Sensorless Control of Permanent Magnet Spindle Motors Used in Hard Disk Drives

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Abstract—**Spindle motors and their control are a very important part of hard disk drives (HDDs). As HDDs tend to be high spin-speed and small form factor, the sensorless control of spindle motors is facing new challenges. This paper explores a new rotor position detecting method for the sensorless PWM control of brushless DC (BLDC) motors, which was originally developed to filter the noises caused by phase commutations. Collaborating with the special PWM chopping sequence of switching devices of the inverter, the proposed method employs the digital filtering procedure to detect the true zero-crossing points of phase back EMFs in PWM BLDC mode as rotor position signals. This paper focuses on how to filter out the noises around the back EMF zero crossing caused by PWM chopping. Also the trends and potential developments of the spindle motor sensorless control are discussed at the end of this paper.**

I. Introduction

Since the first hard disk drive (HDD) was made in 1956, it has grown to be the most effective mass data storage device for computers. Now it begins to be widely applied in consumer appliance, such as, video recorders, game consoles and digital music jukeboxes. Only in 2004, the market volume of the HDDs is about 250 million pieces. It is expected that more and more HDDs will be manufactured and applied in near future.

In each drive, there always is a spindle motor to turn one or multi-platters with the storage media, where the data are stored. Therefore, the spindle motor is one of the most important components of an HDD and its performances have a direct impact on HDD performances in many aspects, especially the data access speed and capacity. Firstly, the motor must provide stable, reliable and consistent rotating for several hundred thousands of hours in order to allow the HDD to function properly and tolerate more than ten thousands of start and stop cycles without failing for each powering on. Secondly, it must be run smoothly and with the minimum vibration, due to the tight tolerances of the platters and heads inside the drive. Thirdly, it should not draw too much power and must not generate excessive amounts of heat. And finally, its speed must be controllable so that it rotates at the proper speed when the data are read and written.

This paper will review the development and evolution of the spindle motor system for HDDs, which includes a spindle motor and a motor control unit. The latest spindle motors and their control methods will be introduced, particularly the sensorless PWM control of spindle motors. Then an effective digital filtering rotor position detecting method for sensorless PWM control of brushless DC (BLDC) motors, i.e., the detection of the zero-crossing points (ZCPs) of the phase back EMFs, will be introduced. It is an improvement of the phase-delay-free ZCP detecting method previously proposed by the authors [1], [2]. After the modifications presented in this paper, the previous method can also be applied in sensorless PWM BLDC control, which is a major control mode in current HDD products. Section III will introduce it in detail. In Section IV, the trends and potential development of the spindle motor control will be discussed.

II. HDD Spindle Motors and Their Control

With the rapid progress of the HDD technology, HDDs have undergone a series of form factor transformations resulting in various smaller size HDDs and at the same time, the capacities and performance doubled almost every 3 years. Today, the capacity of commercial HDDs in 3.5-in has reached 500 Gigabytes (GB), 100000 times of the first drive of 5 Megabytes (MB) in 24-in. During the past 50 years, the evolutions of all parts in HDDs are always proceeding although the HDD principle is almost same and no big change [3]-[5].

At the same time, the spindle motors have also been evolved from induction motors and synchronous motors with the speed around of 3600 rpm directly driven from AC power grid, to BLDC permanent magnetic (PM) motor with position sensors driven by the power electronics controller, currently to sensorless BLDC motors driven by one IC chip. The corresponding spin-speed was increased from 3600 rpm to 4500 rpm, 5400 rpm, 7200 rpm, 10000 rpm and 15000 rpm now. These motor evolutions have played a key role in many ways, such as, HDD capacity, reading/writing speed, power consumption, spin speed, drive size, run-out, etc [3]-[5].

