Simplified Control for Torque and Speed Ripple Mitigation in Brushless DC Motors

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Abstract – Brushless DC motors are characterized by their reliability, low inertia, fast response, and low maintenance. Unlike the conventional DC machines, the BLDC uses permanent magnets in place of brushes, resulting in lower maintenance requirements. Brushless DC motors produce constant torque under ideal conditions, with a trapezoidal back electromotive force (emf). Utilizing power electronic components for commutation in brushless DC motors causes harmonics in the armature current leading to large output torque ripples. This paper proposed a simplified circuit to minimize torque and speed waveform ripples. The circuit incorporates a simple filter, PI controller, and PWM, eliminating the need for a high computational processor. This enables easy execution and reduces the control circuit's energy footprint, resulting in low running costs with a simple design. The proposed circuit was simulated using PSIM software and the results confirm the ability of the circuit to minimize the torque and speed ripples to acceptable values for real and sensitive applications.

Keywords:BLDC motor, voltage control, torque ripple, Emerging technology

1. Introduction

In DC motors with brushes, the armature winding is located on the rotor, and the field winding lies on the stator. Because of brushes, the motor collects debris, and dust, and causes wear on the commutator surface, these motors are quite costly and require maintenance. Furthermore, due to arcing, the usage of DC brushed motors is restricted in certain hazardous locations. It is also prohibited to use it in places where we ensure that the percentage of pollution is low, such as hospitals and closed places. This drawback can be overcome by substituting power electronic switches for mechanical switching components such as the commutator and brushes. The rotor of BLDC consists of a permanent magnet, while its stator usually is a wound field, both are linked by a power electronic switching circuit and a controller in order to control the output torque and speed values. This control relies on the rotor position, which takes place at fixed points at every certain electrical angle of the phase currents. Low maintenance, high efficiency, long lifetime, low noise operation, simple control, and compact design are some of the benefits of BLDC motor drives In addition to the absence of harmful emissions in places of use. Brushless permanent magnet motors can be classified into two main categories: the trapezoidal-based back-EMF brushless DC motor and the sinusoidal-based back-EMF permanent magnet synchronous motor. The trapezoidal-based motor requires a semi-square current waveform for generating consistent torque, whereas the sinusoidal-based motor relies on a sinusoidal current signal to generate a more consistent torque waveform. By employing these distinct current waveforms, each motor type is optimized for specific operational requirements [1].

Torque pulsations are common in permanent-magnetic BLDC motors when operating conditions deviate from ideal. These deviations are caused by motor design variables or non-ideal waveforms of current caused by power inverter current stimulation. In machines that require high precision, these unwanted torque pulsations in permanent magnet BLDC motor drives will lead to drawbacks such as angular velocity fluctuations, kinetic resonances, acoustic audible noise, and apparent vibrations In addition to failure to operate in delicate applications. As a result, eliminating torque ripples is a major concern in BLDC motors. There are two primary methods to accomplish this: better motor design methods and better control schemes.

Skewing, short-pitch coil, multi-phase, utilizing airgaps windings, modifying stator slot openings, and optimizing the mechanical design of the rotor are some improved motor design techniques for reducing pulsating torque.

Advanced motor control strategies encompass a range of techniques such as adaptive control, predefined current waveform, injection of harmonics, estimation techniques, observation methods, disturbance filtration, current control, torque reduction during commutation, and automated self-configuration systems [2].

Torque ripple reduction in brushless motors has been a significant area of research, leading to the development of various techniques for different motor types and applications. In the literature, authors used various control techniques to minimize the torque and speed ripples of the BDCM. Among these algorithms, one approach focuses on brushless DC motors designed for electric vehicle (EV) applications. Researchers have introduced a duty-ratio control method specifically tailored to mitigate the ripples in the torque waveforms. As a result of duty cycle control, the technique improves torque consistency during motor operation which contributes to the literature a new control to achieve a better torque performance of the BLDC [3].

Another method to reduce torque ripple in BLDC motors involves mitigating harmonic currents, as proposed in [4]. This method considers the harmonic orders of torque produced by specific fluxes and currents, the method targets to eliminate specific harmonics which is considered high and hence leads to high ripples in the output torque, after this elimination, the torque ripple is minimized.

