Implementation of a Novel Brushless DC Motor Drive based on One-Cycle Control Strategy

A. Halvaei Niasar*(C.A.) and E. Boloor Kashani*

Abstract: One-Cycle Control (OCC) is developed in this study 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. OCC strategy and sensor-based method are realized using a low-cost general-purpose AVR microcontroller (Atmega8). Computer simulations show improved characteristics of the OCC solution. Furthermore, experimental results with a 260W, 14 poles BLDC motor, demonstrate improved behavior of developed sensor-based BLDC drive operation.

Keywords: BLDC motor, Drive, One-Cycle Control (OCC), AVR Microcontroller.

1 Introduction

Due to advantage 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 automotive, computer, industrial and household 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 BLDC motors are usually controlled via dc-link current regulation method similar to DC motors. BLDC motor drive has lack to develop smooth torque rather than PMSMs [4]. To enhance the performance and reducing the torque ripple, direct phase current control method is employed for current regulation in BLDC motor drive [5]. Both mentioned methods usually use hysteresis current controllers instead of PI controllers. It is simple in implementation, but it has variable switching frequency and leads to high frequency ripple [6]. To improve the performance of current regulation, some fixed-frequency PWM methods have been proposed [7].

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 [8]. 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 [9], power amplifier [10], etc. Lately, it has been used in electrical drives of induction motors [11, 12] and PM synchronous generators [13]. OCC is a simple control technique that has advantages of both PI and hysteresis controllers. This paper develops a BLDC motor drive based on OCC strategy for regulation of dc-link current. After introducing the basic concept of OCC strategy, suggested BLDC motor drive based on OCC strategy is simulated. Moreover, a hardware prototype of proposed drive is implemented to validate the performance of proposed BLDC motor drive.

2 One-Cycle Control Strategy

OCC strategy was developed as a general pulse width modulator control method [13]. 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, where K1 and K2 are the complementary switches in pair. K1 is controlled by the function K(t):

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

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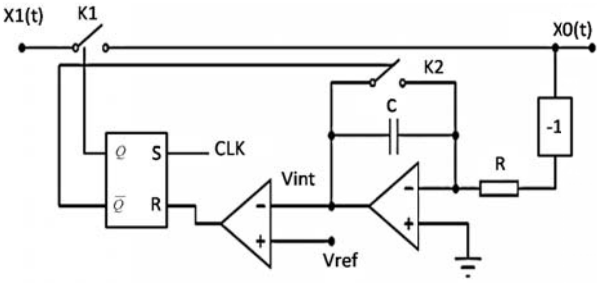


Fig. 1 Schematic of one-cycle control method

where T_S is the clock period, and switching frequency $f_s = 1/T_s$. In each cycle the switch is ON for time duration ton and is OFF for t_{off} as shown in Fig. 2 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. The integration voltage V_{int} as

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

reaches to Vref; 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 xo(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/TS. 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 $x1(t)$. 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 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 currents in BLDC motor drive.

The schematic diagram BLDC motor drive using OCC method has been shown in Fig. 3 OCC technique

