+	-	-	-	-	-	0
10	+	+	+	+	+	0	-	-	-	-	-
11	0	+	+	+	+	+	-	-	-	-	-
12	-	+	+	+	+	+	0	-	-	-	-
13	-	0	+	+	+	+	+	-	-	-	-
14	-	-	+	+	+	+	+	0	-	-	-
15	-	-	0	+	+	+	+	+	-	-	-
16	-	-	-	+	+	+	+	+	0	-	-
17	-	-	-	0	+	+	+	+	+	-	-
18	-	-	-	-	+	+	+	+	+	0	-
19	-	-	-	-	0	+	+	+	+	+	-
20	-	-	-	-	-	+	+	+	+	+	0
21	-	-	-	-	-	0	+	+	+	+	+
22	0	-	-	-	-	-	+	+	+	+	+

As mentioned earlier, the induced voltage waveform on the stator winding produced by permanent magnet rotor is

trapezoidal form. Therefore, for producing constant electromagnetic torque, the actual current waveform should be quasi-rectangular. Fig. 3 shows switching process, BEMFs and the reference currents waveforms. As shown in Fig. 3, in each $\pi/11$ electrical angle, ten phases are conducting and last phase is floating. The commutation period of PMBLDCM is $\pi/11$ electrical angle and conducting period of each phase is $10\pi/11$. Fig. 4 shows the BEMF and current waveforms for a-phase. Existence distortion in BEMF and phase current waveforms is due to the change of mechanical load that it occurs after 0.5 second. The detailed phase current flows according to the 22 operating modes are represented in Table II. Positive sign means that the direction of flowed current is to the motor terminals from the output of inverter. Fig. 5a, 6a have shown the electromagnetic torque and the rotor speed since startup for 1 second, respectively. In figures 5b, 5c, 6b, 6c torque pulsations and speed ripple before and after increasing constant load have been shown. Fig. 7 illustrates interdependence between torque pulsations and speed ripples with a-phase current commutation. Obviously, current commutation is an effective factor on torque pulsations and speed ripples. Fig. 8 shows the rotor speed versus the electromagnetic torque. As shown in fig. 8, the motor speed is reduced to 541.9135 (rpm) by increasing mechanical load. Then, by fuzzy logic controller and hysteresis current controller, rotor speed will return to desired speed.

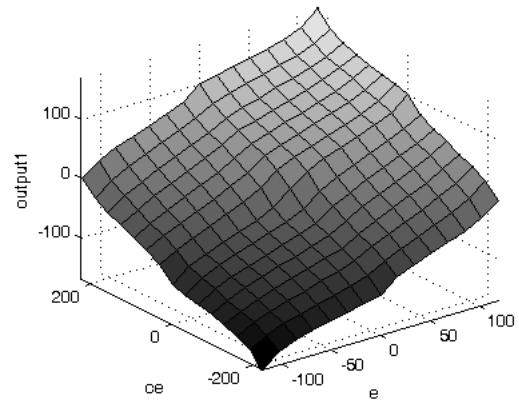


Fig. 2. Surface viewer of FInC.

