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Acoustic Noise Reduction of BLDC Motor Drive using One-Cycle Current Control Strategy

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Abstract. Torque ripple and resulted acoustic noise and vibration are the main disadvantages of brushless DC (BLDC) motor drives. In this study, One-Cycle Control (OCC) is developed for current regulation of brushless DC (BLDC) motor drive as a unified constant-frequency integration control strategy. Employing one-cycle control strategy reduces high frequency torque ripple of conventional hysteresis current controllers leading to lower acoustic noise and vibration in the drive. To enhance reliability and reducing drive cost, an improved rotor position estimation technique is implemented. OCC strategy and sensorless method are realized using a low-cost general-purpose AVR microcontroller (Atmega8). It is shown that torque ripple, acoustic noise and vibration are reduced via OCC method comparing to conventional hysteresis control strategy. Computer simulations and experimental results with a 375W, 16 poles BLDC motor, demonstrate improved behavior of developed sensorless BLDC drive operation.

Introduction

Due to advantages of brushless DC (BLDC) motors including high efficiency, high power density, ease of control and lower cost maintenance, BLDC motors have been widely used in motion control applications [1]. In commercial high performance AC motor drives such as IMs and PMSMs, the field oriented control [2] and direct torque control techniques [3] are employed that are complex and require lots of computations. But the BLDC motors are usually controlled via dc-link current regulation method like to DC motors.

This research improves the performance of conventional current controllers in BLDC motor drives by employing one-cycle control (OCC) strategy. One-cycle control strategy is a large-signal nonlinear control scheme with significant advantages of fast dynamic response, excellent power source anti-interference, and automatic switching error elimination [4]. OCC based current control comparing to other control methods, has the following main features: (1) fast dynamic response due to embedded inner current loop in the PWM modulator, (2) simple circuit, and (3) synchronized turn-on time that is suitable for soft switching. It has been widely used in dc-dc conversion [5], power amplifier [6], etc. Lately, it has been used in electrical drives of induction motors [7]. OCC is a simple control technique that has advantages of both PI and hysteresis controllers where in this study it has been implemented in BLDC motor drive.

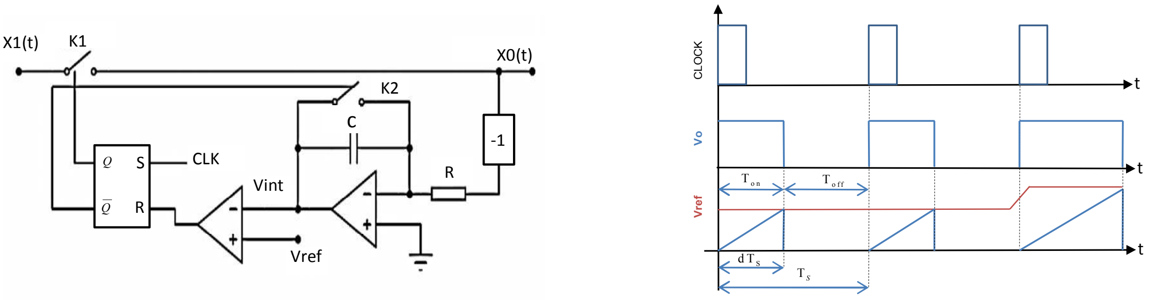
This paper develops a sensorless BLDC motor drive based on the one-cycle control (OCC) strategy for regulation of the dc-link current. After introducing the basic concept of OCC strategy, suggested improved sensorless drive based on OCC strategy is described and simulated. Finally, a hardware prototype of the proposed drive is implemented to validate the performance of the proposed BLDC motor drive.

One –Cycle Control Strategy

One-cycle control (OCC) strategy was developed as a general pulse width modulator control method [4]. OCC is also known as the integration-reset technique where the key element is the resettable integrator. The OCC is composed of controller, comparator, multi-bit integrator and clock, as shown in Fig. 1(a), where *K1* and *K2* are the complementary switches in pair. *K1* is controlled by the function *K(t)*:

$$K(t)=\begin{cases}1, & 0<t<t_{on}\\ 0, & t_{on}<t<T_s\end{cases} \tag{1}$$

Where T_S is the clock period or the inverse of switching frequency $f_s=1/\,T_s$.