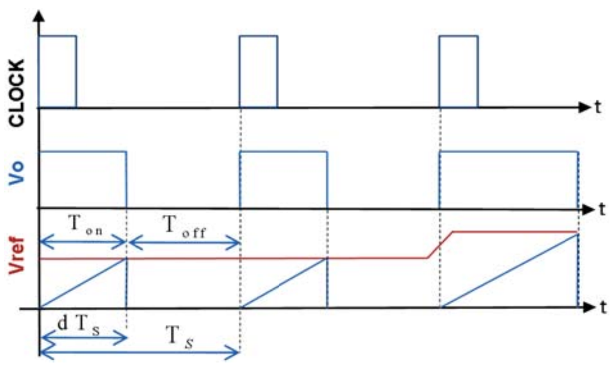
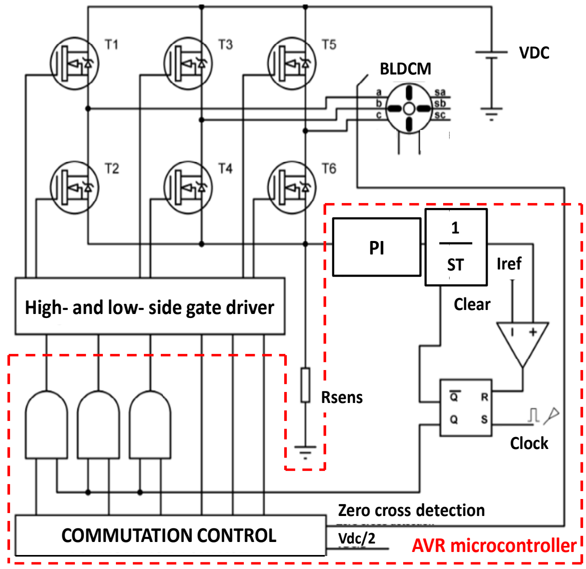


Fig. 2 Control pulses of one-cycle control method.



can be implemented with analog circuits and also via low-cost microcontrollers easily. In this study it is implemented via a low-cost AVR microcontroller.

3 Simulation Results

In this section, some simulation are provided to evaluate the proposed OCC method and compared with hysteresis current control method. Employed BLDC motor is an e-bike BLDC motor with summarized parameters in Table 1.

Fig. 4 shows the overall block diagram of the OCC controlled six-switch inverter BLDC motor drive in Simulink. Speed control block provides the current reference and in OCC current control block, the dc link current is regulated via OCC controller. Developed torque of both hysteresis and OCC current controllers under 75 % rated load are compared in Fig. 5. The torque ripple resulted from OCC strategy is quiet smaller rather than hysteresis method. The switching frequency of OCC strategy is sent to 15.6 kHz that is equal to the maximum switching frequency of hysteresis controller.

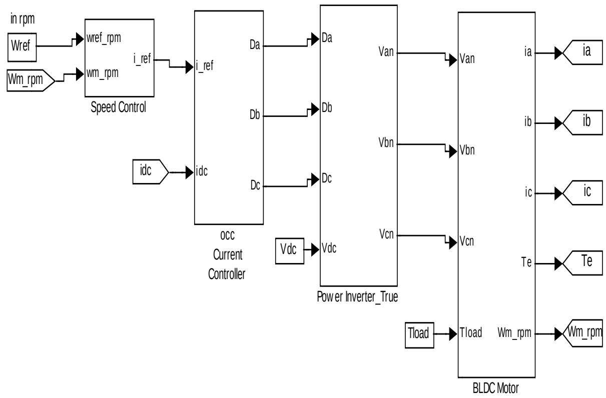


Fig. 4 Simulation block diagram of the OCC-controlled, BLDC motor drive.

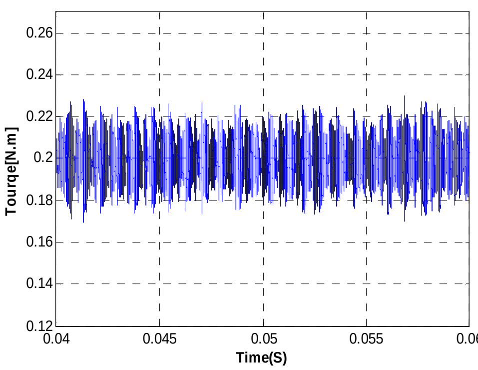
Table 1 Brushless DC motor parameter.