Researchers in [5] have proposed advanced pulse width modulation (PWM) technique to suppress the output torque ripples. This technique is based on the conventional PWM but with a modified algorithm to overcome the drawback of the conventional PWM. However, it is important to note that these methods may not be suitable for low-inference BLDC motor drives.

Another approach involves the use of control techniques for speed regulation of brushless DC motors. An APID controller has been proposed [6]. This controller offers multiple functions and has been compared with existing techniques to evaluate its effectiveness in achieving stable and accurate speed control.

Additionally, researchers have introduced a DC-link current control strategy for BLDC motors [7]. This technique is considered a direct control algorithm that provides dynamic control of the torque by maintaining the response time which is considered a fast response time.

A novel model predictive control-based PWM has been developed to address diode freewheeling and commutation current ripple in BLDC motors in [8]. Through simulations, the technique has demonstrated significant reductions by 32.5% for the torque ripples which is considered a big step towards performance enhancement compared to the conventional PWM. The simulated results are validated by an experimental prototype.

On the other hand, authors in [9] proposed a developed control algorithm that works by rejecting disturbances, this will lead to smooth switching and moving among waveform points that results in stability of the speed control and improve the overall performance of the BLDC.

Another study [10] proposes the utilization of the pulse amplitude modulation instead of PWM for the DC-link voltage, and the objective again was to minimize torque ripple in BLDC motors. Simulations targeted several types of the BLDC and confirms the ripple reduction which reaches 40% for the proposed modulation achieving a better system performance.

In [11], authors make use of switching between two and three phases as a control technique to mitigate the torque ripple in the BLDC. This alternating in conduction control leads to efficient performance enhancement regarding the commutation torque ripples.

These studies aim to improve brushless motor performance and efficiency by reducing torque ripple using different control techniques and modulation methods. However, all these methods rely on advanced processors that demand computational power and incur costs.

This paper presents a simplified circuit for minimizing torque and speed waveform ripples using PSIM's simulation process. The proposed circuit successfully achieves that the torque ripple is not exceed standard of torque ripple minimization for sensitive and clean applications such as an electric vehicle. It incorporates to a well design of simple filter, a PI controller, and PWM, eliminating the need for a sophisticated high computational processor in the circuit implementation. As a result, it offers easy execution and low running costs by reducing the energy footprint of the control circuit unlike the other sophisticated control algorithms that required very high computational power and at high cost. Smart systems often employ advanced control techniques and technologies to optimize the performance and efficiency of various components, including motors. The utilization of a filter circuit, such as the LC filter mentioned, is a part of this smart system approach to mitigate high frequency switching voltage ripple and reduce harmonics in the motor's supply voltage. By incorporating such filtering mechanisms, smart systems can enhance the overall operation and reliability of motor-driven applications.

The remainder of the paper is as follows: section II represents the structure of the BLDC including the power and control circuits, and section III shows the proposed filter design. Simulation and results are represented in section IV. Finally, section V concludes the work.

2. BLDC Structure

A BLDC motor requires a power electronic circuit with an appropriate control to operate. Figure 1 depicts the block diagram of the circuit and the corresponding controller for a BLDC motor.

An inverter drives a 4-pole BLDC motor for 120-degree commutation in the specific case described. A hall-effect sensor is responsible for positioning the rotor and results in three square wave signals with a 120° phase shift. Through combinational logic, these measured signals are used to generate firing signals for 120° conduction on each of the three motor phases.

To address the voltage ripple caused by high-frequency switching, a filter circuit is employed. The main purpose of this filter circuit is to remove the undesirable voltage fluctuations from the inverter before it reaches the motor. In this proposed system, the LC filter is connected between the drive circuit and the motor terminals. This LC filter acts as a low-pass filter, allowing low-frequency power voltage components to pass through easily while impeding the high-frequency voltage components. As a result, the LC filter aids in minimizing the presence of harmonics in the motor's supply voltage which by its means lead to reduction in the ripples of the torque output. The LC filter's series inductance helps to reduce torque ripples. It resists rapid current changes caused by electronic commutation, thus reducing torque output fluctuations [2,3].

