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Abstract

A permanent magnet brushless direct current (BLDC) motor is utilized for actuating the control rod of a miniature neutron source reactor (MNSR). The BLDC motor drive is modeled using MATLAB/SIMULINK, with inverter switching and current control representing the two primary components of the modeling effort. Current control employing chopping techniques is implemented to minimize torque ripple in the MNSR control rod drive. Among the three strategies evaluated, fuzzy logic current control combined with soft chopping control demonstrates the optimal response. The prototype drive mechanism incorporates an ATmega32 controller and power MOSFET switches. Simulation results are validated through comparison with experimental results from the physical drive mechanism.

Full Text

Preamble

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Minimizing Torque Ripple in a Brushless DC Motor with Fuzzy Logic: Applied to Control Rod Driving Mechanism of MNSR

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A permanent magnet BLDC (brushless direct current) motor is used to move the control rod of a miniature neutron source reactor (MNSR). The BLDC motor drive is modeled using MATLAB/SIMULINK. Two main parts of the modeling are the inverter switching and the current control. Current control with chopping is used to minimize the torque ripple of the MNSR control rod drive. Fuzzy logic current control together with soft chopping control shows the best response of all three strategies. The prototype drive mechanism employs an ATmega32 controller and power MOSFET switches. The simulation results are compared with the experimental drive mechanism.

Keywords: Torque ripple, BLDC motor, Fuzzy logic, Control rod, MNSR

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Introduction

II. REACTOR DESCRIPTION The permanent magnet brushless direct current (BLDC) motor has been widely used in industrial applications of variable speed drives. The BLDC motor produces torque from the interaction of magnetic flux of the rotor magnets and the current-carrying stator conductors of the stator core assembly. Its benefits include high power density, high efficiency, low maintenance, high reliability, simplicity, lower price, and fast dynamic response. Stator current commutation torque ripples, occurring due to the loss of ideal phase current commutation and the methods to minimize ripples, have been reported in the literature. Ashabani et al. reduced torque ripple of BLDC motor by control of the DC link voltage during the commutation time [1]. The intelligence method was the basis of their research, where the magnitude of voltage and commutation time were estimated by a neural network and optimized with particle swarm optimization (PSO) algorithm.

In 2011 and 2014, the brushless linear DC motor was proposed to move the nuclear reactor control rod assemblies as primary and auxiliary driving motor, respectively [2, 3]. In this study, the BLDC motor was employed to move the only control rod of a miniature neutron source reactor (MNSR). Torque ripple of the BLDC motor is minimized with fuzzy logic to satisfy the requirements of fast response and precision movement of the control rod.

The MNSR developed by the Chinese Institute of Atomic Energy is a compact research reactor based on the Canadian SLOWPOKE reactor design. It is of a low power tank-in-pool type and uses highly enriched uranium as fuel, light water as moderator and coolant, and metallic beryllium plates as reflector [3]. The core consists of the fuel cage, one central cadmium absorber with stainless steel cladding control rod, fuel pins (fuel rods), dummy rods, and tie rods, with the generated heat removed through natural circulation [4].

A. Reactor Description

The control rod drive mechanism (CRDM) is driven by a servo motor, type SDE-45, through a mechanical gear system. The servo motor ensures position control of the control rod, and hence stability of the neutron flux. The CRDM assembly is mounted on top of the reactor vessel, about 0.6 m above the volume of reactor pool water. The pool top is covered with a Perspex material to protect the pool water from environmental contamination and to reduce evaporation. Although most of the materials in the control rod drive mechanism assembly are made of stainless steel, the servo motor contains corrodible materials [5, 6].

In 2014, an electromagnetic levitation system together with synchronous motor was used to navigate the control rod. The control system was programmed in MATLAB through the open-loop system, closed-loop with state feedback, and closed-loop with state feedback integral tracking. The results from the prototype system showed that the proposed method was useful in such a sensitive drive mechanism [4].

Modeling of BLDC Motor

The BLDC motor back electromotive force (back-EMF) induced in stator windings has a trapezoidal shape. In this study, due to high efficiency, cost-effective control, optimum number of power electronic devices (number of MOSFETs), and low torque ripple, the three phases of BLDC motor have been used. Figure 1 [Figure 1: see original paper] shows the cross section of the three-phase BLDC motor construction.

