Adaptive fourier series speed controller for permanent magnet synchronous motor and brushless dc motor

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Abstract. Permanent magnet motors provide the highest power density and highest efficiency among all types of electric motors. For machine tool components and fast dynamic positioning systems the PMSM motors are commonly used. On the other hand, the BLDC motor delivers a higher torque to size ratio compared to DC motors, making it suitable for applications where weight and space are important factors. The construction of PMSM and BLDC motors is similar. However, they require completely different control approach, (Field Oriented Control for PMSM and Trapezoidal Control for BLDC). In this paper a new adaptive controller for PMSM and BLDC motors is proposed. For this controller a trapezoidal control is implemented and the torque ripple (due to non-trapezoidal back-EMF), is reduced using a Fourier series approach. The proposed controller was implemented experimentally and the results confirm it is effective to reduce the effect of internal torque ripple as well as the speed ripple produced by external periodic torque disturbances applied to the PMSM. Using the Adaptive Fourier Series Controller, the reduction on speed ripple was 2.7% of nominal speed when the first four terms of Fourier series were used, while the standard Field Oriented Control produced a speed ripple of 112% of the nominal angular speed.

1. Introduction

Permanent magnet motors (PMM) provide the highest power density and highest efficiency among all types of electric motors [1-3]. The permanent magnet motors are classified into sinusoidal fed permanent magnet synchronous motors (PMSM) and rectangular fed brushless direct current motors (BLDC) [4]. The PMSM market is rising faster than traditional competitors because of higher reliability and efficiency, as well as lower cost [5].

Regarding induction motors and brushed DC motors, BLDC motors have several advantages, such as high reliability and efficiency [6]. Brushless permanent magnet DC motors are widely used in areas such as home appliances, automotive components and underwater remotely operated vehicles [7, 8].

However, PMSM have an important drawback identified as “torque ripple”. Torque ripple produces deterioration of position trajectory and speed, with increased acoustic noise and additional energy losses, in high-speed applications [9]. To improve PMSM performance and rise its market portion, in recent years much attention has received pulsating torque suppression [5]. Moreover, since the motor windings are inductive, the current controller has often no ability to produce the required current in the commutation period owing to finite dc bus supply voltage, the resulting torque ripple is called commutation torque ripple [10]. The characteristic torque ripple caused by commutations of current
from one phase to another, non-trapezoidal back-EMF, and cogging also limits its applications in high accurate servo systems [11].

For PMSM assuming a sinusoidal back electromagnetic force (EMF), the standard Field Oriented Control (FOC) delivers constant torque. Torque ripple happens in PMSM because of non-sinusoidal flux in the air-gap and the changing magnetic reluctance. Torque ripples produces speed variations that reduces PMSM performance, predominantly at low speeds [5].

Depending on the back-EMF shape, trapezoidal (for BLDC) or sinusoidal (for PMSM), to attain constant torque the BLDC motor is generally controlled by square waveform currents, and the PMSM is usually controlled by sinusoidal currents [6].

BLDC motors are electronically commutated, where trapezoidal commutation is the simplest technique to control the EMF. However, due to a misalignment between the stator current and rotor position, the output torque has a 15% ripple, causing loss of speed and mechanical wear [12].

Some techniques for torque ripple reduction, based on algorithms for closed-loop control, using parameters online estimation have been suggested for PMSM controllers [13]. Repetitive Control techniques include a sinusoidal control element to cope with periodic torque pulsations, some recent articles implement learning control strategies designed for PMSM [5].

Various torque control methods have also been proposed to minimize torque pulsations. For example, Liu et al. propose a variable structure instantaneous torque controller in the d-q [14]. Other control techniques include knowledge-based control system, such as expert systems, fuzzy logic controllers and neural network-based controllers [15, 16]. When a precise dynamic model is difficult to attain, a function approximation can be built using expansion in Fourier series. For instance, a nonlinear controller can use the Fourier coefficients to achieve ripple-free and precise torque control and reduce copper losses for brushless motors [17].

Frequency domain Controllers have some advantages [18]. For unknown time-varying parameters nonlinear systems, an adaptive iterative learning controller can be built to achieve non-uniform trajectory tracking, when the time-varying parameters are expressed using Fourier series [19]. A versatile PMSM model and an adaptive control algorithm allow speed tracking and minimize torque ripple. Information of torque ripple harmonics is used in adapting the control algorithm and the current controller resulting in ripple minimization [20]. For torque ripple minimization an excellent choice is the Iterative learning control (ILC) [21].