Parameter	Value	Parameter	Value
Pn	230 [W]	Zp	14
Tn	0.27 [N.m]	ωn	7750[rpm]
R	0.175 [Ω]	J	0.32e-6 [kg.m2]
Ls	0.501e-3[mH]	M	0.49e-3 [mH]
Kt	0.018 [N.m/A]	Ke	0.6e-3 [V/rpm]

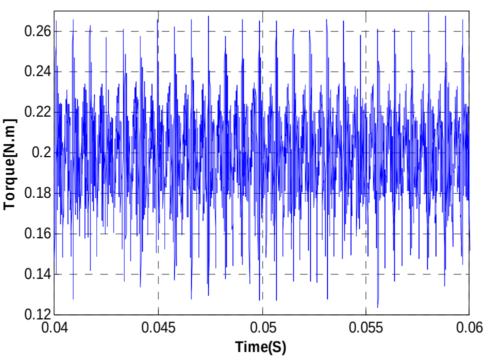
Fig. 6 and 7 show the phase voltage, phase current and hall sensor waveforms at 175 rpm. The voltage and current spikes during commutations in OCC strategy is smaller than hysteresis method.

4 Experimental Results

The hardware prototype of the proposed drive is shown in Fig. 8. Whole of the system is controlled via Atmega8 microcontroller [14]. Control commands are amplified via IR2104 (internally set dead time) gate drivers. The phase current is measured via R_{sens} (0.22 Ω-5 W) that is in series with dc-link. Power MOSFETS IRF640 are chosen for inverters switches, with main parameters as V_{DSS} = 200 V, I_D = 16 A, $R_{DS}(on)$ < 180 mΩ. Resistor dividers are used for voltage measuring needed in position sensor-based method. The generated pulses in microcontroller for OCC strategy are set at 15.6 kHz.

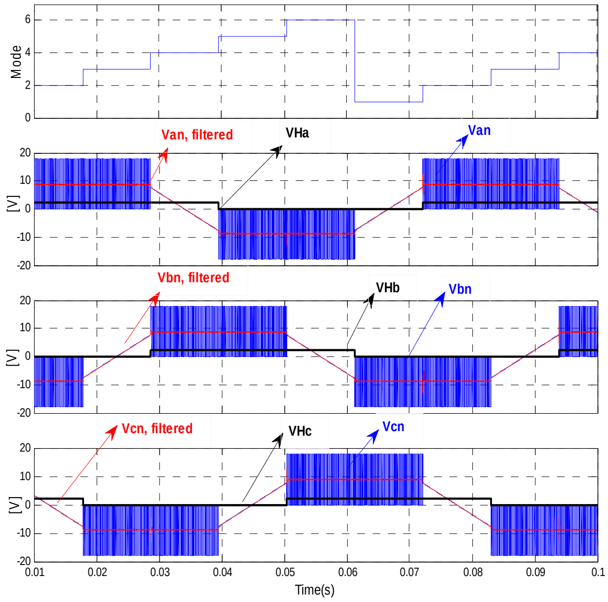


(a) OCC strategy

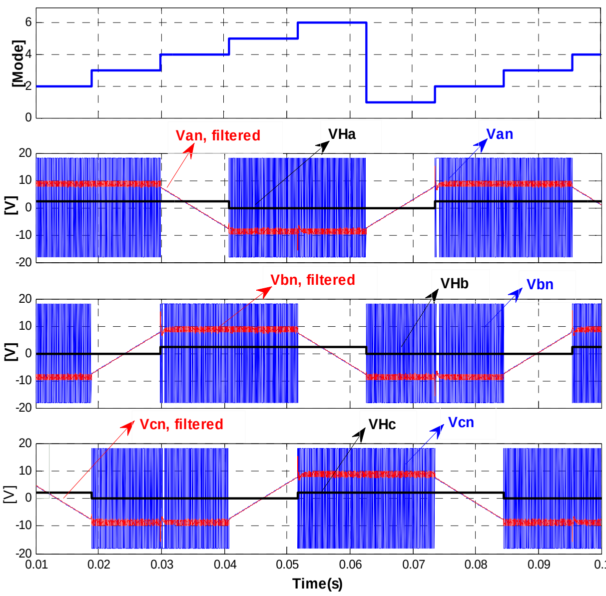


(b) Hysteresis strategy

Fig. 5 Developed electromagnetic torque waveforms.



