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Abstract: Brushless DC Motors (BLDCM) have many benefits for their high efficiency, small size, and low maintenance requirements. On the other hand, high efficiency electronics are usually related to the usage of ARM based microcontrollers. In this work, the behavior over multiple PWM frequencies and after applying PWM compensation is studied using an ARM based board. In general, performance of sensorless and hall-effect based controller show expected differences. However, by using the proposed control schema on a real plant, impactful advantages are obtained showing 67% performance improvement and an average of 20% torque ripple reduction.

Keywords: Brushless motors, Torque motors, Control accuracy, Zero crossings, Hall effect, Pulse-width modulation, Torque ripple, Sensorless.

1. INTRODUCTION

Nowadays, Electric Motor Drive Systems (EMDS) represent between 40% - 50% of total global electricity consumption (International Energy Agency (IEA), 2017). Optimizations to these systems, such as speed adjustment, have significant energy savings compared to ON/OFF switching (Ferreira and de Almeida, 2016b). Traditionally, applications of low and medium power use classic brushed DC motors or induction motors at constant speeds regarding the efficiency. However, implementation of efficient electronics and control methods impact positively on the total energy consumption. In single operation point systems, efficiency is improved by increasing individual component efficiency. Moreover, in variable speed systems the energy savings are associated with better speed/torque control (Ferreira and de Almeida, 2016a).

BLDCM are becoming popular due to their superior controllability, performance and small size compared to single phase induction motors. Additionally, it is well known that they are also noiseless and require none or few maintenance procedures. These latter features are major reasons to extend the range of applications by including aviation, robotics, automotive, industry and household appliances (Gamazo-Real et al., 2010).

There are different definitions for Brushless DC Motors as was presented by (Xia, 2012). Nevertheless, in this work, are defined as a type of Permanent Magnet Motors (PMM) which only require six discrete points for commutation. Such electronic commutation is the main characteristic of these motors and in order to accomplish it, information of the rotor position is needed.

Theoretically, ideal BLDCM performance is featured by having constant torque/speed characteristics, synchronization of commutation instants with the rotor position and interaction of electrical current with the back electromotive force waveform (Bertoluzzo et al., 2015). However, in practice, deviations from ideal conditions related to design factors of the motor, electronic components, non-ideal current waveform and displacement on commutation instants may cause non-ideal performance (Jahns and Soong, 1996).

A major factor that prevents achieving ideal performance is called torque ripple and it is generated by imperfections in the design of the motor and inadequate control schemes. Besides, it has been reported that high frequency Pulse Width Modulation (PWM) causes high frequency small torque ripple and commutation torque ripple leads to a significant ripple of 50% of the average torque (Jiang et al., 2017). In this paper commutation torque ripple compensation and different PWM frequencies are applied to a BLDC motor, while current and speed response are measured and compared between experiments.

This paper is organized as follows, section II defines the background of torque ripple reduction. Then the experimental set-up and data acquisition is indicated in section III. Torque ripple reduction methodology used for the experiments is described in section IV. Section V analyses and present experimental results. Finally, conclusions are drawn in Section VI.

2. BACKGROUND

2.1 Position Detection

BLDCM's maximum torque is produced when the magnetic flux angle between rotor and stator is 90 degrees, hence the importance of knowing the position of the rotor: to ensure this alignment. Sensor based methods raise costs and device's final size. Furthermore, they are also subject to physical misalignment or failure. In contrast, sensorless methods can overcome the previous problems of size, cost and reliability by applying complex control algorithms and electronics.

2.2 Pulse Width Modulation Frecuency

The speed in BLDCM is controlled by the voltage applied with the inverter or driver. In order to vary this voltage, PWM techniques are used. Machines driven by inverters have high frequency current ripples that introduce energy losses on the rotor, this is sensitive to the switching frequency, the machine inductance and the dc-link voltage. Previous research (Chang and Jahns, 2017), (Van Der Geest et al., 2014) showed that low switching frequencies and high-frequency current ripple generate losses in the motor parts concluding that the magnitude of current ripple decreases as the switching frequency increases.

