Position Estimation and Control of BLDC motor Based on Hall effect sensor and Angular Magnetic Encoder IC

Hamzaoui Nabil

Abstract— **In the last few years the high efficiency, reliability and the low cost of both permanent magnet synchronous machine (PMSM) and brushless direct current motors (BLDC) in industry and many applications drives most companies and laboratories throughout the world to focus on those type of machines. BLDC motor has advantage of long lifetime, faster response and capability of highspeed drive in comparison with brushed DC motor and has been more widely used in industrial area in line with the development of power switching device, microprocessor and digital technology.**

The control of BLDC motor is one of the most side should take on consideration when we talk about this type of motors. there are two main technologies to control BLDC, sensors and sensorless control. in this paper two types of sensor control methods are presented. First a hall effect sensor is studied, the study including both theoretical and practical part with experiment and results. on the other hand, and the main focus of this work is the design and implementation of an angular magnetic encoder IC which is AM8192B. the implementation contains a general description of the chosen model, then the schematic part using Altium designer software and hardware construction; Printed Circuit Board (PCB).

The last part of this work is testing of the implementation encoder for detection angular position of BLDC motor, and shows the original results of the designed encoder.

Index Terms— **Angular magnetic encoder, BLDC motor Control, Hall effect sensors, PCB design.**

I. INTRODUCTION

Electric drives are the most important component of developed automation industry and technology, especially as part of motion control system, these devices are whished for capability of precise position, speed and torque control.

A perfect motion control system consists of three parts: motor, a drive and the controller. The controller used to provide information and calculation to obtain desired motion in result.to gain high accuracy and performance, feedback devices such as sensors, resolvers, and encoder play spirited role by informing the drive or the controller with details about actual position and speed of the motor shaft.

Brushless direct current motor is one of the motor types that have rapidly gained popularity, mainly because of their ideal characteristics and its high performance [1]. this type of motor is used in great number of industrial sectors because their flexibility and simplicity for any safety critical application.

BLDC motors have many advantages over the other types of motors for example brushed motors or induction motors such as high dynamic response, reliability, speed and torque characteristics, long operating life (without brush erosion), less noise and high minimization of electromagnetic interference(EMI).

A key parameter to perform an accurate and efficient control of an BLDC motor is the position sensor. The sensor measures the angular position of the rotor shaft and there are several ways and techniques to do that.

A. *POSITION SENSING:*

The step of sensing rotor position is very required in order to synchronize electronic commutation in a brushless dc motor. several different options for position sensing exist, with variation in performance and cost [2]. For high precision, a rotary encoder maybe added to the rotor shaft. An encoder uses electrical, magnetic or optical sensors to provide analog or digital electronic measure of position. Incremental encoders produce square wave output that may be counted to calculate position. Absolute encoder will directly report instantaneous position however it requires more digital channels to do so. these two types of encoders are available in range of resolution and maybe interfaced directly to the motor control software.

In fact, the most common method of position sensing in BLDC motors is the addition of hall-effect sensor to the design, these are robust, cheap and operate over wide range of temperature [3].

B. *Hall effect:*

The Hall effect was discovered in 1879 by the American physicist Edwin Herbert Hall. It is a result of the Lorentz force, which a magnetic field exerts on moving charge carriers that constitute the electric current [4, 5].

How the hall effect works:

- A particle with charge Q, velocity V and moving within a magnetic field B, will present the Lorenz Force **F=Q(V×B)**.
- This force is mutually perpendicular to direction of particle velocity and the magnetic field.
- In a current carrying conductor, the electrons will go to one edge of the conductor and the positive charge will go to the other edge.
- This gives rise to an electric field E (do to uneven lateral charge distribution), which exerts a force **F= Q E** which is opposite to Lorenz force.
- A voltage is produced that is perpendicular to direction of current flow V_H (Hall voltage).

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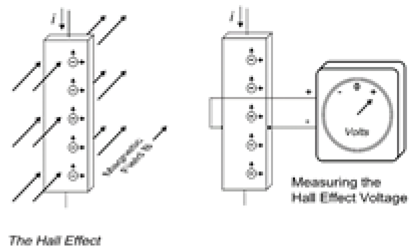
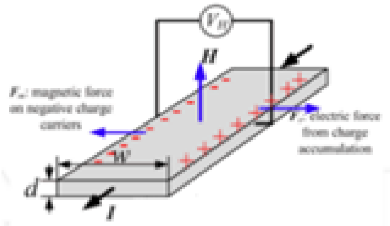


(a)



(b)

Figure 1: (a)Hall effect principal. (b) Schematic view of the bar (n-type) Hall device.