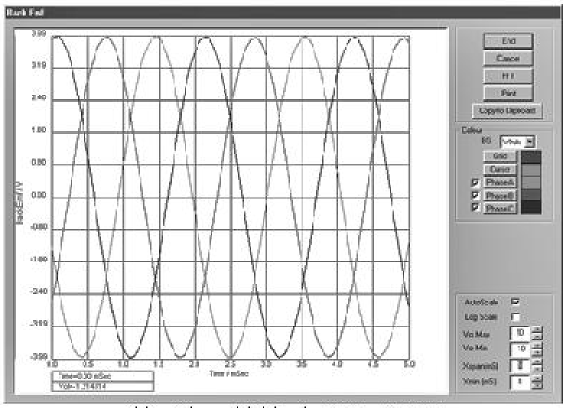
During the evolutions of spindle motors, one major milestone is that HDDs employ self-controlled BLDC spindle motors and power electronics controllers instead of the AC grid powered motors. The biggest difference is that spindle motors in HDDs must be driven by a special design controller with a self-commutation control while the spindle motors in the first generation HDDs could be driven directly by AC power grid without any kind of controllers. Then the spindle motor was an induction motor or a wound synchronous motor and its rated speed was 3600 rpm, which is the maximum possible value and was easy to be affected by the quality of AC power grid. In the middle of the 1980s, the BLDC motors were widely applied to HDDs with the rapid developments of the power electronics technology and PM material. Comparing with other electrical motors, the advantages of using BLDC motor system in HDDs are as following:

(1) High spin speed. With the power electronics controller, the spindle motor can run at high speeds, such as, 4500, 5400, 7200, 10000, 15000 rpm and maybe 30000 rpm in near future.
(2) High efficiency. As the exciting magnetic field in the air gap is produced by permanent magnets, the current used to produce the exciting field is eliminated, and the copper loss is thus reduced.
(3) High reliability. The rotor structure of a PM BLDC motor is simpler than other motors. Therefore, its reliability is better than other motors. Now sensorless drive technology is applied and the reliability becomes even higher.
(4) High ratio of torque to volume. As the high energy Neodymium-Iron-Boron (NdFeB) PM is used, for a given volume, the motor rated torque or power can be designed to be much higher than the traditional motors. This is important to hard disk drives since the space for the spindle motor is very limited. Also, this is great help to improve starting torque and reduce the drive spin-up time and start ready time.
(5) Low cost. The structure of bonded and surface mounted PM BLDC spindle motor is simple and it is easy to be mass-produced. Also the controller can be integrated in one chip. The drive cost can thus be much reduced.
(6) Multi types of power supply voltages, such as, 12V, 5V, 3.3V or lower voltage DC power supplies for different HDDs.

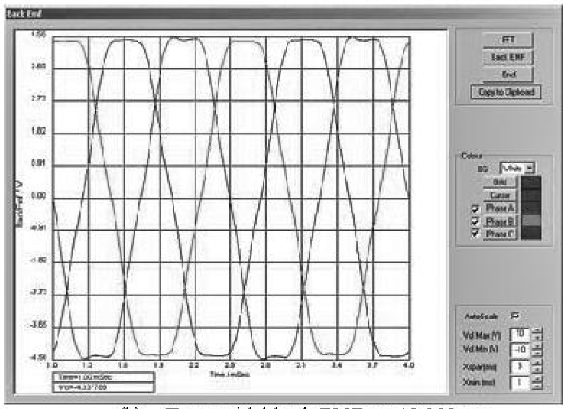
Fig. 1. Typical HDD spindle motors (Courtesy of Nidec Corporation).

Fig.1 displays the typical commercial HDD spindle motors and some of them are integrated with HDD base to further save the space and cost [6]. Now all HDD spindle motors employ the fluid dynamic bearing instead of the previous ball bearings. And most of spindle motors for 1.8-in to 3.5-in HDDs adopt the external rotor structure while small form factor HDD spindle motors employ the internal rotor structure in order to have a large torque constant in a limited space.

Due to the difference designs of each HDD manufacturer, the PM spindle motors can be also classified as two categories of sinusoidal back EMF motors and trapezoidal back EMF motors, as shown in Fig. 2. The former is suitable to both six-step BLDC mode and sinusoidal PWM (SPWM) mode while the latter only to six-step BLDC mode. In general, the trapezoidal back EMF spindle motors have higher power density and bigger torque constant.