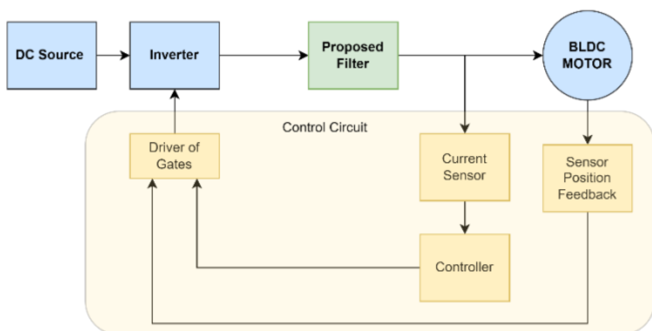

Figure 1: BLDC Topology

The BLDC includes the power supply, a three-phase voltage source inverter, the three phase BLDC motor, and the proposed filter. The filter circuit serves as an interface between the drive and the motor. Its function is to mitigate the high-frequency component of the voltage during the switching of the inverter. The LC filter functions as a low-pass filter, forming a high impedance value to high-frequency components and a low impedance value to low-frequency components. This configuration helps harmonics mitigation in the motor's supply voltage. Furthermore, the series inductance in the LC filter helps to reduce torque ripples by opposing rapid changes in current caused by electronic commutation.

The current value sensing and the position sensing are considered the main parts of the sensing system. The Position Sensor System utilizes three Hall Effect cells positioned inside the motor to determine the rotor position. On the other hand, the Current Sensor System employs current sensors placed in any random two phases out of the three-phase BLDC motor. Due to the absence of a neutral wire, the third phase current can be derived from the first and second phase. The current sensing is primarily required to measure the value of the current, whereas the phase angle and sequence information are provided by the position sensor [14], [15].

Figure 1 depicts the BLDC motor's controller using the filter. The rectification of the phase currents produces a DC signal, where diodes are utilized to rectify the signal. This choice of diodes helps mitigate nonlinearity issues arising from the voltage drop characteristic of typical diodes used in rectifiers.

Because of its primary benefit of providing zero steady-state error, a PI controller is used in the architecture of the current controller. The position of the rotor shaft is sensed using a Hall Effect sensor, slotted optical disc, or another type of transducer, which generates signals as shown in the diagram. Combinational logic is used to decode these signals and generate firing signals for 120° conduction on each of the three motor phases [16]. The upper and lower phase lag transistors are controlled by the commutation logic or rotor position decoder's six outputs.

The commutation of the switches firing the appropriate stator coil to provide a specific torque generation depending on the rotor position. In a BLDC motor, the controller responsible for determining the firing angle must know the position of the rotor and commutate at the appropriate time.

The basic block diagram of the current controller is shown in Fig. 2. When the reference current (Iref) is compared to the DC current (Idc), an error signal (Ierr) is produced. This error signal is then fed into a PI controller, whose output is compared with a triangular carrier signal to generate the PWM signal.

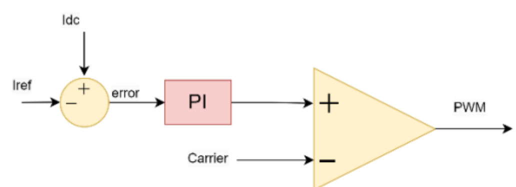

Figure 2: BLDC motor control

Current control of the BLDC motor can be accomplished by using a constant DC signal [17]. A hysteresis-type regulator is used to keep the current in each phase of the brushless DC motor within adjustable limits. This method is known as "current mode" control, and the switching can be controlled by a variety of algorithms. In this case, sensors are required in each phase, and their bandwidth must be greater than the sensing resistor's [18].

A tach generator (TG) is utilized to generate a feedback signal of the motor speed, which can be determined from the shaft position sensor via a frequency-to-voltage converter. This feedback signal is essential in controlling the BLDC motor. A resolver or optical encoder is usually utilized as the shaft position sensor in system that required high performance, along with dedicated decoding algorithm. This level of control, which varies with speed and load, is used to improve performance in areas such as dynamic response, speed range, and efficiency.

3. Filter Design

The parameter value of the filter LC components has a significant impact on the drive system performance. The LC filter improves the voltage quality supplied to the motor by utilizing the charging/discharging characteristics of the capacitor. This filter combines the advantages of the L and C filters.

The same values of L and C in the LC filter result in lower ripple factor than the L or C filter alone. The LC filter effectively reduces the high frequency switching voltage ripple component, resulting in a more stable and smooth supply voltage to the motor. This aids in the reduction of harmonics and the overall performance of the drive system.