The force acting on a single electric carrier can be done as :

$$F = q(E + (v \times B)) \qquad (1)$$

Where:

F: The force vector acting on the charged carrier.
Q: The charge of the carrier,
E: The vector of the applied electric field.
v: The instantaneous drift velocity vector of the moving carrier.
B: The magnetic field vector.
qE: is the electric force.
qv × B: the magnetic force **Fm**.

In a solid conductor as shown in Figure 1(b), the current presented in terms of the flow velocity is :

$$I = j \times A = nqvwd \qquad (2)$$

Where:

j: The current density.
n: The number of charge carriers.
A = wd: The cross-section area of the conductor. **w, d:** are the width and thickness of the conductor respectively.

Then the drift velocity is expressed as :

$$v = \frac{I}{nqwd} \qquad (3)$$

When the magnetic force **Fm** is equivalent to the electric force **Fe** generated by the Hall electric field, an equilibrium state is gained

$$Fm = Fe \Leftrightarrow qv \times B = \frac{V_H q}{w} \qquad (4)$$

V_H is the output voltage caused by the electric field of the accumulated charges.

Using equation (3) and (4), **V_H** can be expressed in terms of the magnetic field and the applied current.

$$V_H = \frac{IB}{nqd} \qquad (5)$$

II. HALL EFFECT SENSORS:

Many types of sensors based of Hall effect principle to sense the presence of magnetic field. the next figure is a explicative drawing of Hall effect sensor.

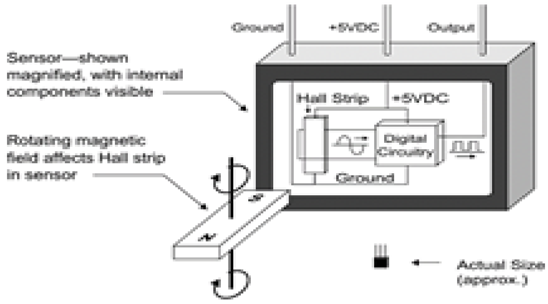


Figure 2: Hall effect sensor.

Constant current runs through a conductive Hall strip inside the sensor. a rotating magnet near the sensor as shown in figure 2 above, the alternating field from this rotating magnet will cause an alternating Hall effect voltage to be generated across the strip then this alternating voltage is fed into circuitry that shaped the wave form. [7]

A. Hall effect sensors for BLDC motors commutation:

Most BLDC motors have three Hall effect sensors inside the stator on the non-driving end of the motor, it is necessary to keep the angle between stator and rotor flux close to 90° to operate properly.

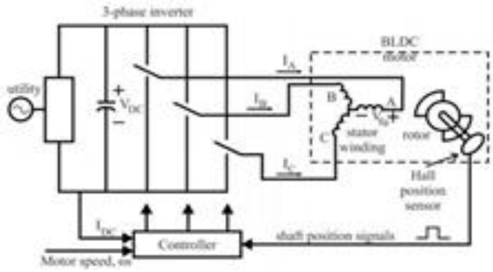
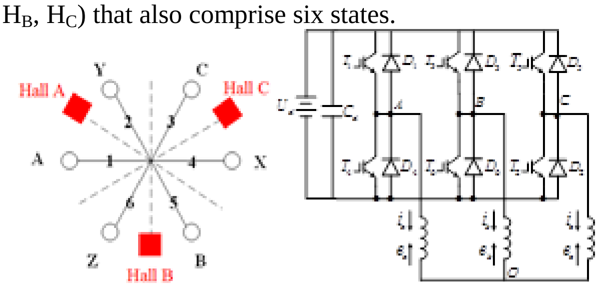


Figure 3: Electronically commutated BLDC motor drive.

Six-step control creates a total of six possible stator flux vectors. The stator flux vector must be changed at a certain rotor position. The Hall sensors generate three signals (H_A, H_B, H_C) that also comprise six states.



(a) **(b)**

Figure 4-(a) Hall sensors position detection. (b) Six steps Control Strategy for 3phase BLDC motor

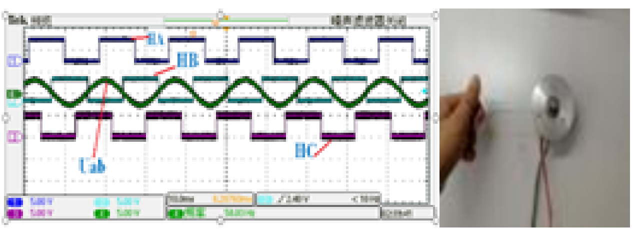


Figure 5 – Hall sensors waveform by rotating the rotor axis of BLDC motor with hand.