2.3 Torque Ripples

This phenomenon causes vibrations, noise, speed ripples and fluctuations that limits the applications of BLDCM. Torque ripples's sources in BLDCM related to device design are referred as cogging torque and reluctance torque. But the most studied sources of torque ripples are related to mutual torque.

Mutual torque is generated by the coupling of the stator electromagnetic field and rotor magnetic field. Ideally, if the waveform of the current phase BEMF and electrical current are perfectly matched, torque ripple is minimized and mutual torque component is maximized (Khudhair and Turker, 2016)(Park et al., 2000). Although mutual torque is related to the origin of torque ripples, it is worth noting that mutual torque is the predominant mechanism used by BLDCM to produce torque.

Factors that prevent reaching an ideal mutual torque are PWM frequency and commutation. PWM causes small ripples with high frequency at constant average value. High efficiency, low maintenance BLDCM are becoming popular in speed and servo control but vibrations, acoustics noises and energy losses limit the applications making torque ripple reduction a hot research topic.

The behavior of currents in commutation region is crucial for torque ripple analysis. Ideal zero torque ripple is the result of maintaining the current of non-commutated phase constant. This is achieved by matching the slews of incoming and outgoing phases (Carlson et al., 1992). PWM control compensation, DC Bus voltage control, current control, torque control, phase conduction methods are some techniques employed to reduce commutation torque ripples (Salah et al., 2011).

Previous works meant to reduce torque ripples by obtaining the commutation period in zero crossing point and calculating a new duty cycle for the PWM applied only in that region (Kim et al., 2011). Extra operational amplifiers were also used to determine the commutation period (Lin and Lai, 2011). On the other hand, in order to control mixed duty cycles that appear between conduction and commutation regions when modified PWM control is applied, a discrete controller employment was explored to reduce torque ripples where results were obtained by numerical simulations (Khudhair and Turker, 2016). Further analysis showed that there are many terminal voltage combinations to maintain the non-commutated phase steady, but for different combinations of terminal voltage, the commutation period is also different, therefore the duty cycle that is applied must minimize the commutation period (Cao et al., 2017).

3. EXPERIMENTAL SETUP

A PSoC 4 Pioneer of CyPress was used as controller and the PSoC 4 Motor Control Evaluation Kit was employed to drive a BLY17 Series Brushless DC Motor.

The PSoC4 is based on a 32-bit ARM-Cortex family microcontroller, this device enables concurrent hardware and firmware editing. Applications for the PSoC were created with pre-designed peripheral components. Controller uses position information and feeds a look-up Table (LUT) that manages the sequence of commutation, speed is obtained by time measure between electrical cycles, latter a PI controller calculate PWM duty cycle needed to reach a desired speed.

CY8CKIT-037 is a Motor Control Evaluation board that present a MOSFET dual H-Bridge and a dual H-Bridge PWM drivers, capable for drive sensored and sensorless BLDC motors. It presents sensing circuits for Hall and back electromotive signals. Also, three low value resistances sense the current in each leg of the inverter. Provided with hall-effect sensors, an eight pole three phases delta configuration sinusoidal BEFM brushless DC motor of the BLY17 series was used for experiments.

Digital ports reads the Hall effect sensors state in sensored based controller, whereas a digital comparator between half DC voltage and motor phases determine zero crossing point, also current signal is amplified with operational amplifiers integrated in the PSoc4 controller.

4. METHODOLOGY AND EXPERIMENTS

Two different controllers: hall-effect sensors feedback position information and sensorless based on zero crossing point detection for commutation point were studied. PWM frequency was modified by changing the clock and period values of a pre-designed component in the controller. For commutation torque ripple reduction, duty cycle reduction before commutation point by modifying an specific line in controller's script was performed.