(a) OCC strategy

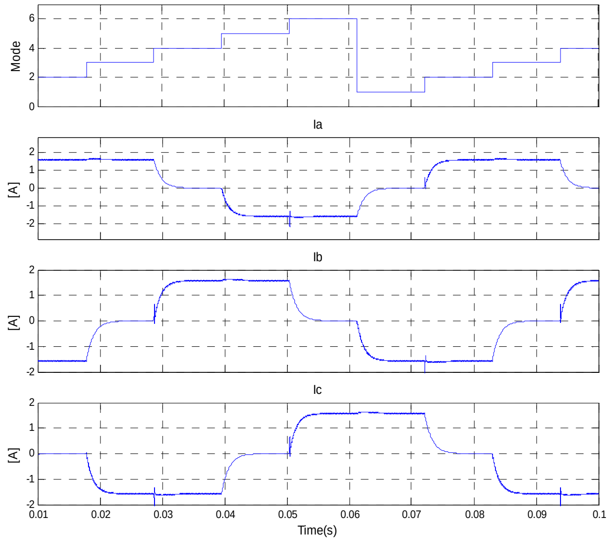


(b) Hysteresis strategy

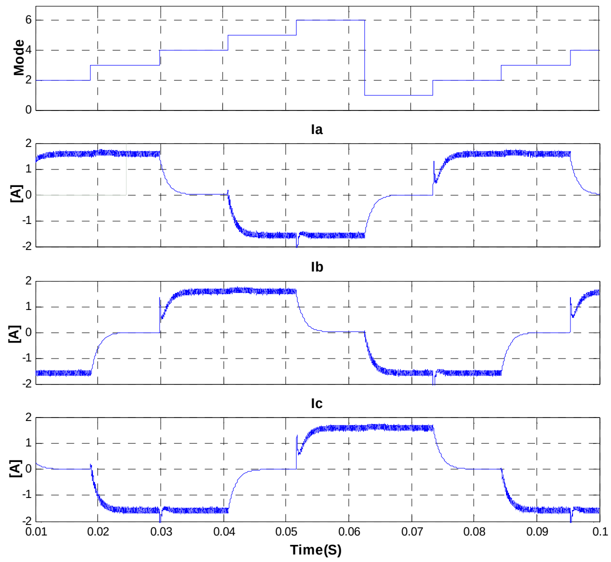
Fig. 6 Waveforms of terminal voltages, and their filtered signals and Hall sensor signals at speed of 115 rpm.

Fig. 9(a) shows the current waveform under %20 full load condition at 2500 rpm with applied OCC method. Fig. 9(b) shows the current waveforms under %20 full load condition with hysteresis control strategy respectively. It indicates that the current ripple in OCC strategy is smaller than hysteresis method.

Fig. 10 shows the measured terminal voltage and Hall sensors waveform at the speed 2500 rpm. Voltage spike is created by the residual current when the stator current is blocked by the power switches. The effect of voltage spike can be reduced using proper low pass filters. Sa, Sb and Sc are position signals that are generated by Hall sensors.



