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Relationship detection between the signals of composite photoelectric encoder and the windings of BLDC Motor

***Abstract**. In the servo control system of brushless DC (BLDC) motor, the inverter replaces the brush of DC motor. The output signals of encoder provide phase conversion logic for the inverter. In this paper, first, the logical relationship between the output signals of encoder was analyzed and the correctness of the relationship was verified. Also, the property of back electromotive force (BEMF) wave was stated. Next, the relationship between the zero-crossing point of BEMF and the phase conversion point was calculated. Then, a detection method based on line-to-line BEMF was proposed for establishing the corresponding relationship between the output signals of encoder and stator windings. The theoretical analysis and experimental results demonstrate the feasibility and convenience of the proposed method.*

***Streszczenie.** W układach sterowania z silnikami bezszczotkowymi DC szczotki zastępuje układ przekształtnika. Sygnał wyjściowy enkodera służy do konwersji fazy w przekształtniku. W artykule analizowana jest zależność między sygnałem enkodera i kształtem przebiegu napięcia. Badano także zależność między punktem przecięcia osi czasu tego napięcia a fazą konwersji. (**Zależność między sygnałami enkodera i napięciem uzwojeń w bezszczotkowym silniku BLDC**)*

Keywords: Composite photoelectric encoder；BL DC motor；Stator winding；Line BEMF
Słowa kluczowe: encoder fotoelektryczny, silnik bezszczotkowy

Introduction

In comparison with brush DC motor, the phase conversion of brushless DC (BLDC) motor is controlled by inverter. In order to make BLDC rotate, the stator windings must be conducted in sequence. The on and off states of the switching tube of the inverter are controlled by detecting the pole position of the rotor. Therefore, it is critical to determine the relationship between the rotor position and the stator winding. In high precision servo control, composite photoelectric encoder has been widely used. Thus, it is necessary to research on the relationship between the output signals of the encoder and the stator windings in practice [1-3].

When the nameplate of a motor is lost and the type of a motor cannot be determined, technicians need to measure the phase sequence and determine the relationship between the rotor position and the stator windings. However, so far, there have not been many researches on detection of the phase sequence of BLDC. The detection method of the relationship between rotor and stator windings by conducting two arbitrary phases was analyzed in [1]. However, it is difficult to fix the motor at a certain electrical angle (for instance, 60°, 180° and so on). Besides, auxiliary power devices are needed and the detection process is complicated. In [2], the different results are not distinguished in detail in the measurement, which may mislead the readers. The feedback signal of the encoder is sine in [3], which cannot be extended to square output signal.

In this paper, correct output signal of composite incremental encoder was deduced by analyzing the logical truth table of phase conversion. The relationship between the zero-crossing point of back electromotive force (BEMF) and the phase conversion point was calculated by considering that there are shortcomings to directly use BEMF to measure the phase sequent. Further, a detection method based on line BEMF was proposed to determine the relationship between the output of encoder and stator windings.

Judgment of the output signals of composite photoelectric encoder

Introduction to composite photoelectric encoder

Composite photoelectric encoder is based on incremental photoelectric encoder, and combines a photoelectric position sensor which is used to detect the pole position of BLDC motor. There are 3 slots in the photoelectric disk. There is an angle difference of 120° within each of the slots. Thus, three-phase signals with an angle difference of 120°are produced by light-emitting elements through the slots. Amplified and inversed, the signals output 6 routes with 3 pairs of square signals PHU , $PH\overline{U}$, PHV , $PH\overline{V}$, PHW , $PH\overline{W}$, as shown in Fig.1. The output differential signals are reduced for the rotor position signals through the differential signals receiver to realize the phase conversion of the electronic of the BLDC motor.