Step input zero-load experiments with a real plant were performed for sensored and sensorless controllers using different speeds and PWM frequencies. Also, commutation torque ripple reduction for sensorless controller was applied. Later, speed and current measures were analyzed and compared between experiments. For speed step input response, three fixed set points were used , see first column of Table 1.

A total of four experiments with two different controllers were done. Sensor based controller used 20K$[Hz]$ PWM frequency while three experiments with sensorless controller were performed at 20K$[Hz]$, 147K$[Hz]$ and commutation torque ripple reduction with 147K$[Hz]$. Additionally, three samples of forty-eight seconds for speed analysis were acquired. These were used as a way of determining steady state error, the root-mean-square deviation of three seconds segments between the reference point and measured speed. It should be noticed that for electrical current signals twelve samples of 120 electrical degrees per experiment were analyzed.

Once the experiment was set, the motor driver sent the data via UART communication to a PC at an average speed of 720 samples per second. Additionally, current signal was obtained with an ADS1000 Series Digital Oscilloscope trough driver test points. Obtained data is later analyzed in MATLAB, *stepinfo* function measure speed settling time and a script computes the root-mean-square deviation in steady state. For electrical current, median filter is applied first to reduce oscilloscope noise and 120 electrical degrees current phase peaks values are measured. Fig. 1 and Fig. 2 present speed and current measure data systems.

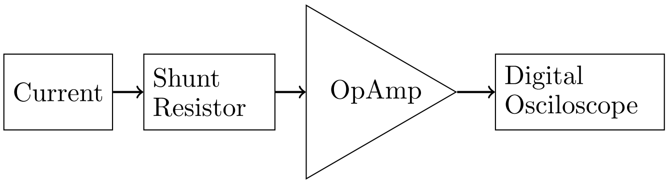

Fig. 1. Electrical current data acquisition system.

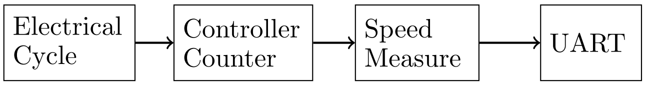

Fig. 2. Speed data acquisition system.

5. RESULTS AND DISCUSSION

ARM processors family are versatile, cheaper, energy efficient compared to other processors, in this work, changes on PWM frequency and commutation behavior are allowed by the capabilities of the controller, also, speed and protection (over-current) characteristics about motor and driver are measured in the controller.

Sensor based controller steady state error proves the problems related to this position detection method: sensor physical misalignment delays or anticipates commutation moment disturbing the speed performance. Speed result were compared between experiments where high PWM frequency controller showed minor settling time and steady state error than a slower PWM frequency controller, steady state error is presented in Fig. 3 whereas settling time obtained by *stepinfo* is presented in Table 1. Related to sensorless controller it is worth noting an overshoot due to align-and-go algorithm. Application of duty cycle compensation in commutation time improved the speed response, reducing the start-up overshoot and steady state error, speed response is show in Fig. 4.

Electrical current results show that high frequency current ripple is also reduced with high PWM frequencies. Fig. 5 shows torque ripples related to low PWM frequencies and commutation moment correspondent to physical misalignment, whereas a high PWM frequency sensorless controller reduced these pulses.

Table 1. Speed Settling Time in seconds

Speed (RPM)	Sensored Controller	20KHz PWM Freq.	143KHz PWM Freq.	Ripple Reduction
2700	2.254	2.359	0.272	0.231
3250	4.857	3.061	0.242	0.235
3600	5.602	3.544	0.168	0.172

In sensorless based controller with high PWM frequencies and low speeds, commutation torque ripple increases, altering speed control performance in steady state, response was corrected with PWM compensation while commutation torque ripple was reduced. See Fig. 6. Besides, Fig. 5 illustrates that the experimental motor has and non-ideal BEMF waveform shape. In low speeds, the electrical current waveform changed into a sinusoidal like shape while an increase on performance and current ripple reduction is obtained.