(a) OCC strategy

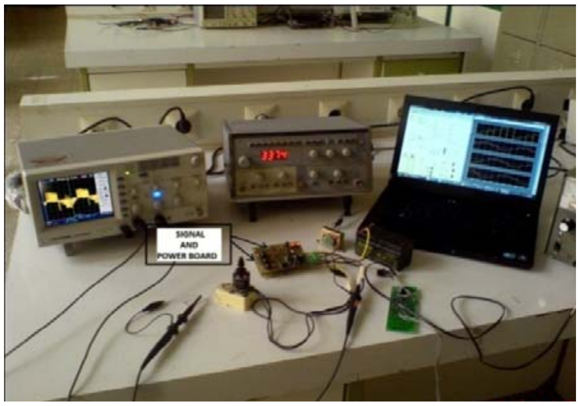


(b) Hysteresis control strategy

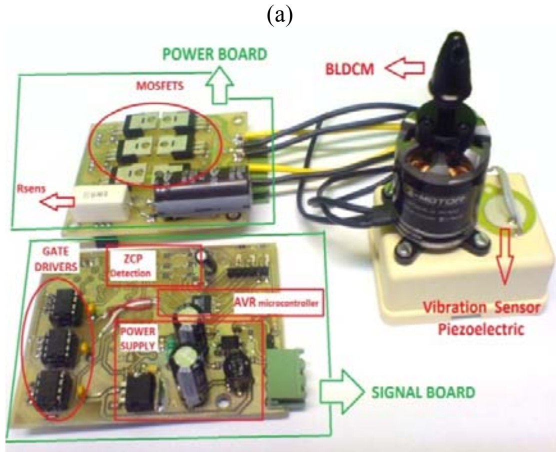
Fig. 7 Waveforms of phase current, and their filtered signals and Hall sensor signals at speed of 115 rpm.

Fig. 11 shows the instantaneous terminal voltage with respect to the ground point during commutation-cycle. Fig. 12 shows applied pulses to switches. It confirms the constant frequency that is achieved by OCC strategy (T1 = T2).

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. 13 shows the acoustic noise and Fast-Fourier Transform (FFT) waveform at 2500 rpm for hysteresis control and OCC strategies. The amplitude of harmonics in hysteresis control strategy is higher than OCC strategy.



(a)



(b)

Fig. 8 Experimental setup of BLDC motor drive system.

5 Conclusion

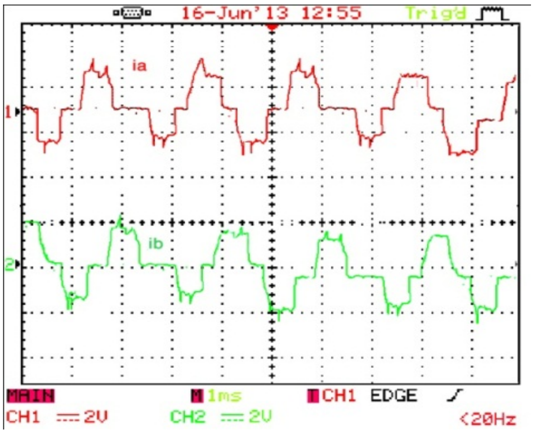
A low-cost, simple current control strategy based on OCC has been proposed in this paper. Traditional hysteresis current control has been substituted via a unified controller and PWM modulator based on one-cycle control strategy. Proposed OCC strategy for current regulation of dc-link, takes the simplicity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

- Cost effective: Current control in one cycle as well as an improved simple position sensor-based needs lower computation time rather than other techniques, so the low-cost microcontrollers can be employed instead of costly digital signal processor.

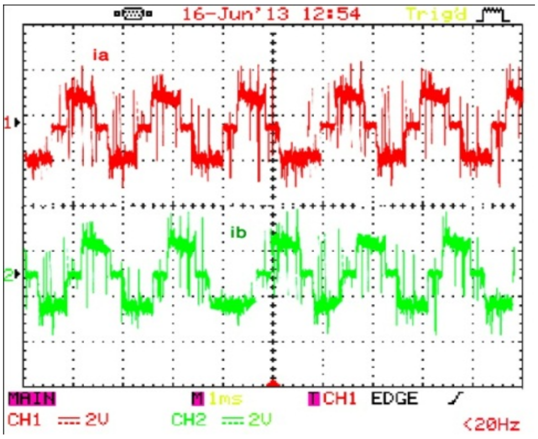
- Fast response: The dynamic response of developed current controller is similar to hysteresis controller and it is faster than traditional PI controllers because the control is carried out in one cycle.