(a) (b)

Fig. 1. (a) Schematic of one-cycle control method, (b) One-cycle control pulses

In each cycle the switch is ON for time duration t_{on} and is OFF for t_{off} as shown in Fig. 1(b).The duty ratio $d=t_{on}/T_S$ is modulated by an analog control reference V_{ref}. In beginning of each switching cycle, clock pulse signal is sent out that *K1* goes to ON; *K2* to OFF; and the integrator begins to work. While the integration of V_{int} as:

$$V_{\text{int}}=\frac{1}{RC}\int_0^{t_{on}}x(t).dt=V_{ref} \tag{2}$$

Reaches to V_{ref} the comparator output makes *K1* to OFF; *K2* to ON; and resets the integrators immediately. Since the switching frequency is constant, in the switching cycle, $x(t)$ is equal to average of $x_o(t)$:

$$x(t)=\frac{1}{T_s}\int_0^{t_{on}}xo(t).dt=K\,V_{ref}(t) \tag{3}$$

where K is equal to RC/T$_S$. The input signal $x_0(t)$ at the input node of the switch is chopped and transferred to the output node of the switch to form variable $x_1(t)$. The frequency and the pulse width of switching variable $x_1(t)$ is equal to the switching function $k(t)$, and the envelope of $x_1(t)$ is equal to input signal $x_0(t)$. Therefore, the average value of to output voltage is exactly equal to the reference signal in each cycle. In this paper, the proposed OCC controller is employed for regulation of dc-link current. Actually, all voltage variables in Fig. 1 including V_{ref}, V_{in} are substituted with corresponding current in BLDC motor drive that are described in details in the next section.

Sensorless Control of BLDC Motor Drive

The schematic diagram BLDC motor drive using one-cycle control (OCC) strategy is shown in Fig. 2. It consists of control unit (Digital OCC controller and gate signal generator), IGBTs, back-EMF zero crossing point detection circuit and dc-link.

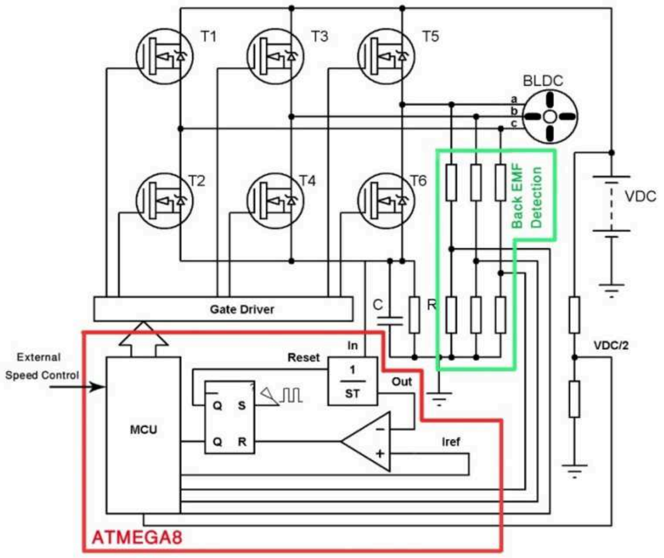


Fig. 2. Schematic diagram of proposed sensorless BLDC motor drive using OCC strategy

The phase current of the BLDC motor is controlled to follow the developed current reference from speed controller (I_{ref}) via digital OCC current controller. The dc-link current is passed through resistance R; converted to voltage; filtered by small capacitor C; and then it is digitalized in A/D converter unit of AVR microcontroller. Integrator block (1/ST) is implemented by taking the average of numerical value from A/D converter and then it is compared with the reference current. A timer in microcontroller is used to generate the constant frequency pulses. This pulse signal sets the SR Flip-Flap and the comparator's output signal resets SR Flip-Flap (this Flip-Flap has been implemented by a programming routine). Flip-Flap's output signal consists of fixed frequency signal with variable duty cycle according to both reference and feedback currents. The measured back-EMF signals are used to identify commutation instants in microcontroller unit (MCU) and MCU generates fixed frequency gate driver's pulses. The voltage of $V_{DC}/2$ is needed for detection of zero crossing points [8], which makes reference voltage for comparators in MCU.

Experimental Results

The hardware prototype of the proposed drive is shown in Fig. 3. The system is controlled entirely via Atmega8 microcontroller [9]. Control commands are amplified via IR2104 gate drivers. The phase current is measured via R_{sens} (0.22Ω-5W) that is in series with dc-link. Power MOSFETS IRF640are chosen for inverters switches, with main parameters as V_{DSS}=200V, I_D=16A, $R_{DS(on)}$<180mΩ. Resistor dividers are used for voltage measuring needed in position sensorless method. The generated pulses in microcontroller for OCC strategy are set at 15.6 kHz. The motor is started using open-loop startup algorithm as mentioned earlier. Forced alignment step interval takes about 100 msec.