6. CONCLUSION

Brushless DC Motors are becoming popular for their benefits compared to other type of motors. Efficiency and performance improvements rely on control methods development. Application of sensorless techniques is seen as the best option because of the implied advantages; lack of noise and almost free maintenance required.

In general, it can be noticed that sensorless experiments have better results than the sensored ones. For example, experiment with 2700 RPM as reference point results in an steady state error above 6 RPM with sensored controller. In contrast, sensorless based controller presented an error below 2 RPM. See Fig. 3

Additionally, electrical current peak is reduced about 15% with PWM compensation compared to current ripples of sensored based controller. Steady state error illustrates that reduction of high frequency torque ripple is obtained when comparing Sensorless PWM 20K$[Hz]$ frequency with Ripple Reduction sensorless controllers. Similar to (Do-Hyeon Park et al., 2017), the position of

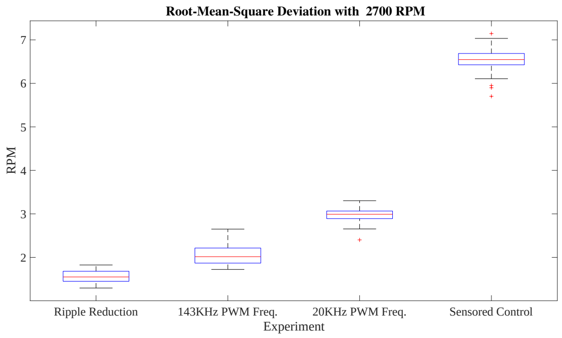

Fig. 3. Steady State error at 2700 RPM for each experiment. Boxplot show median error of RPM with 25th and 75th percentiles.

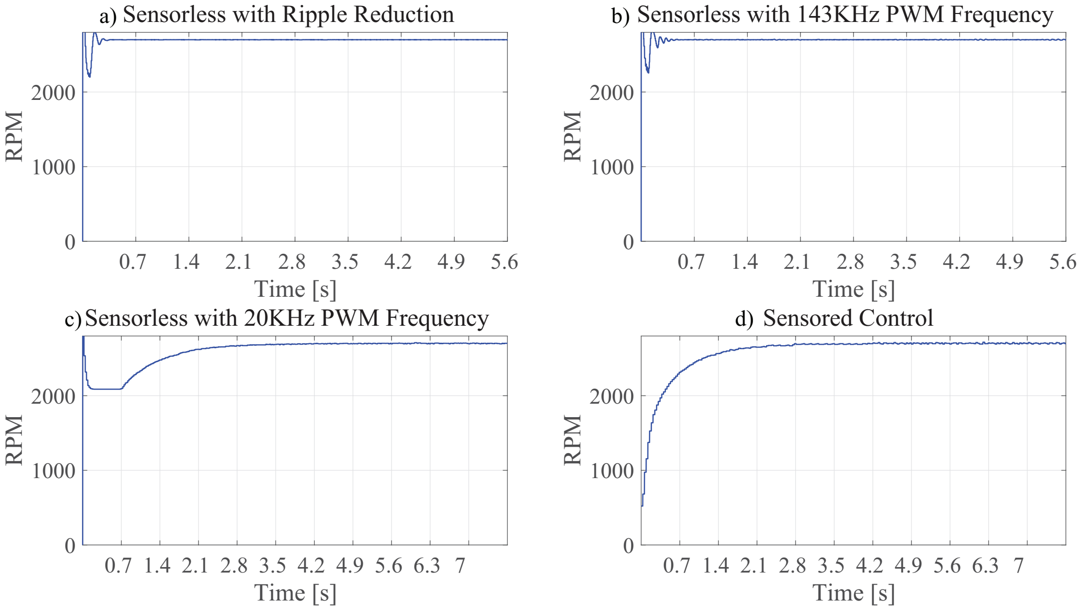

Fig. 4. Speed Response at 2700 RPM. a) Sensorless experiment at 143K[Hz] and duty cycle compensation b) Sensorless experiment at 143K[Hz] c) Sensorless experiment at 20K[Hz] d) Sensored experiment at 20K[Hz]