It is possible to utilize the Fourier series as an instrument for examining the convergence of the iterative learning control rules since the Fourier series typifies the frequency property of the time function signal, [22]. Moreover, the Fourier series can be used in several periodic phenomena, many physical systems are affected for periodic disturbances and for some applications tracking of periodic reference is required [23].

To stabilize a nonlinear system, Fourier series can represent the adequate control signal, with a finite number of terms and the correct update law for the coefficients. As a control law, Fourier series can be used even if the error and/or the reference are not periodic [24].

In this paper a new adaptive controller for PMSM and BLDC motors is proposed. For the proposed controller, a trapezoidal control is implemented and the torque ripple (due to non-trapezoidal back-EMF), is reduced using a Fourier series controller. This controller was implemented experimentally, showing a reduction in the effect of internal torque ripple as well as the speed ripple produced by external periodic torque disturbances applied to the PMSM.

The remaining of this paper is as organized as follows: section 2 briefly describes the control methods for the PM motors. Section 3 presents the proposed adaptive controller for the PMSM and the BLDC motor. In addition, section 4 shows the experimental setup. Finally, section 5 present the experimental results. Section 6 closes with conclusions and future work.

2. Control techniques for PM motors
A rotor position sensor is required by PM motor drives to accurately execute phase commutation. Position information is necessary for controlling PMSM motors; therefore a high resolution position
sensor, such as an encoder, is normally used. To control BLDC motor, only the information of the six commutation moments per cycle is required; consequently, Hall-effect sensors are typically used [25].

2.1. Vector control for PMSM
Vector control is a complex technique of commutation. This method operates controlling currents and voltage, with reference to the direct and quadrature axis rotor. This requires a constant field and quadrature with the rotor field. The currents detected in the stator are transformed in direct and quadrature components, through of Clarke transforms and Park. The direct component controls the flow, and the quadrature component the torque [12].

Sinusoidal back-EMF waveforms need a flux density with sinusoidal distribution around the airgap. Constant torque sinusoidal phase currents are normally established by means of a current-regulated inverter, that involves separate phase current sensors and a high resolution rotor position sensor in order to conserve precise synchronization of the rotor angular position with the excitation waveforms at every time instant [26]. This kind of control approach has the best response in all speed ranges, maintaining constant torque. However, it is the most complex and expensive to implement [12].

2.2. Trapezoidal control for BLDC
The trapezoidal commutation method is the simplest and the most common approach to control BLDC motors, resulting in straightforward implementation. This technique controls the current in the windings of the motor; then, only a pair of terminals will be energized while the third is disconnected. This is done successively, alternating the pair of energized terminals, in all six possible combinations [11]. For proper commutation and motor rotation, the rotor position information is crucial to ensure the proper electronic switching in the inverter bridge and direction of current flow in respective coils. Hall Effect sensors are used in general as position sensors for trapezoidal commutation. Each Hall sensor is typically placed 120 degrees apart. The speed of BLDC motors is proportional to the voltage applied. The commutation logic specifies the winds to be connected for each 60 degree of electrical revolution based on Hall sensor inputs [12].

2.3. Fourier series to reduce torque ripple on PMSM
Mathematical background and the general scheme for torque ripple minimization is presented in [5]. The Fourier Series Controller is not started during transient state, so the Field Oriented Control sets the motor in to operation. After transient state, the Fourier Series Controller is started and it delivers the compensation to reduce torque ripple. In the inner loop, the control voltages is generated by the standard PI controllers according to the field oriented control algorithm.

To reduce the velocity ripple, the control voltage, associated to the position \( \theta_r(t) \), is as follows:

\[
u(\theta_r) = \sum_{k=1}^{n} [c_k \cos(k \* \theta_r(t))]
\]

A sinusoidal function can be used to approximated each component \( c_k \cos(k \theta_r(t)) \), for the position ripple \( \theta_{ripple}(t) \). Speed variations alter the temporal representation of each term \( \cos(k \theta_r(t)) \), therefore its distortion \( S \) can be used to adjust the coefficients \( c_k \) for reducing the distortion, thru regulating \( \omega_r(\theta_r) \). If \( \tau = 2\pi \) is the mechanical-revolution spatial period:

\[
S = \int_0^{2\pi} \cos(k \* \theta_{ripple}(t)) \, dt
\]

\[
c_k(t) = c_k(t-1) + \delta \* S
\]

This algorithm can be used to adjust the parameters of the control voltage, adjusting for torque ripple changes, using the parameter \( \delta \) for adjusting the adaptation speed.