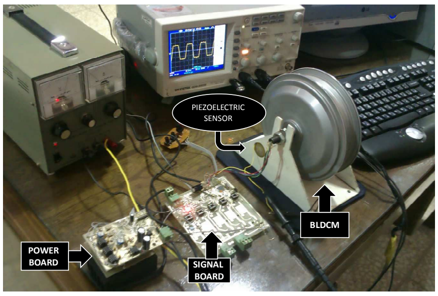
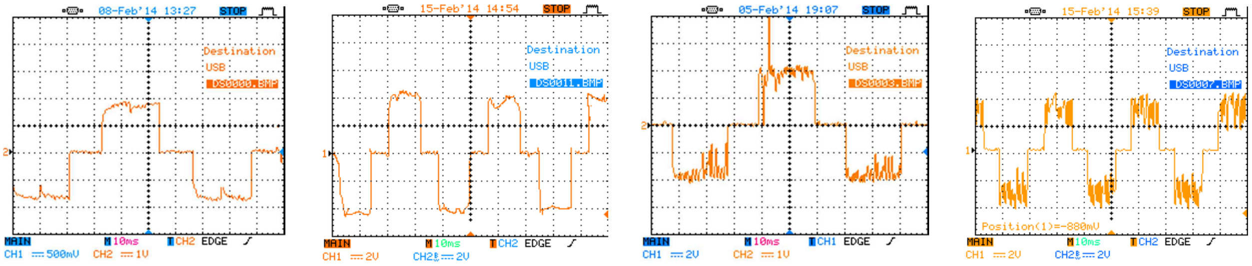


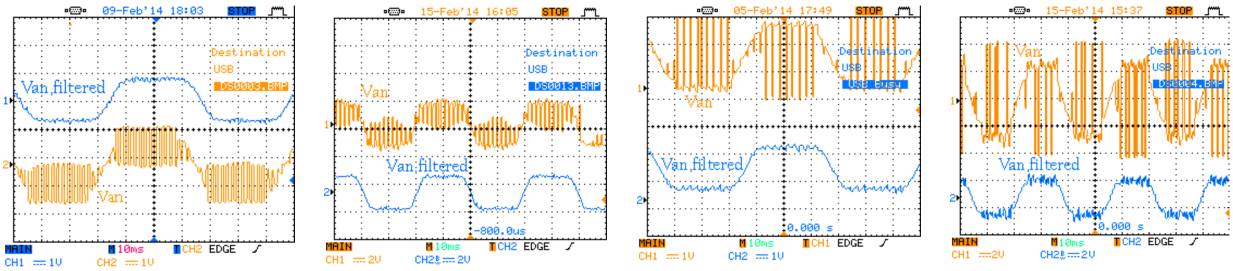
Fig. 3. Experimental setup of the sensorless-controlled BLDC motor drive system

The current and voltage waveforms under 25% and 40% of rated load at 115 rpm and 200 rpm with OCC and hysteresis strategies are shown in Fig. 4 respectively. It indicates that the current ripple in OCC strategy is smaller than hysteresis method. Fig. 5 shows the measured terminal voltage at 110 rpm and 200 rpm using OCC and hysteresis strategies.



(a) (b) (c) (d)

Fig. 4. Current waveform (a) under 25% rated load at 115 rpm (OCC), (b) under 40% rated load at 200 rpm (OCC), (c) under 25% rated load at 115 rpm (Hysteresis), (d) under 40% rated load at 200 rpm (Hysteresis)



(a) (b) (c) (d)

Fig. 5. The instantaneous and filtered terminal voltages, (a) 110 rpm at 25% rated load (OCC), (b) 200rpm at 40% rated load (OCC), (c) 110 rpm at 25% rated load (Hysteresis), 200rpm at 40% rated load (Hysteresis)- (scope probe scale: × 10)

A vibration sensor (piezoelectric) is used for acoustic noise measurement to validate the effect of OCC strategy. As the acoustic wave propagates on the base of BLDC motor, any changes to the characteristics of the propagation affect the velocity and/or amplitude of the wave. Fig. 6 shows the acoustic noise and fast-fourier transform (FFT) waveform at 115 rpm for hysteresis control and OCC strategies. The amplitude of the harmonics in hysteresis strategy is higher than OCC strategy.

Conclusion

A low-cost, simple current control strategy based on one-cycle control (OCC) has been proposed in this paper. Traditional hysteresis current control has been substituted via a unified controller and PWM modulator based on one-cycle control strategy. Proposed OCC strategy for current regulation of dc-link, takes the simplicity of conventional current controller as well as the advantage of PI controller with fixed-frequency PWM modulator.

(a) (b)

Fig. 6. FFT signal related to acoustic noise by using (a) OCC, (b) Hysteresis strategies at 115 rpm

Moreover, an improved position sensorless control strategy, based on detection of zero crossing points of back-EMF voltages, has been developed with employed OCC strategy. The developed sensorless, OCC based BLDC motor drive has following advantages:

1. *Cost effective:* Current control in one cycle as well as an improved simple position sensorless needs lower computation time rather than other techniques, so the low-cost microcontrollers can be employed instead of costly digital signal processor.
2. *Low torque ripple and acoustic noise:* This advantage is achieved by constant frequency and lower switching frequency of OCC strategy that is confirmed by piezoelectric sensor.
3. *Fast dynamic:* The dynamic response of developed current controller is similar to hysteresis controller and it is faster than traditional PI controllers because the control is carried out in one cycle.

To reduce the commutation torque ripple of proposed drive, OCC strategy can be used for direct phase current regulation of three phases. Developed drive has low-cost control algorithm and components where it can be used for cost sensitive demands such as home applications.

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