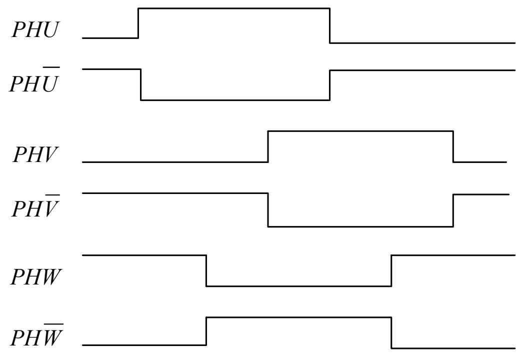

Fig.1 Differential output signals of photoelectric encoder UVW

Table 1 Logical truth table of the output signal of motor in reverse rotation

Space between Sensors	Output of Sensor			Space between Sensors	Output of Sensor		
	H_U	H_V	H_W		H_U	H_V	H_W
60°	0	0	0	120°	1	0	1
	1	0	0		0	0	1
	1	1	0		0	1	1
	1	1	1		0	1	0
	0	1	1		1	1	0
	0	0	1		1	0	0

Verification of the correctness of encoder position

In practice, if the nameplate of a motor is lost and the type of a motor cannot be determined or the manufacturer cannot provide the materials about connection definitions, the logical truth table of phase conversion is employed to distinguish and determine the connections. In this experiment, the encoder used in the BLDC motor belongs to the OAH48 series of TAMAGAWA. Our measurement is conducted based on the definitions of the connection pins. The experimental results are verified by the truth in Table 1.

When the motor axis rotates in counter-clockwise direction (reverse rotation), the output position signals H_U , H_V and H_W can be measured by dual-trace scope, as shown in Fig.2.

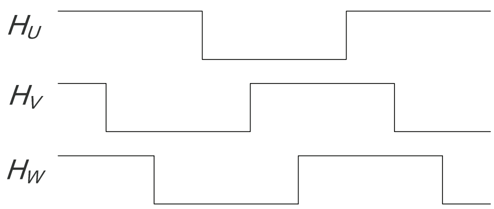

Fig. 2 Output of the measured positions of the encoder

According to Table 1, it is known that the measurement result is not 60 ° installation or 120 ° installation. Furthermore, using waveform graph to visual analysis, it is known that the phase of H_U is 120° back of the phase of H_V while the phase of H_V is 60° ahead of the phase of H_W . Therefore, the problem is found obviously that the ideal output wave drawn according to the truth table is the square wave where there is an angle difference of 120° within each of the 3 routes. Furthermore, it is found that in Fig.2 if the upper and the lower levels are overturned, the signals with a difference of 120° will be obtained. Hence, the reason of the problem is found that the signal connections of PHW and $PH\overline{W}$ are inverse. After adjustment, the correct output signals are shown in Fig.3.

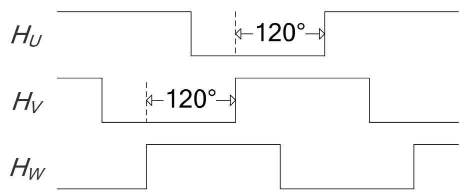

Fig.3 Correct position output signals after adjustment

After determining the correctness of the position signals, the relationship between the position output signals and the windings can be measured. It should be noted that this step is especially important for composite photoelectric encoder. If the definition of the encoder output terminal is unknown, we can observe the output wave of each terminal in Fig.1, and determine the 3 sets of difference signals and their rough sequence. Then, the method proposed later can be employed to determine the relationship between the output signals of encode and the windings, and the definition of the output terminal can be correctly determined.

Detection of the relationship between the output signals of the composite photoelectric encoder and the windings of the Motor

Principle of line BEMF detection

Suppose the three phases of BLDC are completely symmetric, the magnetic circuit is unsaturated, and the hysteresis and eddy lost are neglected. Then the voltage equilibrium equation of the three phases is as (1):

(1)
$$\begin{bmatrix} u_A \\ u_B \\ u_c \end{bmatrix} = \begin{bmatrix} R \\ R \\ R \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \mathbf{P} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} e_A \\ e_B \\ e_c \end{bmatrix} + \begin{bmatrix} u_N \\ u_N \\ u_N \end{bmatrix}$$

where u_A, u_B, u_C are the voltages of the three phases, e is the BEMF of the winding of each phase , i is the current of each phase, u_N is the center voltage, and L is the composite inductance of the mutual and self inductances.