L-C filters are commonly used to reduce ripple in output voltage. An L-C filter equivalent circuit is shown in Fig 3. It is critical to ensure that the inductor's current rating matches the motor's current rating when designing an L-C filter.

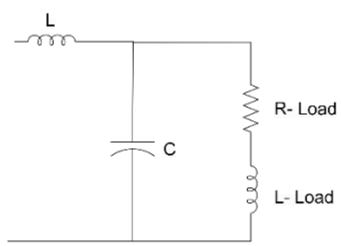

Figure 3: LC filter per phase

The value of the filter capacitor (C) can be calculated using a variety of methods depending on the system's specific requirements. One common method is to determine the desired cutoff frequency (fc) of the filter.

$$C = \frac{10}{2\omega\sqrt{R^2 + (2\omega L_L)^2}} \tag{1}$$

where;
R is the resistance of the load
L_L is the inductance of the load.
The Inductor L of the filter can be determined by

$$VRF = \frac{\sqrt{2}}{3}\left[\frac{1}{(2\omega)^2 LC - 1}\right] \tag{2}$$

The capacitor selection depends on the load change which its curves are represented in Fig. 4. Whereas Fig. 5 determines the VRF per unit as LC parameters change in per unit.

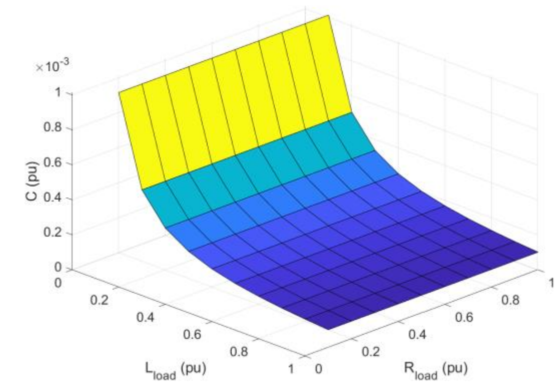

Figure 4: Capacitor Curves as per load change

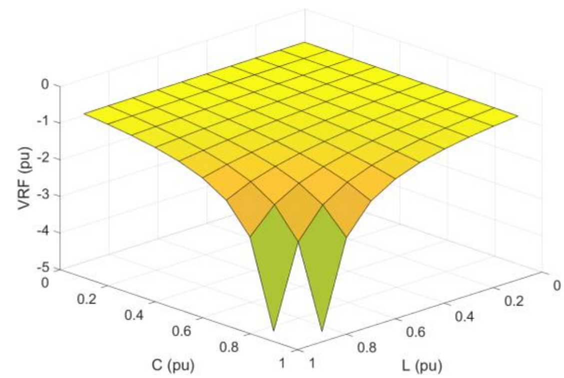

Figure 5: VRF as per LC values

The voltage ripple factor (VRF) measures the amount of voltage fluctuation in the output. In this case, a VRF value of 0.01 is chosen to conform to the IEEE standard, which specifies a maximum allowable range for ripples of up to 10%. The inductor (L) is calculated using the previously determined value of the capacitor (C).

4. Simulation Results

To execute a comprehensive comparison of the proposed circuit, the PSIM software is utilized simulate the BLDC circuit. The simulation involves two topologies, one represent the conventional topology with no filter used, and the other consider the filter in its topology. These topologies are visually represented in Figure 6 and Figure 7, respectively. By employing the PSIM software, a detailed analysis and comparison of these two configurations are conducted, allowing for a thorough evaluation of their performance and effectiveness in minimizing torque and speed.