The BLDC drive modeling is implemented based on the following steps: (1) The phase currents and position are measured; (2) Differential equations of the BLDC consist of speed, position, and the current of phases a and b; (3) Trapezoidal back-EMF of BLDC drive is simulated using a look-up table; (4) By means of torque ripple minimization, an inverter with soft chopping has been used; (5) The current control unit provides a DC voltage level of the inverter. Figure 2 [Figure 2: see original paper] shows the schematic of the BLDC drive modeling.

A. BLDC Differential Equations

Fundamentals of differential equations in BLDC motor can be written as (refer to Figure 2 for the variants) [7]:

$$v_{ca} = Ri_{ca} + R\frac{di_{ca}}{dt} + E_{ca}, \quad (1)$$

$$i_{ab} = i_a - i_b, \quad (2)$$

$$E_{ab} = e_a - e_b, \quad (3)$$

$$i_{bc} = i_b - i_c, \quad (4)$$

$$E_{bc} = e_b - e_c, \quad (5)$$

$$i_{ca} = i_c - i_a, \quad (6)$$

$$E_{ca} = e_c - e_a, \quad (7)$$

$$i_a + i_b + i_c = 0, \quad (8)$$

where v_{ab} , v_{bc} , and v_{ca} are line-to-line voltages in the three phases a, b, and c; i_{ab} , i_{bc} , and i_{ca} are line-to-line currents in the three phases; i_a , i_b , and i_c are currents of the three phases; E_{ab} , E_{bc} , and E_{ca} are line-to-line back-EMF in the three phases; e_a , e_b , and e_c are voltages of the three phases; and R is the phase resistance (Ω).

The back-EMF for three phases is [6]:

$$e_a = k_e\omega K(\theta), \quad (9)$$

$$e_b = k_e\omega K(\theta - 120^\circ), \quad (10)$$

$$e_c = k_e\omega K(\theta - 240^\circ), \quad (11)$$

where

$$K(\theta) = \begin{cases} 1 - 6(\theta - 120^\circ)/\pi & 0 \leq \theta < 120^\circ \\ 1 - 6(\theta - 300^\circ)/\pi & 120^\circ \leq \theta < 180^\circ \\ & 180^\circ \leq \theta < 300^\circ \\ & 300^\circ \leq \theta < 360^\circ \end{cases}$$

and $k_e\omega = k_e\omega_m/2$, where k_e is the back-EMF constant ($V \cdot s/\text{rad}$), ω is angular velocity (rad/s), θ is the angular displacement (radian), and $K(\theta)$ is the trapezoidal waveform of the back-EMF.

The electromechanical torque can be expressed as [7]:

$$T_e - T_L = k_f\omega_m + J\frac{d\omega_m}{dt},$$

where T_e is electromagnetic torque ($N \cdot m$), T_L is load torque ($N \cdot m$), k_f is motor friction constant ($N \cdot s/\text{rad}$), and J is rotor inertia ($\text{kg} \cdot \text{m}^2$).

The BLDC torque is a function of the current and the back-EMF:

$$T_e = k_t[K(\theta)i_a + K(\theta - 120^\circ)i_b + K(\theta - 240^\circ)i_c]/2,$$

where k_t is torque constant ($\text{N} \cdot \text{m}/\text{A}$).

From the system equations, one has:

$$v_{bc} = R(i_a + 2i_b) + L\frac{d(i_a + 2i_b)}{dt} + E_{bc},$$

where L is phase inductance (H). According to the fundamental equations, the BLDC motor differential equations for three-phase can be reduced to two-phase as follows:

$$\begin{aligned}\frac{di_a}{dt} &= -\frac{Ri_a}{L} + \frac{2(v_{ab} - E_{ab})}{3L} + \frac{(v_{bc} - E_{bc})}{3L}, \\ \frac{di_b}{dt} &= -\frac{Ri_b}{L} - \frac{(v_{ab} - E_{ab})}{3L} + \frac{(v_{bc} - E_{bc})}{3L}.\end{aligned}$$

The voltage equations can be simplified to:

$$\begin{aligned}v_{ab} &= Ri_{ab} + R\frac{di_{ab}}{dt} + E_{ab}, \\ v_{bc} &= Ri_{bc} + R\frac{di_{bc}}{dt} + E_{bc},\end{aligned}$$

where

$$\begin{aligned}\frac{d\omega_m}{dt} &= \frac{T_e - T_L - k_f\omega_m}{J}, \\ \frac{d\theta_m}{dt} &= \omega_m.\end{aligned}$$