When each phase of BLDC is open circuit, i.e., $i_A = i_B = i_C = 0$, the following results can be obtained:

(2) $$u_{BA} = u_B - u_A = e_B - e_A$$

(3) $$u_{CA} = u_C - u_A = e_C - e_A$$

where u_{AB} and u_{CA} are the line voltages of the three phases. From (2) and (3), it can be seen that when each phase of BLDC is open circuit, the above two variables can be denoted by BEMF.

When BLDC motor rotates, the field generated by the permanent magnet (PM) of the rotor cuts the stator windings and generates BEMF e($e = BLwr$). BEMF has it name because the direction of the electromotive force (EMF) is opposite to the direction of the current in the windings. When the polarity of PM through the stator changes, the wave of the BEMF becomes positive or negative. Therefore, to measure the zero-crossing point of the BEMF of stator in each phase is to determine the position of the rotator. Then, the relationship between the rotator position and the stator winding can be measured.

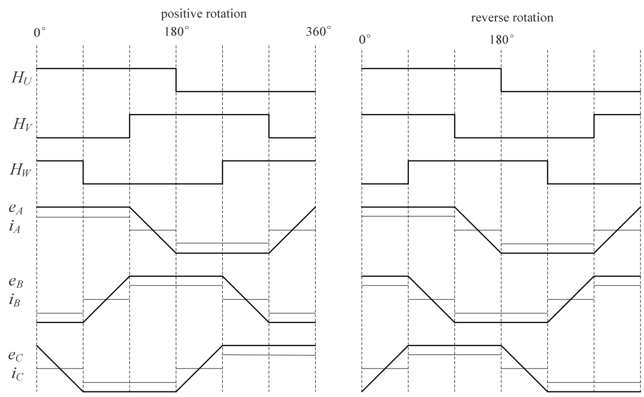

Fig.4 Relationship between the position signals with a distance of 120°, the BEMF and the phase current

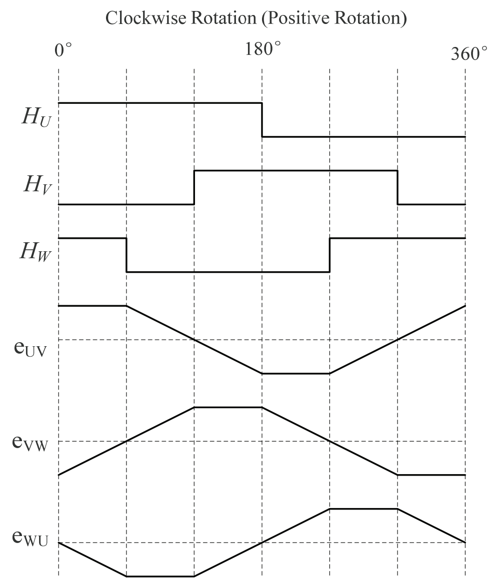

Fig.5 Corresponding relationship between the position signals and the line BEMF in clockwise rotation

From Fig.4 it is known that in order to get the phase conversion points, the 6 zero-crossing points of the three-phase BEMF must be delayed 30° . Thus, the relationship between three-phase BEMF and the output position signals of the encoder cannot be measured directly. Fortunately, it is found in Fig.4 that there is a relationship between the zero-crossing points of the line BEMF and the phase conversion points that the zero-crossing points of the line BEMF correspond to the phase conversion points. As shown in Fig.5, using this corresponding relationship, the relationship between the position signals of the encoder and the motor windings can be measured.