According to the hall sensors waveform and the voltage output we can select the six steps stator flux vectors as it shoes in figure 6.

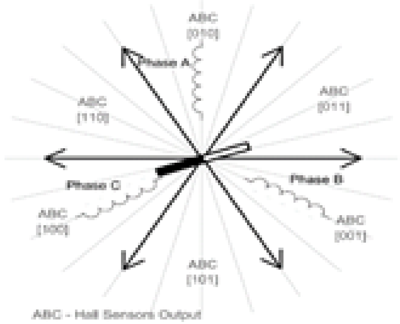


Figure 6 - Stator Flux Vectors at Six-Step Control.

In order to control the BLDC motor in clockwise or counter-clockwise direction, it is necessary to know the relationship of the six inverter switches state and the Hall sensor position. An DSP control board and an IGBT-based inverter have been used for the experiment to test the relationship of the inverter switch on-off states and the Hall sensor position. The test results are shown below in Table 1 and 2.

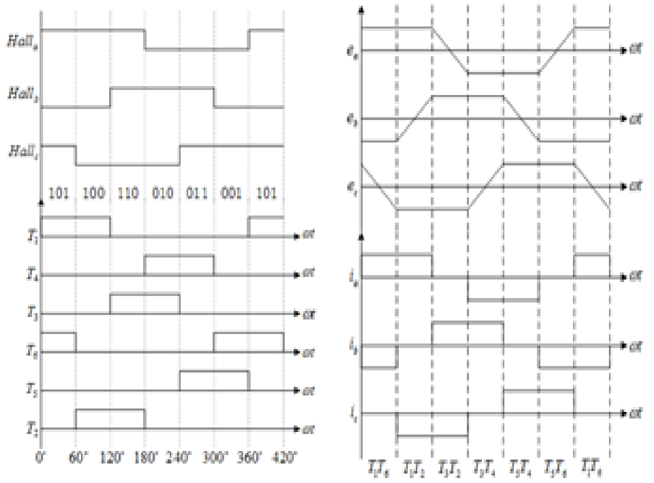
Theta-elec	State	H_A	H_B	H_C
0°- 60°	1	1	1	0
60°-120°	2	1	0	0
120°-180°	3	1	0	1
180°-240°	4	0	0	1
240°-300°	5	0	1	1
300°-360°	6	0	1	0

Table I: Six states Hall sensor with respect to rotor electrical angle.

Ph A	Ph B	Ph C	T_1	T_2	T_3	T_4	T_5	T_6
NC	$+V_{DCB}$	$-V_{DCB}$	off	on	on	off	off	off
$+V_{DCB}$	NC	$-V_{DCB}$	on	on	off	off	off	off
$+V_{DCB}$	$-V_{DCB}$	NC	on	off	off	off	off	on
NC	$-V_{DCB}$	$+V_{DCB}$	off	off	off	off	on	on
$-V_{DCB}$	NC	$+V_{DCB}$	off	off	off	on	on	off
$-V_{DCB}$	$+V_{DCB}$	NC	off	off	on	on	off	off

Table II - six steps Commutation Sequence for control of BLDC motor.

For every 60° there is a specific combination output from the three Hall effect sensors.
Corresponds to the Hall sensors' state ABC [110]; The actual voltage pattern can be derived from Table 2. Phase A is unpowered, Phase B.is connected to the positive DC Bus voltage by the transistor T3; Phase C is connected to the ground by transistor T2;
These discrete switching events assure that the sequence of conducting two of stator terminals is preserved.
As shown, when using a six-step control technique, it's impossible to keep the angle between the rotor flux and the stator flux precisely at 90°. The actual angle varies from 60° to 120°.



(a) *(b)*

Figure 7- (a)Hall signal and inverter drive signals. (b)Three opposite potential and current waveforms.

Figure 7 shows an example of Hall sensor signals with respect to back-EMF and the phase current.
Commutation is repeated every 60° electrical. The commutation event is critical for its angular (time) accuracy. Any deviation causes torque ripples, leading to a variation in speed.
With table 2 in the memory, the commutation software driver becomes simple; using a small code memory footprint as obverse to the sensorless method which needs big memory space and more software bandwidth.