(a) Sinusoidal back EMFs at 7,200 rpm



(b) Trapezoidal back EMFs at 10,000 rpm

Fig. 2. Phase back EMF waveforms of typical HDD spindle motors.

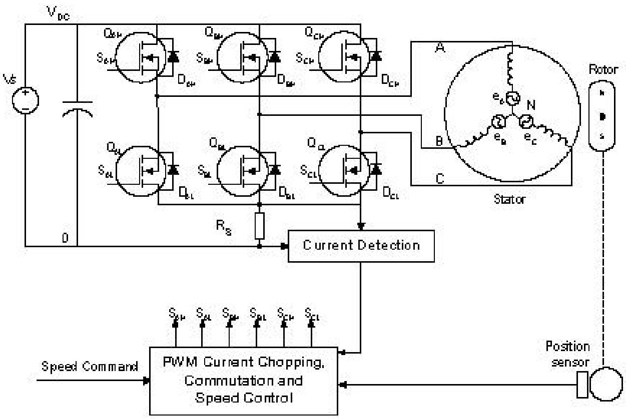


Fig.3. Schematic of a spindle motor system with rotor position sensors.

As mentioned before, the BLDC spindle motor must be driven by a sophisticated control unit. Conventionally, the control unit consists of the inverter, the microcontroller and the rotor position detecting circuit as well as the auxiliary circuits, as shown in Fig. 3. The DC link voltage V_{DC} of the inverter is fixed and usually at 12V, 5V, 3.3V or other lower voltages. At the early stage of the BLDC motor applications, the Hall sensors were employed to provide the rotor position and commutation information to achieve the BLDC control.

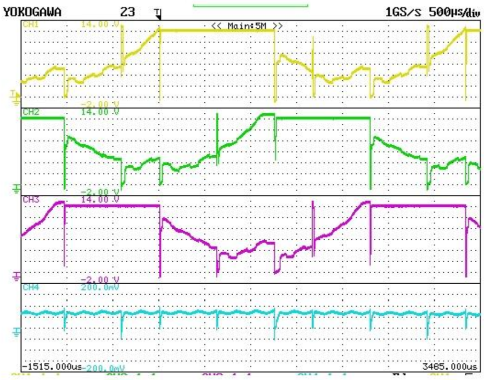


Fig. 4. Waveforms of terminal voltages and DC link current of a typical HDD spindle motor in MOESFET on-resistance control mode.

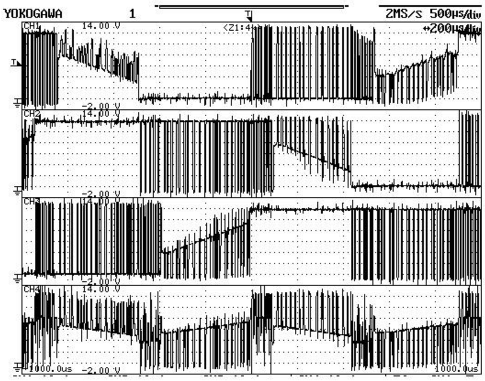


Fig. 5. Waveforms of terminal voltages and neutral voltage of a typical HDD spindle motor in PWM chopping control mode.

Because the HDD operation is very sensitive to the speed variations, the accurate control of the platter spinning speed is critical for data error-free reading and writing. This requires speed variation smaller than 0.1% and even smaller than 0.02% for high performance drives. Before the middle of the 1990s, the speed control strategy of most of HDDs uses the PWM technique at the bias of MOSFETs [5], [7], [8]. Fig. 4 shows the typical waveforms of an HDD spindle motor terminal voltages and the DC link current. It is simple in control but inefficient because the spin-up and speed control are implemented through controlling the voltage drops of one inverter switch MOSFET or transistor. Obviously, this control strategy creates a large voltage drop across the switch at the rated speed due to the voltage overhead for the motor spinning-up and thus causes unnecessary power losses. In Fig. 4, the lower arm MOSFETs work in the linear mode, not operating as perfect switches. In order to reduce the power losses, the PWM chopping BLDC speed control is applied in the current HDDs. This kind strategy definitely is more efficient. Fig. 5 shows the typical spindle motor terminal voltage waveforms of the current commercial HDDs.