Now, we are in a position to verify the relationship between the line BEMF and the zero-crossing points.

The BEMF of the three-phase stator winding of BLDC motor can be decomposed into fundamental wave, trio-time harmonic wave, and harmonic wave with even higher odd times.

(4) $e_U = E(\sin(wt+30^0)+k_3\sin(3wt+30^0)+ k_5\sin(5wt+30^0)+\cdots)$

(5) $e_V = E(\sin(wt-90^0)+k_3\sin(3wt-90^0)+ k_5\sin(5wt-90^0)+\cdots)$

(6) $e_W = E(\sin(wt+150^0)+k_3\sin(3wt+150^0)+ k_5\sin(5wt+150^0)+\cdots)$

Subtracting (6) from (4), we can get the line BEMF

$$e_{UV} = \sqrt{3}E(\cos(wt-30^0)-k_5\cos(wt-30^0)+\cdots)$$

$$e_{VW} = \sqrt{3}E(\cos(wt-150^0)-k_5\cos(wt-150^0)+\cdots)$$

$$e_{WU} = \sqrt{3}E(\cos(wt+90^0)-k_5\cos(wt+90^0)+\cdots)$$

The line BEMF does not contain component of the harmonic wave with the time of 3 and the multiple of 3. Besides, the harmonic wave with the time of 5 and higher can be ignored [4-6]. Then the reduced equations for line BEMF are

(7) $e_{UV} = \sqrt{3}E\cos(wt-30^0)$

(8) $e_{VW} = \sqrt{3}E\cos(wt-150^0)$

(9) $e_{WU} = \sqrt{3}E\cos(wt+90^0)$

From (7)-(9), it is known that when it is at 0°，60°，120°，180°，240°and 300°, there are zero-crossing points in the line BEMF, which is in accordance with the zero-crossing points in Fig.5. Therefore, it is feasible to measure the relationship between the line BEMF and the rotor position signals.

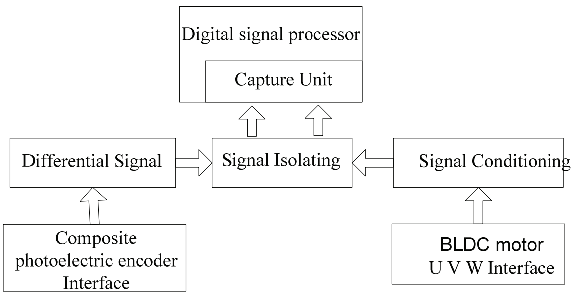

Fig.6. Architecture block-diagram of detection system

The detection system

The detection system is an embedded system designed on DSPs, which consists of digital signal processes unit, differential signal unit, signal isolating unit and signal conditioning unit. Differential signal unit is connected with composite photoelectric encoder interface and signal conditioning unit is connected with BLDC motor U, V, W interfaces. These two groups of signs are sent to capture unit of digital signal processor through signal isolating unit, shown as Fig.6.

The principle of detection system is as follows. Firstly, initializing system is ready for detection. Secondly, rotating manually motor is that uniformly rotating motor by hand,in order to let 6 ways capture unit of digital signal processor capture respectively rising and failing edge of there output signs of encoder and BEMF zero-crossing of three windings, As is the third . Fourthly, storaging state of capture unit is of interrupt request signal when digital signal processor captures signal. Fifthly, detecting U, V, W phase sequence is that order of BEMF zero-crossing. The first zero-crossing BEMF is e_{VU} *,then,* e_{WU} *.Sixthly,* determining corresponding relationship of encoder and winding is according to Formula (4),(5),(6) and Table 1.

The program flow diagram of detection system is shown in Fig.7.