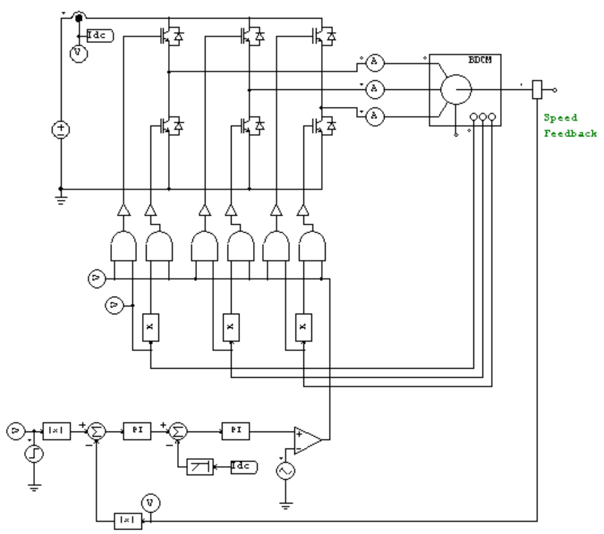

Figure 6: BLDC Simulation without Filter

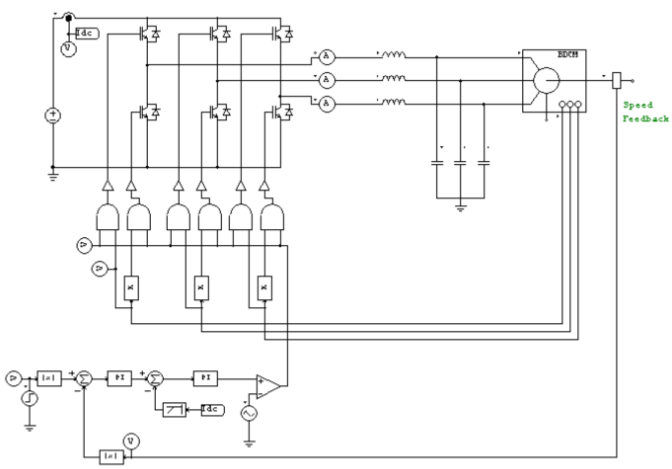

Figure 7: BLDC Simulation with Filter

Table 1 represents the parameters of the BLDC used in the simulation, for the filter L and C values, these were calculated from equations 1, the approximate values are L= 2mH , C=500 µF.

Table 1: BLDC Parameters

Parameter	Value
Torque	0.9 (N.m)
R (stator resistance)	1.2 Ω
L (stator self-inductance)	2.07 mH
Motor inertia	7×10^{-5}
Rated Speed	6500 rpm
No. of Phases	3
No. of Poles	4

The simulation results for the circuits without filters are illustrated in Fig. 8 and Fig. 9. Figure 8 shows the torque waveform, while Fig. 9 represents the speed waveform. The graphs indicate that the torque ripple is unacceptable, particularly at the points where it reaches zero torque. Despite the average torque being close to the desired value, the significant ripple, accounting for approximately 90% of the waveform, needs to be addressed. Regarding the speed waveform, although the ripples are relatively low, there is still room for further improvement.

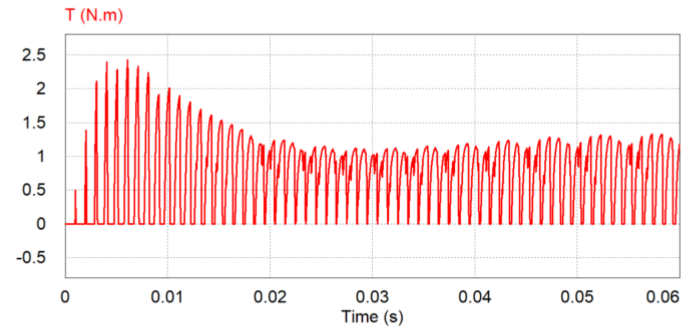

Figure 8: No Filter BLDC Torque waveform

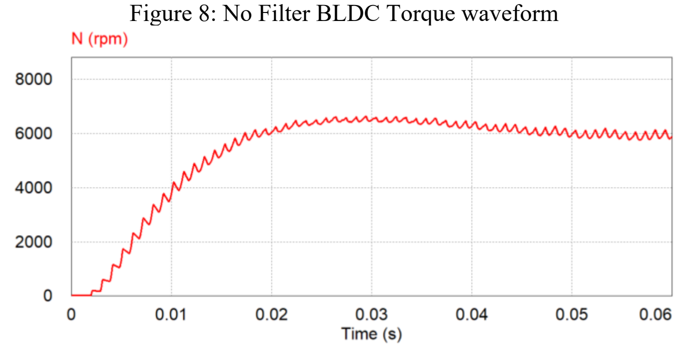

Figure 9: No Filter BLDC Speed waveform

Upon integrating the filter into the circuit, significant improvements were observed. The torque ripples reduced to less than 10%, as depicted in Fig. 10. This substantial reduction demonstrates the effectiveness of the filter in mitigating torque fluctuations. Furthermore, the speed waveform exhibited a ripple factor of less than 1%, which can be considered as virtually no ripples as represetend in Fig. 11. These findings highlight the successful impact of the filter in minimizing both torque and speed waveform ripples, leading to enhanced stability and smoother operation of the system.