As HDD sizes become smaller and smaller, the sensorless control has been widely applied in HDDs in order to reduce the cost and size. Since the 1970s, many methods have been developed to detect the rotor position without the shaft encoders or sensors [1], [5], [9]-[18]. For BLDC motor sensorless control, the zero crossing detection of the phase back EMFs is the most popular method because the ZCPs are dependent only on the rotor position are invariant with speed. Fig. 6 introduces a typical schematic of the sensorless spindle motor system based on the back EMF zero crossing detection. Together with the previous phase-delay free method of the back EMF ZCP detection, a speed variation of 0.01% between the actual speed and the reference speed has been achieved when the DC link-voltage is adjustable [1].

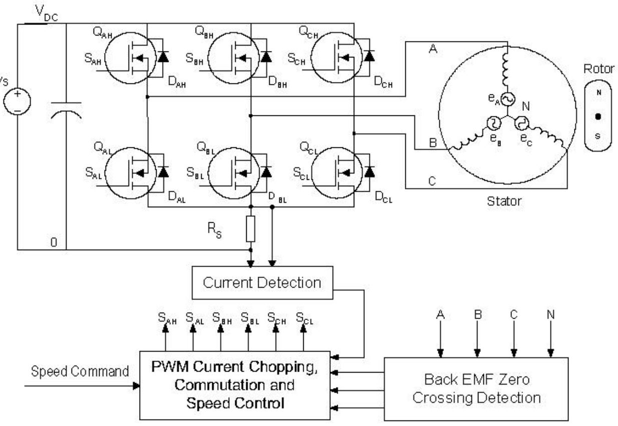


Fig. 6. Schematic of a sensorless spindle motor system.

However, when the PWM chopping control is applied, the terminal voltages and the neutral voltage are superimposed with the PWM voltage pulses. Due to the bandwidth limitation of the detecting circuit, the mutual inductance differences between every two phases and the device parasitic capacitances, there are a lot of noises on the phase voltages or the phase back EMF even though the current of the silent phase is zero, as shown in Fig. 5. One conventional method to filter out these noises is to apply the low-pass filter (LPF) [10]-[13]. But the LFP causes the unwanted phase delay, particularly in high-speed operations. The back EMF integration [14] and the third harmonic voltage integration [15] have been developed to detect the rotor position. However, the back EMF integration still need to detect the ZCPs of phase back EMFs and the third harmonic method can only be applied for the motors with the trapezoidal back EMFs. Also they still have the accuracy problem at low speeds because the DC offsets influence the integrals. ZCP detecting method based on the anti-parallel freewheeling diode conducting state of the unexcited phase was presented in [16]. But it is only suitable to high voltage motor and high-speed range, i.e., the phase back EMF should be big enough. Its implementation is also complicated and costly because it needs quite a lot of isolating power supplies. By properly choosing the PWM and sensing strategy, a directly back EMF ZCP detecting method was introduced in [17]. It is good for high voltage motor when the MOSFET switch conducting voltage drop can be neglected and the anti-parallel freewheeling diode forward voltage can be approximately compensated. But for the low voltage powered HDD spindle motor system, the MOSFET conducting voltage drop and the freewheeling diode forward voltage are relative large, comparing with the motor back EMF crests.

This paper adopts a direct problem-solving route and develops a new ZCP detecting solution through digitally filtering out the noises caused by PWM chopping. This method will not be affected by the motor speeds and MOSFET conducting voltage drop as well as the free-wheeling diode forward voltage drops.