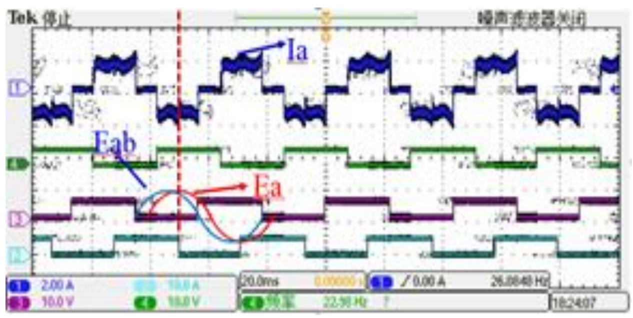


Figure 8 - Maximum torque output state.

As conclusion, BLDC motor drives require a rotor position sensor to properly perform phase commutation, the hall effect sensors which are used to detect the position of the shaft rotor can also use to uncover the speed of the motor by measuring the time it occupy for the sensors to be switched .the microcontroller timer calculate the length of pulse gained from one of the hall sensor , then the measured time convert it into revolution per minute(RPM) .The torque can calculated from the current consumed by the motor.it just needs one signal channel and the software resources to convert the signal to torque information.
but there are several disadvantages when such types of position sensors are used. The main drawback are the increased size and cost of the motor, and a special order needs to be made for placing the sensors. Moreover, Hall sensors are very sensitive to temperature and the magnetic interference signals which could reduce the system reliability.

III. ENCODERS:

Encoders are a type of sensor that measures the movement of a mechanical part. For example, a rotary encoder can measure the rotation of a motor, or the position of a dial or knob. A linear encoder could measure the position of a piston in a robot, or it could be used in a digital caliper to precisely measure the width of the object it's gripping.

Encoders can be categorized into two broad types: contacting and non-contacting. The contacting types requires brushes or finger sensors that electrically transmit a signal to indicate a change in position. Noncontracting encoders rely on magnetic, capacitive or optical phenomena to sense the motion. Outputs can be either absolute, a digital coded word that indicates absolute position, or incremental, with repetitive pulses that are counted to accumulate total motion. Rotary position sensing, either absolute or incremental, indicate the rotation of a shaft. The encoding disc is patterned with radial lines that are sensed as the input shaft is rotated. Mechanical packaging varies greatly depending on application requirements. [8]

Encoders are often used in control systems, as a type of feedback to ensure that a mechanical part is moving exactly as much as planned. For example, when you normally use a DC motor, it will simply spin as fast as it can base on how much power you provide it with. If you use a motor controller, you have control over the direction of the rotation and the approximate speed of the motor, but still have no way to tell your software what exactly the motor is doing in the physical world. If you also use an encoder, you can give your program access to the motor's current position, allowing it to make fine adjustments to speed and position.

A. Angular magnetic encoder IC:

As we said above, the main focus of this paper is the design and implementation of the angular magnetic encoder sensor which is AM8192B IC. First the schematic circuit was designed using Altium designer, then it assembled on PCB.

The AM8192B is a magnetic encoder which used for angular position sensing. The IC's magnetic encoders can provide linear and rotary magnetic encoding. Hall sensors technology are used to detect the magnetic flux density at the surface of silicon. The permanent magnet can be above or under the chip but it must be absolutely polarized and correctly placed.

Encoder's sensors provide sine and cosine voltage outputs which depends on the magnet position. These outputs are converted to position digital data by configurable interpolator.

From the name classification of the AM8192B encoder, we can know about the maximum resolution which is 8192 counts per revolution, this rate coms from 2 power the number of available bits.

Resolution: 2^{13} =8192 (counts per revolution).

The AM8192B can provide both absolute angle position data which accessed through SSI interface and incremental output as A QUAD B signals which determine the relative changes of the angle position.

B. Applications:

The AM8192B encoder is one of contactless position or velocity measurements:

Angular magnetic encoders are very useful for different high-resolution applications, including motor motion control, flux measurement, medicine products, cameras positioning, robotics, etc.

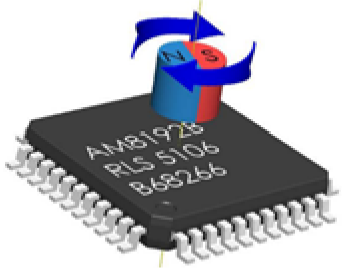


Figure 9: AM8192B with the magnet. [9]

Pins description for AM8192B chip is presented in figure 10.