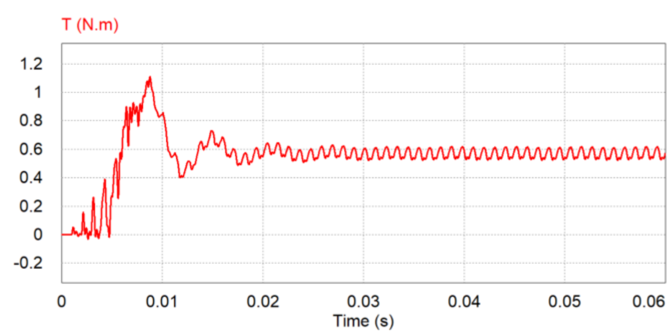

Figure 10: Filter BLDC Torque Waveform

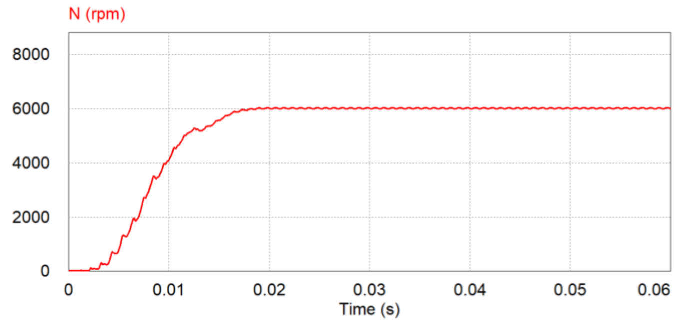

Figure 11: Filter BLDC Speed Waveform

Furthermore, to conduct a more thorough analysis of the simulation, additional parameters such as the back emf, armature current, and firing signal were examined for the case without the filter. These detailed waveforms are presented in Figures 12, 13, and 14 respectively. It is evident from these figures that the observed waveforms deviate significantly from the expected theoretical waveforms. This discrepancy provides an explanation for the failure of the no-filter technique and, consequently, the presence of ripples in the output torque.