III. A New Back EMF ZCP Detecting Method for PWM BLDC Motor

A. Voltage PWM Control

In order to clearly explain the principle of the proposed method, the voltage PWM control is employed in this paper. It means that the chopping carrier frequency is fixed and the duty ratio is adjustable to control the applied voltage on the spindle motors, thus the speed. The chopping control signal is coupled to the BLDC control signal on each MOSFET as shown in Fig. 7. At any time instant, only one of the two active switches executes the PWM chopping for the voltage regulation while the other switch is held on its "On" state, i.e., the alternate PWM chopping control. This sequence has the beneficial effect of distributing the PWM switching operation evenly among the inverter switches.

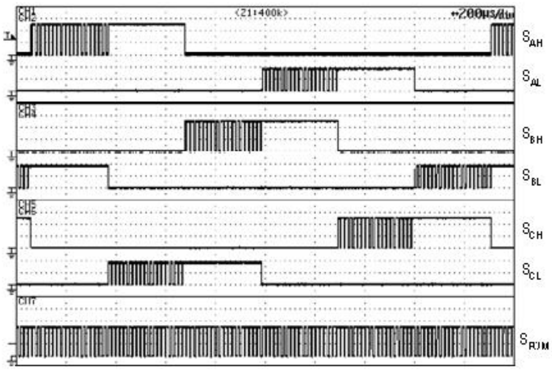
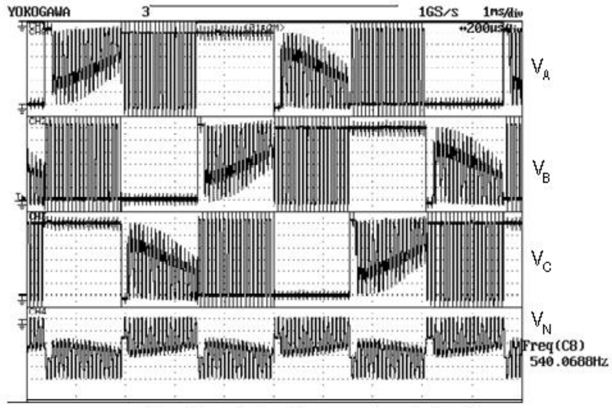


Fig. 7. MOSFET control signals for the inverter switches under alternate chopping control.

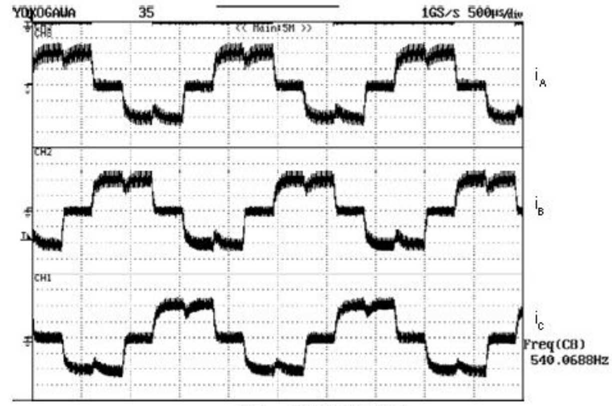
B. Voltage PWM BLDC Operations

When the PWM BLDC voltage control is applied to a HDD spindle motor with six pole-pairs and one platter at the speed of 5400 rpm, its three terminal voltages and phase currents are recorded as shown in Fig. 8, where the chopping frequency is 60 kHz and the duty ratio is 68.7%.

In order to detect the ZCPs of the phase back EMFs, the detecting circuit in Fig. 9 is employed to generate the phase voltages and the corresponding ZCP level signals. When the motor back EMF waveforms are sinusoidal and the phases are symmetric, the neutral terminal of the motor can be omitted and the neutral voltage can be obtained from the equivalent circuit to save the cost of motor with only three terminals. Otherwise, the neutral terminal should be connected to the ZCP detecting circuit. With the circuit in Fig. 9, subtracting the neutral voltage from the terminal voltages, the three phase voltages and their ZCP level signals can be obtained as shown in Fig. 10.



(a) Terminal voltages and neutral voltage



(b) Phase currents

Fig. 8. Typical terminal voltages and phase currents in voltage PWM BLDC mode.