- 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.

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 applications such as home applications.



(a) OCC strategy



(b) Hysteresis control strategy

Fig. 9 Current waveform under 20% full load.

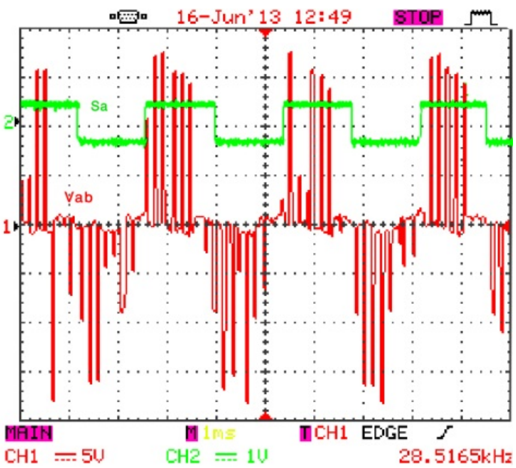


Fig. 10 The instantaneous voltage and Hall sensor waveform at 2500 rpm.

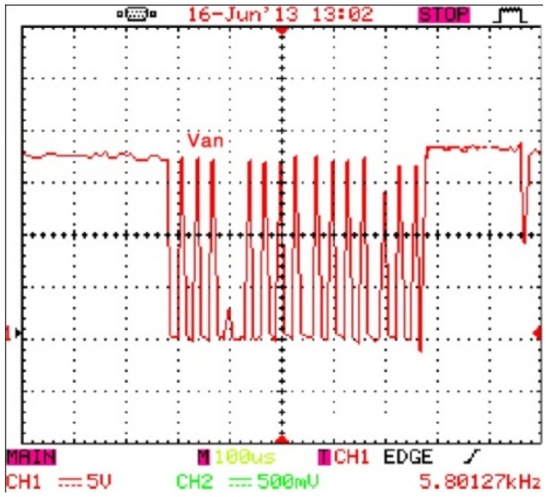


Fig. 11 The instantaneous phase voltage at 2500 rpm.

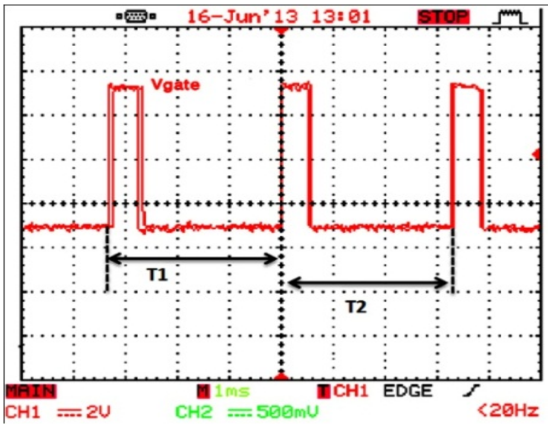


Fig. 12 Gate pulse.

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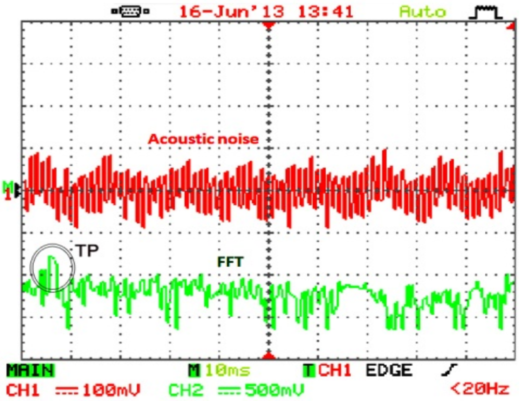

(a) OCC strategy

(b) Hysteresis control strategy

Fig. 13 Acoustic noise and FFT signal at 2500 rpm.

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