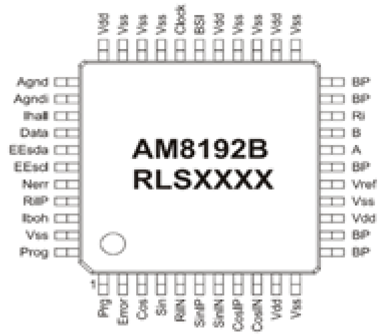
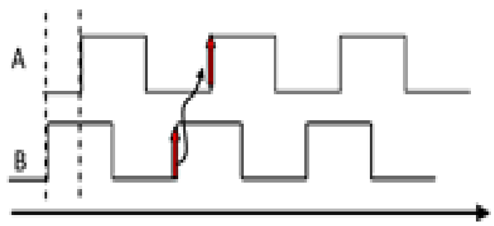


***Figure10: pins description for AM8192B.* [9]**

C. Incremental output:

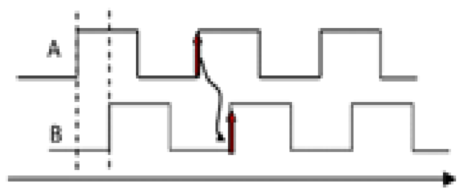
The output from incremental rotary encoders is called a "quadrature" signal. Quadrature encoder output indicators are described via the section shift relations hip between the A channel and the B channel signals. This phase relationship (90° phase shift) presents the information required in order that the encoder shaft direction as well as the velocity of the encoder shaft can be determined. The direction of the rotor shaft may be determined through evaluation of the A or B signal degree. The direction "CW" or "CCW" can be determined by comparing the sign stages relative to the change channel at the time of the rising edge.

Channel A rising edge occurs before Channel B rising edge (CW rotation).



(a)

Channel B rising edge occurs before Channel A rising edge. (CCW rotation).



(b)

Figure 11. (a): B leads A CW rotation of the magnet and positive counting direction. (b): A leads B CCW rotation of the magnet and negative counting direction.

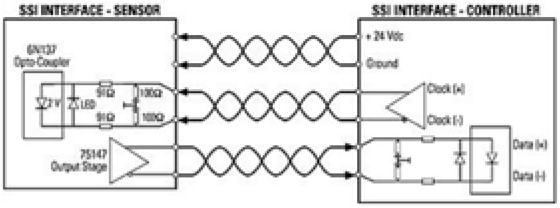
D. Binary synchronous serial output SSI

SSI (Serial Synchronous Interface) is a widely used serial interface between a controller and an absolute position sensor a. SSI uses a clock pulse train from a controller to initiate a gated output from the sensor.

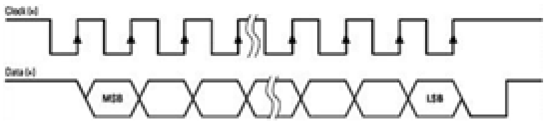
Position data is continually updated by the sensor and made available to the shift register. Between each clock pulse train there is a minimum perch of 25 microseconds during which nwe data is moved into the register. Data is shifted out when the sensor receives a pulse train from the controller. When the least significant bit (LSB) goes HIGH and the minimum perch time has finished, new data is available to know.

E. Synchronous Mode:

A synchronous pulse from the control system starts the measuring time of the sensor, the measured result is available before the next synchronizing pulse is generated. The synchronizing pulse is the first high to low transition of the clock train after the perch time.



(a)



(b)

(c)

Figure 12: (a)SSI block diagram. (b) SSI Timing diagram. (c) Sequential measurements of SSI Timing.

F. Application scheme:

Based on theory and data sheet information about AM8192B sensor, a full schematic circuit model presented in **figure 13**. The model designed using Altium designer software. this model contains all details about the application requirement.

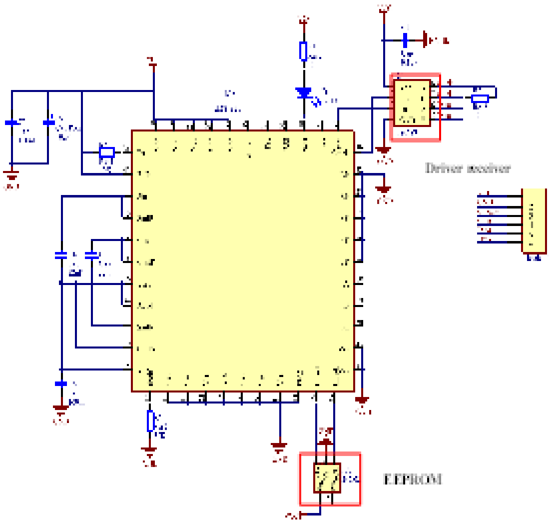


Figure 13: Schematic circuit model of AM8192B using Altium designer.