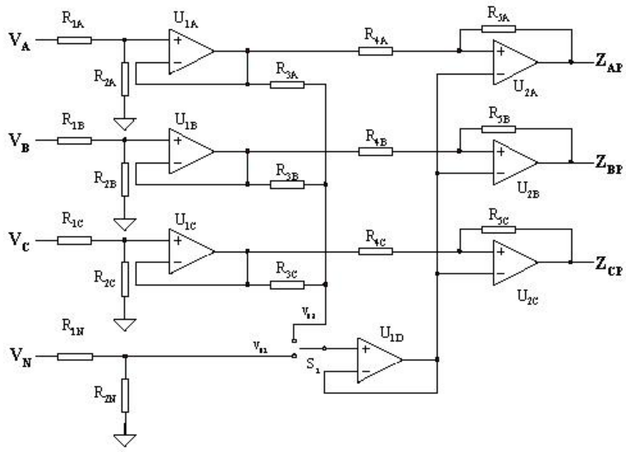


Fig. 9. Phase voltages and their ZCP detecting circuit.

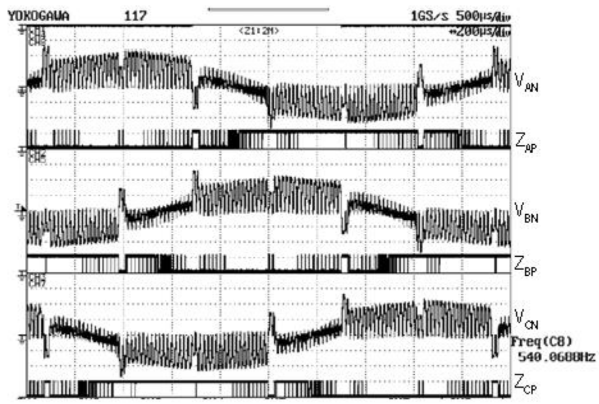


Fig. 10. Phase voltages and their ZCP level signals.

C. ZCPs of Phase Back EMFs

When a three-phase motor runs in six-step BLDC mode, there is always two unexcited periods of one phase while other two phases are excited. During each unexcited period, the phase current is zero and the phase voltage is equal or very close to the phase back EMF. Just during this period, the phase back EMF occurs once zero-crossing from the negative to the position or vice versa. It is more easily seen when the speed control is implemented through adjusting the DC link voltage [1].

However, when the PWM chopping control is employed, there are a lot of noises on the phase voltage and back EMF as shown in Figs. 5 and 10, which are caused by the chopping operations of a conducting switch. Under ideal condition, there should be no such noises. But due to the bandwidth limitation of the detecting circuit, the mutual inductance differences between phases and the device parasitic capacitances, each chopping operation generates an apparent resonant noise on the unexcited phase [18]. Zooming in Fig. 10, the noises and error ZCP pulses of the phase A can be observed clearly in Fig. 11, which are caused by the chopping operations. And the true ZCPs of the phase back EMF are drowned in a lot of false ZCPs.

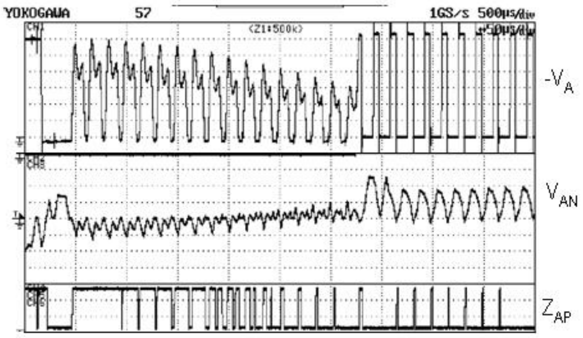


Fig. 11. Zooming in the phase voltage noises by PWM chopping.