3. Adaptive fourier series controller for PMSM and BLDC motors
A BLDC motor is similar to a PMSM motor. Both motors have permanent magnets in the rotor that interact with the magnetic field produced by the stator coils. However, the appropriate control techniques for each type of motor are completely different. To achieve constant torque, the PMSM motor is controlled by field oriented control, and torque ripple would increase if trapezoidal control
were used. However, a PMSM motor has an encoder sensor to estimate angular position. The proposed Fourier series torque ripple reduction takes advantage of the angular position sensor.

The adaptive controller proposed in this paper uses trapezoidal commutation with a torque ripple reduction based on Fourier series. This algorithm applies to BLDC and PMSM motors without the need to change the control technique. Additionally, the Fourier series controller can be used to compensate external torque ripple disturbances. The Fourier series controller is activated until the motor is under stable operation, working on top of the PI controller. Estimated Fourier coefficients are used to achieve precise torque control.

Figure 1 shows the proposed control for torque ripple minimization, detailed description for the function of blocks is presented in references [6] and [25]. The controller based on Fourier series is off during transition of speed control loop, and the trapezoidal control initially operates the motor at stable regimen. Besides, position and speed are estimated with the encoder sensor. In stable mode, the Fourier series controller is activated, providing a compensation for minimize torque ripple.

4. Experimental implementation
In figure 2 the configuration of the experiment is shown. A TMDSHVMTRPF (Texas Instruments, Dallas, TX, EE.UU.) development system based on a F28035 DSP electronic board is used for implementation, featuring a 128 KB flash memory, 60 MIPS, 14 PWM channels, QEP interface and 12-bit 4.6 MSPS ADC, programmed with the software Code Composer Studio version 6. The EMJ-04APB22 Interior Permanent Magnet Synchronous Motors (Anaheim automation, Anaheim, CA, EE.UU.) contain four pole pairs and the following specifications: 2.7 A, 200 V, 400 W, 3000 rpm nominal speed, 0.014 H, 4.7 Ω stator inductance and resistance respectively, with a 2500 PPR optical encoder. A cyclic perturbation load is connected to the PSMS. A Variable Transformer Selector (Variac), is connected in the power supply to adjust to 117 VRMS, containing the following features: 50-60 input frequency, 0-140 output voltage and 5 A maximum.
Figure 2. Experimental setup, 1) TMDSHVMTRPF development module, 2) Variable auto transformer selector, 3) EMJ-04APB22 PMSM and 4) Periodic torque load.

The motor is connected to a cyclic perturbation load, where the torque magnitude is \( \tau_0 = 0.064 \) Nm. The PI current controller works with the following parameters: \( K_p = 1, K_i = 0.005 \), speed = 57 rpm. The variables are formatted in per unit values, and gamma is specified to 0.002.

5. Experimental results

In order to implement the adaptive controller algorithm proposed in the previous section, experiments were conducted for the slow speed range (less than 4% of the nominal speed). To evaluate the proposed controller, the variation of the angular speed was analyzed, calculated from the encoder position.

For the conventional Field Oriented Control applied to PMSM motors, figure 3a show the angular position versus time, the desired triangular waveform [5] is distorted by the perturbation load under the low speed condition. Figure 3b presents the speed ripple, which is as high as 112% of the nominal angular speed.

Figure 3. Conventional Field Oriented Control applied to PMSM motors. a) Motor angular position, at 57 rpm, b) Angular speed ripple, at 57 rpm.
Figure 4 correspond to the proposed algorithm, considering the first four terms of Fourier series. Figure 4a show a decrease in the waveform distortion for the angular position. Figure 4b shows that angular speed ripple was reduced to 2.7% of the specified speed. Figure 4c represent the control signal $u(\theta)$.

**Figure 4.** a) Motor angular position, at 57 rpm applying the proposed scheme (first four terms), b) Speed ripple, at 57 rpm applying the proposed scheme, c) Control signal $u(\theta)$.

### 6. Conclusions
A new proposed adaptive controller for PMSM and BLDC motors was implemented. For this controller a trapezoidal control is applied to a PMSM and the torque ripple due to non-trapezoidal back-EMF was reduced using a Fourier series controller. The standard Field Oriented Control shows a peak speed ripple of 64 rpm, for a 57 rpm set point (i.e. a 112% variation in nominal speed). With the proposed Adaptive Fourier Series Controller, the torque ripple is decreased to 2.7% of specified speed using the first four terms of Fourier series. No further reduction of the speed ripple was observed with
five of more terms of Fourier series. The experimental results confirm the suitability of the Adaptive Fourier Series Controller for PMSM and BLDC motors. Future work could evaluate the suitability of implementing different torque ripple reduction approaches.

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