G. PCB design:

The encoder printed circuit board (PCB) was decided to be a multilayer and to have four layers made out of the regular glass epoxy panel FR-4 with copper foil laminated on each layer. The four layers made it possible to have a ground plane, a power plane and two signal layers. The four-layer structure was a very cost-effective approach in order to reduce current loops and trace inductances that can cause EMI and signal noise. The final PCB design presented in figure 14 below.

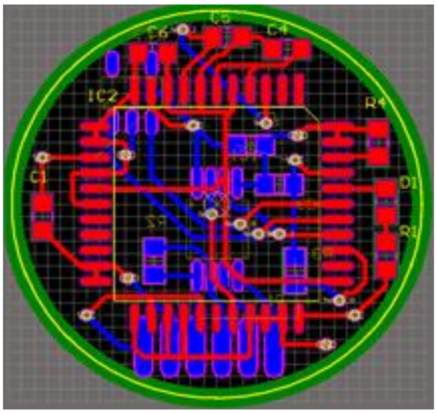


Figure 14: AM8192B -Angular magnetic encoder PCB.

H. Experiment test and results:

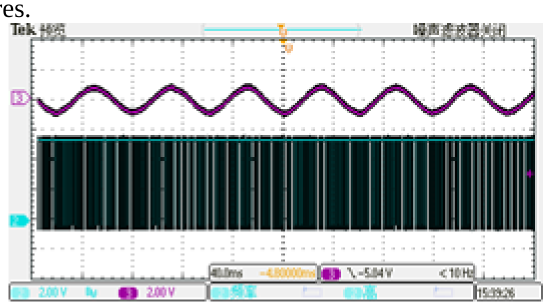
Based on study established above the experiment has been done.

Figure 15 shows the experimental setups. It consists of a BLDC motor placed on electromechanical actuator to facilitate the use of designed angular magnetic encoder, Control board, a computer with used software, Emulator, and a scope to show the output results.

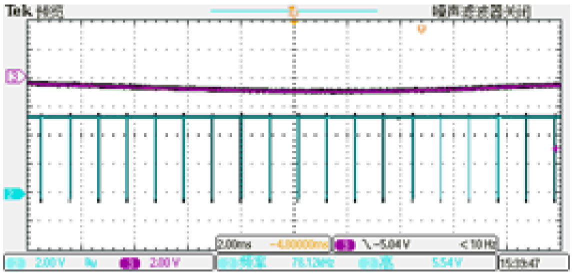
The angular magnetic encoder is used to measure the rotation angle of the motor shaft. And convert the ration angle to digital position outputs. Thus, both the position and speed can be measured and controlled.

Figure 15- Test Experiment of designed AM8192B angular magnetic encoder.

All original signals of studied encoder are monitored by oscillograph. The main results signals are shown in the next figures.



(a)



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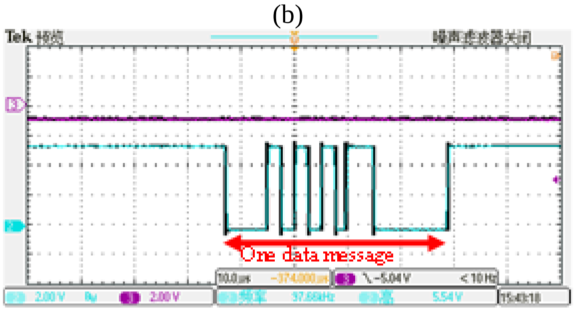

(c)

Figure 16 -(a), (b), (c): Experiment results of designed encoder by oscillograph.
Angular position data vs time.

IV. CONCLUSION:

- In this paper, two position feedback sensors for BLDC motor were described. It has been shown the Hall effect sensor results which well suited to be used for motor commutation in BLDC application.
- With hall effect sensors a simple BLDC control system need only 9 pins from a microcontroller ,6 pins to control the
  H-bridge and 3 pins to sense the hall outputs.
- The use of AM8192B Angular magnetic encoder deliver not just three outputs over one revolution like the hall sensor but can provide much higher angular resolution.
- Advances in RLS's devices technology now make the angular magnetic encoder more accurate, speed and high resolution which drive it to b product of choice for position feedback system.

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