To identify the true ZCPs, the switch control signals are employed to form the masking level signals, which allow the ZCP signals, Z_{AP}, Z_{BP} and Z_{CP} in Fig. 10, effective only when the corresponding phase is silent. It is:

$$Z_{xPf} = Z_{xP} \cdot \overline{S}_{xL} + S_{xH}, \; x = A, B \text{ and } C \tag{1}$$

After the above masking, the masked ZCP level signals will be "1" when the corresponding upper arm switch is "On" and "0" when the lower arm switch is "Off". But the noises during the silent period still exist and need to be further filtered out, as shown in Fig. 12.

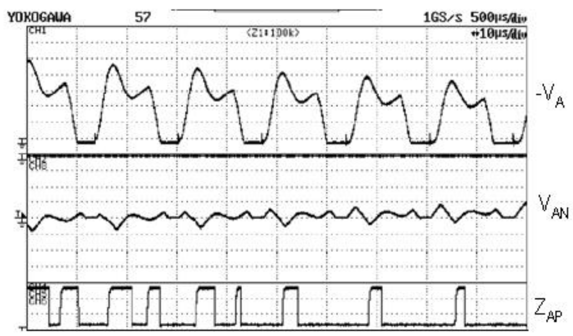


Fig. 12. ZCP level signal of phase A during silent period.

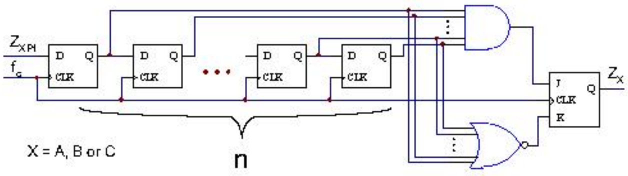


Fig. 13. Noise pulse filter with a set maximum noise width.

Since the noise pulses of ZCP level signals are caused by the "On" and "Off" chopping of a "On" switch, they last only during the switching transient periods, their maximum width is very limited and is smaller than 6 microseconds in this kind of spindle motors. The maximum possible noise width mainly depends on the switch parasitic capacitance and the motor inductances [18].

To filter out these noise pulses, a noise pulse filter in Fig. 13 is developed, which uses a clocked n-stage shift register followed by a J-K Flip-Flop for each masked ZCP signal, Z_{xPf}. The Q outputs of the n D Flip-Flop are applied to an n input AND gate and an n input NOR gate whose output are used to drive the J and K inputs of a J-K Flip-Flop. Filtering occurs since the ZCP level signal must be at the same level for n consecutive clock periods before that level becomes the new output. If a noise ZCP pulse lasts shorter than n consecutive clock periods, then the J-K Flip-Flop will not change and the noise ZCP caused by chopping will be filtered out. In this paper, the clock frequency f_C is set to 1 MHz and the 8-stage shift register is adopted. Therefore, the noise ZCP pulses, which are shorter than 8 microseconds, will be filtered out as shown in Fig. 14. It should be noted that this noise pulse filter brings a fixed delay of n clock periods or 8 μs, which can be easily compensated by control unit. Fig. 15 displays all three-phase voltage ZCP signals without PWM chopping noises.

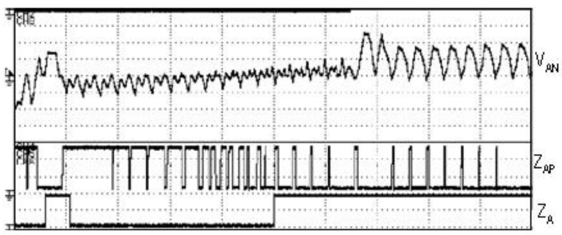


Fig. 14. Phase A voltage ZCP signal without PWM chopping noises.

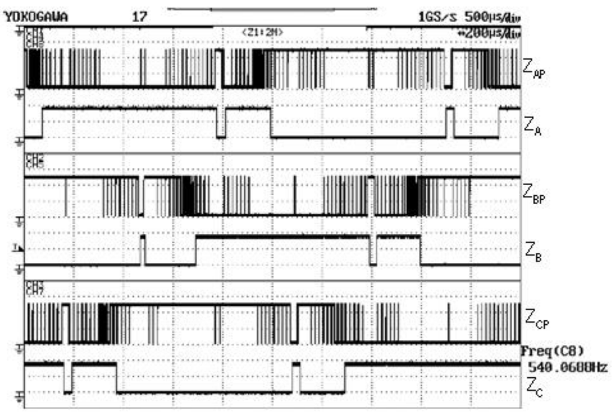


Fig. 15. Phase voltage ZCP signals with PWM chopping noises.