B. Inverter of BLDC Drive

The BLDC motor drive was actuated by a six-switch inverter as shown in Figure 3 [Figure 3: see original paper]. The switches are metal oxide semiconductor field effect transistors (MOSFET) [7]. In an inverter, the current in the active phase is turned on and off by the electronic devices, usually at a high frequency. This is called chopping. Chopping can be done by hard chopping or soft chopping. In hard chopping, the upper and lower switches are driven by the same signal;

while in soft chopping, only the upper switch is driven by the chopping signal and the lower switch is left on during the whole interval. The advantage of soft chopping is that it creates less switching losses and current ripple than hard chopping, hence minimizing torque ripple. The proposed soft chopping circuit is shown in Figure 4 [Figure 4: see original paper]. The inverter voltages in soft chopping mode applied to the six-switch inverter are given in Table 1 .

C. Current Control of BLDC Drive

There are two main sources of torque ripple generated by the BLDC drives: chopping in the inverter and current control. By means of torque ripple minimization, a new soft chopping control has been presented in this study, and the current control in the BLDC drive via hysteresis current control (HCC) and fuzzy logic current control (FLCC) was investigated. Figure 6 [Figure 6: see original paper] shows the block diagram of the current control scheme using fuzzy logic.

1. Hysteresis Current Control Reviewing research in the past decade about torque ripple reduction in BLDC drives, most authors worked on torque ripple reduction by HCC. Current control of hysteresis band is a simple and common current closed-loop control. In HCC, the value of the controlled variable is forced to stay within limits (hysteresis band) around a reference value. The HCC technique generates high switching frequencies when a narrow hysteresis is used, and the wider the hysteresis band is, the larger the ripple produced. Figure 5 [Figure 5: see original paper] shows the block diagram of HCC. The uncertain switching frequency makes filtering of electromagnetic noise difficult. Moreover, current chattering produces noise in electronic devices and generates high mechanical stress.

2. Fuzzy Logic Current Control The torque ripple of BLDC drive can be minimized by using fuzzy logic current control. The block diagram of FLCC for minimization of torque ripple of BLDC drive is shown in Figure 6. Current error is the differential between current reference and root mean square (RMS) of three-phase current. In the FLCC method, fuzzy rules act on current errors (five membership functions for $-0.5-0.5$ A) and current error derivative (seven membership functions for $-0.06-0.06$ A/ms) as inputs, and also act on inverter voltage level (five membership functions for $0-1$ V) as output. Figure 7 [Figure 7: see original paper] shows the fuzzy logic membership functions for the proposed FLCC. Table 2 shows the fuzzy logic rules used to reduce the torque ripple.

Simulation Results and Discussion

The proposed BLDC drive applied to the CRDM of MNSR has been simulated by MATLAB/SIMULINK. The parameters of the model are listed in Table 3 . The BLDC drive has been operated in three cases: (a) HCC with hard chopping, (b) HCC with soft chopping, and (c) FLCC with soft chopping. Figure 8 [Figure

8: see original paper] shows the fast dynamic response of the BLDC motor where the speed of the motor was regulated at 360 RPM. The simulation results of the BLDC drive operation are shown in Figure 9 [Figure 9: see original paper].

From Figure 9, the total torque of the BLDC motor is affected by current control. The hard chopping control has a good response with HCC rather than soft chopping control with HCC. However, the best performance can be obtained using soft chopping with FLCC. This torque ripple reduction technique can be used for such precision movement of the MNSR control rod drive. A prototype of the optimized drive mechanism with BLDC motor is shown in Figure 10 [Figure 10: see original paper]. This setup includes the BLDC motor, drive, gearbox, and the moving rod. The drive consists of three parts: power switches (6 MOSFETs), micro-controller, and interface circuits.

Conclusion

The BLDC motor drive mechanism has been investigated for use in a research reactor CRDM. MATLAB/SIMULINK was used to simulate the three under-study cases: HCC with hard chopping, HCC with soft chopping, and FLCC with soft chopping. The results showed the combination of FLCC method with soft chopping as an improved technique for reduction of torque ripple has good performance. This minimized torque ripple of the BLDC motor drive will directly affect the movement of the MNSR control rod. In nuclear industrial applications, frequent control rod movements for load-following operation induce xenon oscillation. Therefore, such an FLCC controller together with soft chopping that can subdue this phenomenon effectively is needed.

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Note: Figure translations are in progress. See original paper for figures.

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