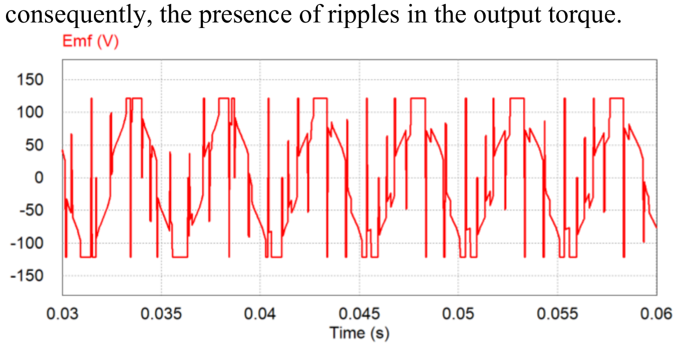

Figure 12: No-Filter BLDC Back-emf waveform

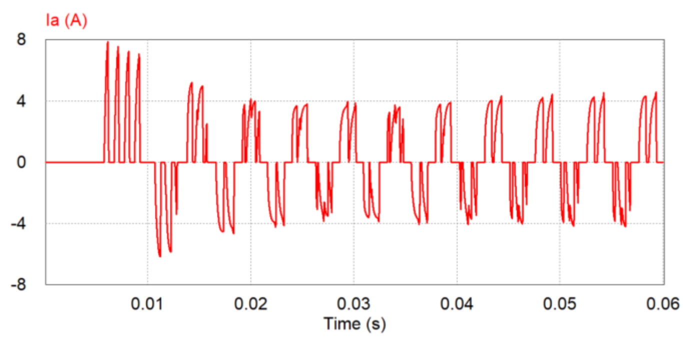

Figure 13: No-Filter BLDC armature current waveform

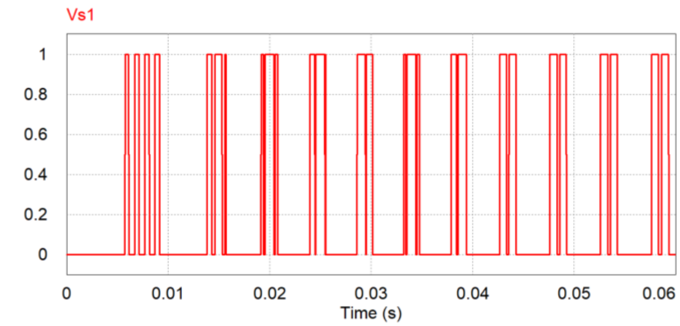

Figure 14: No-Filter BLDC Leg 1 switch firing signal

However, with the installation of the filter, a notable difference is observed. Figures 15, 16, and 17 depict the back electromotive force (emf), armature current, and firing signal, respectively. These figures demonstrate a striking similarity between the waveforms and the corresponding theoretical curves. This alignment emphasizes the effectiveness of the control method employed, as it effectively minimizes the ripple torque in the output. The validation provided by these waveforms further strengthens the credibility and efficiency of the implemented control approach.

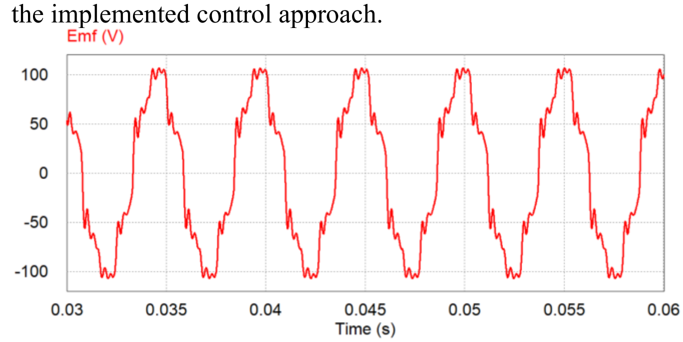

Figure 15: Filter BLDC Back-emf waveform

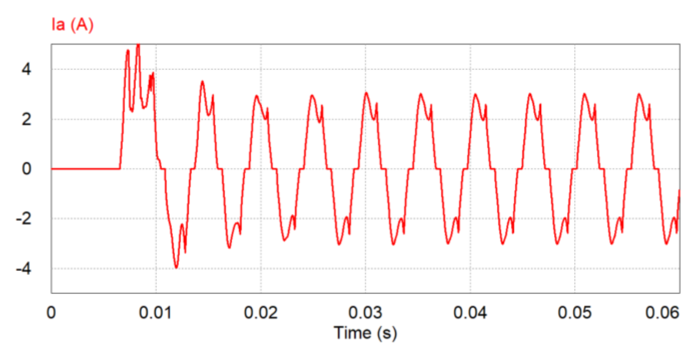

Figure 16: Filter BLDC armature current waveform

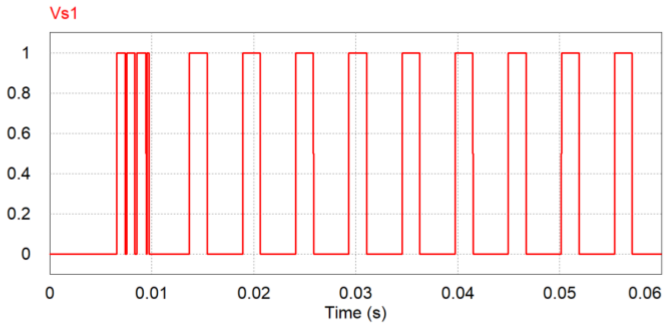

Figure 17: Filter BLDC Leg 1 switch firing signal

5. Conclusion

This paper has proposed a simplified control scheme for BLDC motors. By employing a filter in BLDC topology, the torque ripples are effectively reduced. This approach offers several advantages over conventional control methods. The main advantages of the proposed topology over other control strategies used for the same purpose is its simplicity, low cost, balanced phase currents, and reduced ripple content in voltage and current waveforms. A comparison between cases with and without filters demonstrates that the use of filters leads to a reduction in torque and speed ripples. The simulated proposed circuit successfully achieves the desired torque performance according to IEEE standards. It incorporates a simple filter, PI controller, and PWM, eliminating the need for a complex computational processor in the circuit implementation. Consequently, the main advantage of this control over other advanced controls is that this approach facilitates easy execution and minimizes running costs by reducing the energy footprint of the control circuit with minimum cost of control.

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