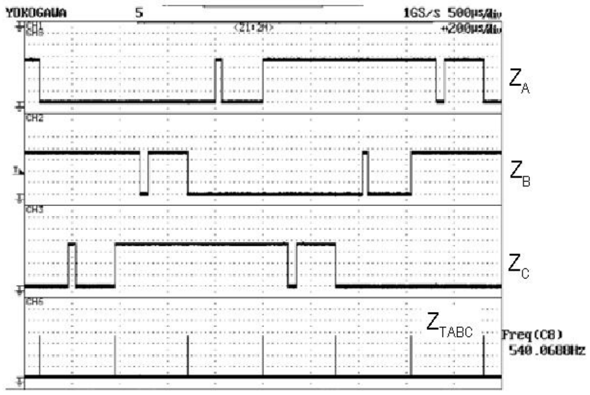


Fig. 16. Phase back EMF ZCP pulse signals.

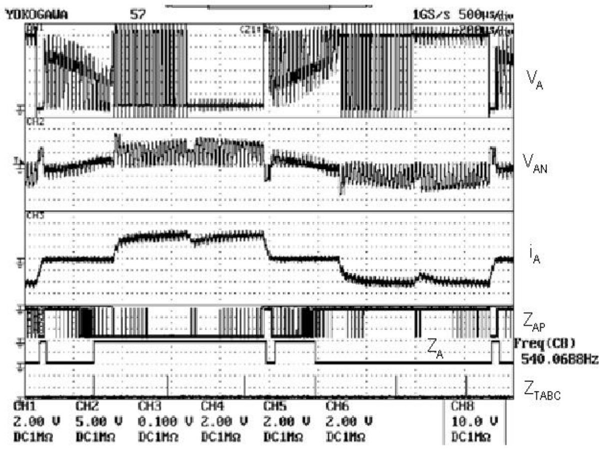


Fig. 17. Typical voltage and ZCP signal waveforms of phase *A*.

From Fig. 15, the PWM chopping noises in the phase voltage ZCP level signals have been filtered out but the phase commutation ZCP noises are still there because these noises last longer and depend on the speed, phase current and motor parameters. These ZCP noises should be filtered out too. Through authors' developed method [1], they can be filtered out without any phase delay, as shown in Fig. 16. Fig. 17 displayed the key voltage and ZCP signal waveforms of a phase when the motor runs in voltage PWM chopping mode at the speed of 5400 rpm. With the true ZCP pulse Z_{TABC} in Figs. 16 and 17, the correct phase commutation and speed control can be implemented [1].

IV. Future Work and Development Trends

With the proposed ZCP method, the 0.1% speed stability has been achieved when the spindle motor operates in sensorless voltage PWM mode, which is the simplest and lowest cost BLDC control mode. In order to reduce the switching loss and torque ripple, the current PWM mode and over 120° BLDC control should be applied. For the spindle motors with the trapezoidal back EMFs, the minimum torque ripple control can be improved through the suggested back EMF ZCP detecting method. When the back EMFs are sinusoidal, SPWM mode should be adopted to reduce the current ripple, torque ripple, vibration and acoustic noise of HDD spindle motors. However, when SPWM mode is applied, the accuracy of the sensorless rotor position detection faces challenges and at the current stage, its speed accuracy is only 1%, not matching the HDD requirement. Therefore, the more accurate detecting method of rotor position should be investigated for SPWM mode. Based on the modern control theory of electrical machines, advanced power electronics and high performance DSP, it is quite possible to improve the HDD spindle motor performance through developing new SPWM sensorless control technology.

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