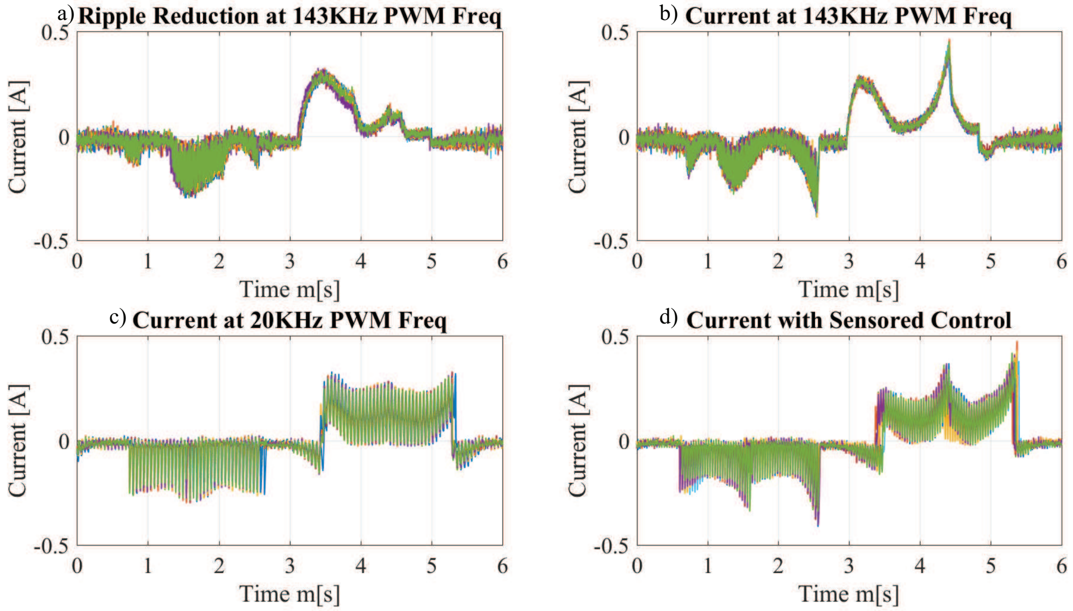

Fig. 5. Current Response at 2700 RPM. a) Sensorless experiment at 143K[Hz] and duty cycle compensation b) Sensorless experiment at 143K[Hz] c) Sensorless experiment at 20K[Hz] d) Sensored experiment at 20K[Hz]

sensored based controller is improved by using a sensorless method whereas torque ripple is reduced.

Finally, as studies about torque ripples, speed behavior and reduction of losses were explored, it was possible to us conclude on the improved performance of BLDCM by using sensorless techniques. The speed response and current phase behavior are clearly influenced by PWM frequencies as results show that high PWM frequency improves steady state response, accelerating settling time and reducing high frequency torque ripples.

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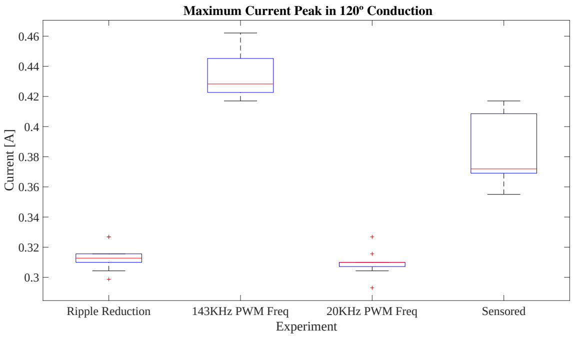

Fig. 6. Current peak value for each experiment at 2700 RPM. Boxplot show median value of current peak value with 25th and 75th percentiles

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