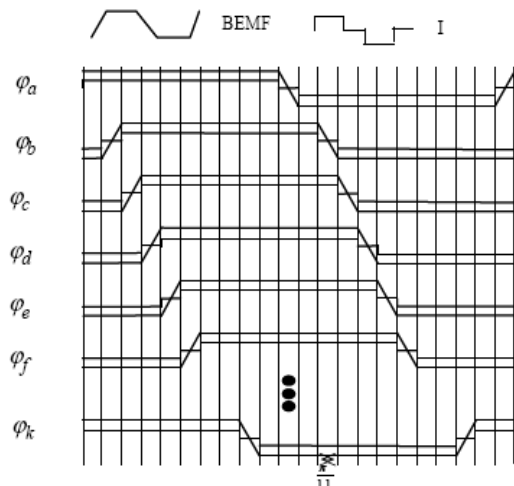


Fig. 3. BEMF and reference phase currents waveforms

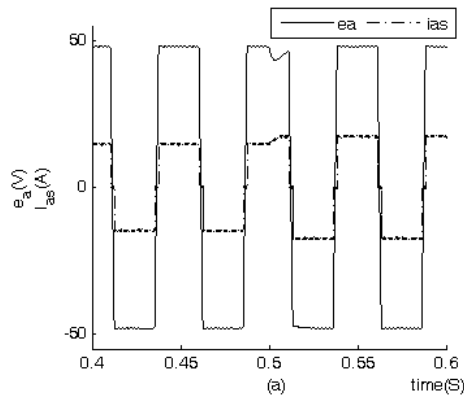


Fig. 4. BEMF and actual a-phase current waveforms

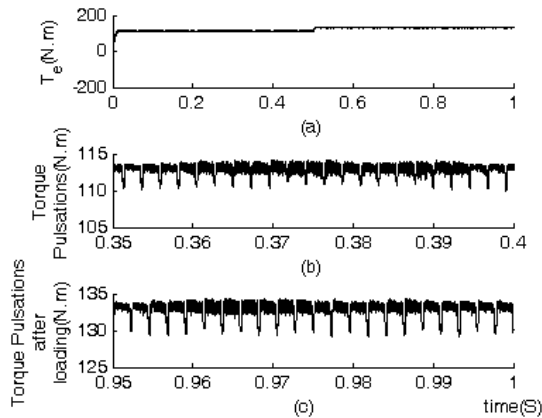


Fig. 5. (a) Electromagnetic torque (b) electromagnetic torque pulsations (c) electromagnetic torque pulsation after increasing load

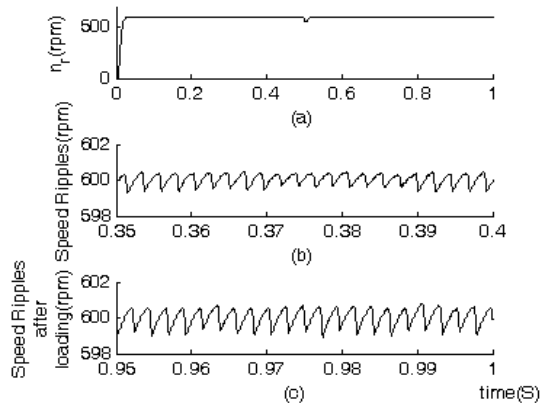


Fig. 6. (a) Rotor speed, (b) Rotor speed ripples, (c) Rotor speed ripples after increasing load

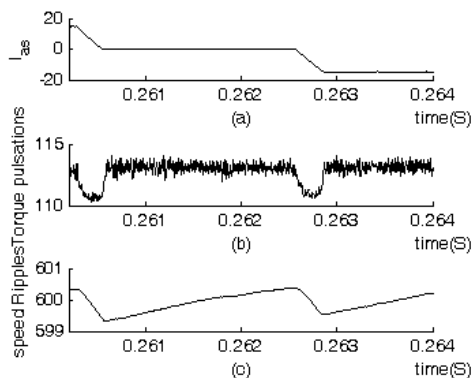


Fig. 7. (a) Actual current of a-phase, (b) Electromagnetic torque pulsations, (c) Rotor speed ripples

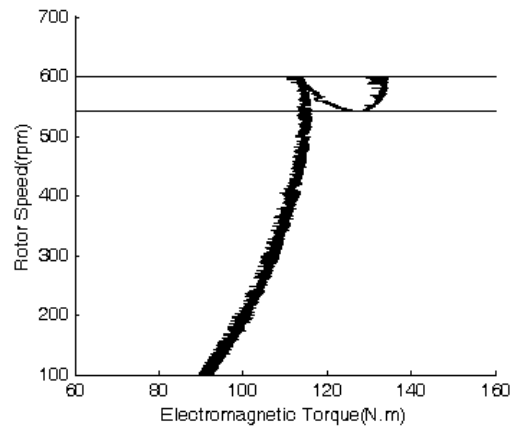


Fig. 8. Rotor speed versus electromagnetic torque

V. CONCLUSION

Simulation results illustrate the multiphase brushless DC motors are proper choice for many applications especially for military equipments. In military applications reliability and fault tolerance and high torque are the main important factors. Therefore, multiphase PMBLDCM drive is fit for military applications.

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