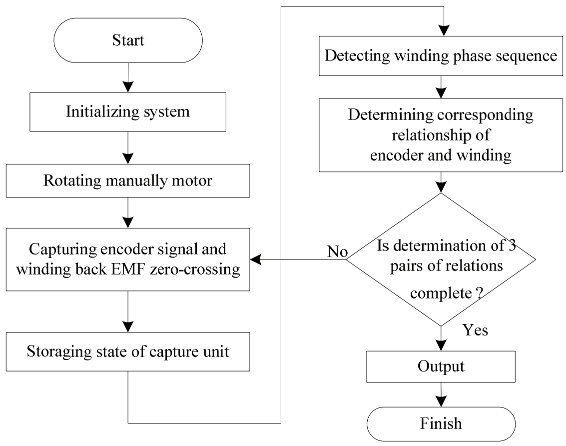

Fig.7. Program flow diagram of detection system

Experiments and analysis

Determination of the phase sequence of motor

In this experiment, the type of the motor is XC-EMB92-203, the standard power is 2KW, and the composite photoelectric encoder is of 2500, shown as Fig.8.

Fig.8 Typical BLDC motor named XC-EMB92-203

The detection and determination of the phase sequence of the BLDC mainly depends on the sequence of the stator windings. When the motor is not conducted, it rotates in clockwise direction. Take any phase as the reference phase and mark it as U. Measure the phase relationship between the other two phases and the reference U, shown as Fig.9. Then the leading phase is e_{VU} and phases V and W can be determined.

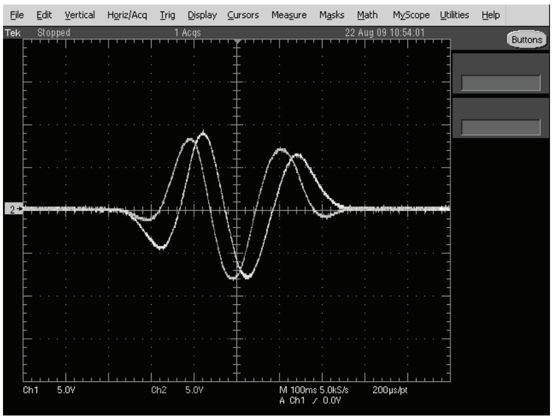

Fig.9 Wave of the line BEMF

Measurement of the relationship between the rotator position signals and the stator windings

When the motor rotates in clockwise direction, take e_{VU} as the reference phase. Observe the wave of the position signals by scopes. The one corresponding to the wave in Fig.9 is H_V which corresponds to V phase winding. Similarly, according to Fig.10, H_U and H_W which correspond to U and W, respectively, can be found.

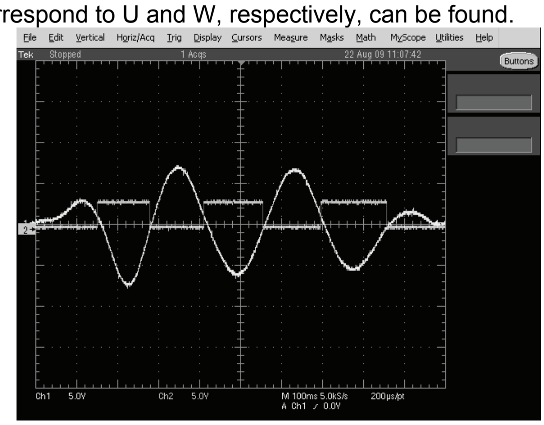

Fig.10 H_V Wave corresponding to the line BEMF of UV

Conclusions

When the materials about the output signals of BLDC motor with position sensors are lost, the phase sequence cannot be determined and accurate phase conversion logic cannot be provided accordingly. To solve this problem, in this paper, a detection method based on line BEMF was proposed for establishing the relationship between the output of encoder and stator windings. Also, the relationship between the output signals of composite photoelectric encoder was discussed, and the relationship between the zero-crossing point of BEMF and the phase conversion point was calculated. The feasibility and convenience of the proposed method was analyzed by theoretical and experimental results.

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