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Methods for controlling brushless DC electric motor (BLDC) applicable in robotics

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Abstract: *This paper will present the most popular BLDC management methods using additional sensors and sensorless. Methods using Hall effect sensors, back EMF, PWM, and rotor positioning methods will be examined. Their advantages and disadvantages will be noted according robotic use. There will be a realization of two of these methods using the effect of Hall and PWM, which will be used to manage a gyro-stabilized platform. For the purpose of the experiment, an experimental setup controlled by Wi-Fi was built.*

Key words: *bldc,sensored driver,sensorless driver,pwm,hall-effect,robotics*

1. INTRODUCTION

With the development of radio-controlled models, brushless DC motors (BLDC) become extremely popular. Their advantages are in the relatively low price, high power and good torque, effective, light and practical lack of maintenance. Constructively, they allow them to be run extremely precisely, making them useful in the field of robotics. The disadvantage of these motors is their more sophisticated handling than a conventional brush motor. There are two main approaches to their management:

- Using additional sensors to measure the position of the rotor relative to the stator (Hall effect sensors, Variable reluctance (wheel) speed sensor, Accelerometers, etc.)
- Sensorless (by measuring the back EMF, by integrating the third harmonic of the EMF, using the "freewheeling diode", using PWM, by predicting the position of the rotor (Sliding Mode Observation, Extended Kalman filter, Artificial Neural Networks) and others.)

Each of them has its advantages, disadvantages and peculiarities. Some are applicable and effective only for fast moving systems (RPM> 1000) others are suitable for slow and precision moving systems. The presence of a sensor that controls the operation of the motor creates the possibility of its failure. This will cause unstable motor operation and from there on the system. It also raises the price of the final product. On the other hand, the knowledge of the rotor position allows us to control the motor accurately and strive for the angle between the stator magnetic flux and that of the rotor to be close to 90 degrees, which gives us maximum torque and smooth running. On the other hand, sensory approaches are cheaper and do not rely on external motor operating systems. With the available powerful microprocessors and prediction algorithms, sensorless control can be done at low cost and high reliability. In the following chapters we will try to introduce some of the approaches and compare two of them (one touch and one without a touch).

2. HOW BLDC WORKS

Normal brush motors use a switching mechanism using brushes to transfer the supply voltage to the rotor windings. With the brushless motor the coils are located on the stator and there is no need of brushes, and the permanent magnets are at the rotor (Fig.1).

Fig. 1.BLDC construction.

The rotation of the rotor is accomplished by controlling the magnetic field created by the stator windings. The change in speed and direction of rotation is determined by the direction and magnitude of the applied voltage. Managing is done by feeding electrical impulses to two of the three coils at a time (Fig.2). The magnetic field created by the active windings interacts with that of the permanent magnets from the stator and creates a torque that drives the motor. It is extremely important the moment of switch the active windings. It depends on achieving maximum torque and smooth motor operation. For this reason, accompanying electronics are required for BLDC control.

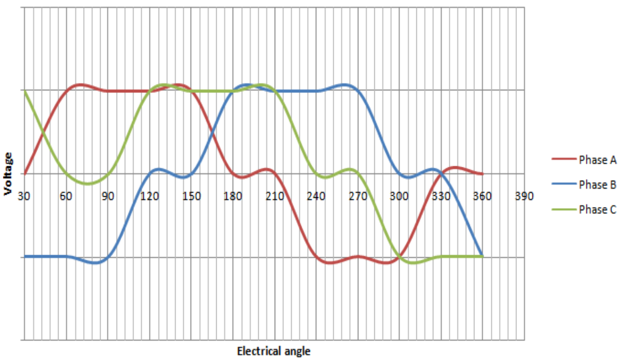

Fig. 2. Operation of BLDC.

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For a standard BLDC control, 6 transistors divided into 3 groups (½ H-Bridge) are needed (Fig.3).

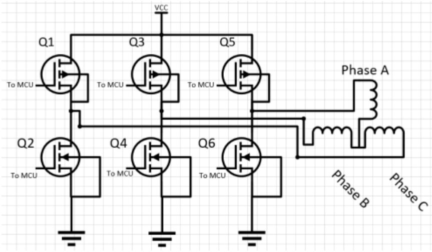

Fig. 3.BLDC inverter.

At any one time, voltage is applied to 2 of the windings through one of the upper transistors and one of the lower and third coils remains float. Due to this fact there are 6 possible combinations defining 6 steps of the magnetic field vector. By using these 6 steps, it is always difficult to keep the angle between the rotor magnetic stator and the stator 90 degrees. Typically, it varies between 60 and 120 degrees. The commutation process is done every 60 degrees. Because of these facts, the voltage control to the windings must be very precise to get an efficient and smooth operation. There are a number of methods to achieve this. We will look at some of them in the next chapter and we will present a realization of two of them.

3. BLDC CONTROL METHODS

Several methods of managing the BLDC will be examined, with the pros and cons of each of them addressing the specific need. At the core of each method is the desire to keep the angle between the magnetic rotor vector and the stator close to 90 degrees, which provides us with proper motor operation.

3.1. Sensored methods

They use additional sensors to measure the position of the rotor magnetic vector relative to the stator. These sensors make it possible at any point to determine in which area the magnetic field vector is located and to control the switching of the motor. Sensors use different positioning methods: magnetic, optical, magneto-resistive, etc.

3.1.1 Hall Effect Method

It is based on Hall effect sensors. Their output is either 0 or 1 (for digital one, and for analog is according specifications), depending on whether the north or south pole of the magnet is near them.

Three sensors are placed at 30 degrees to each other. The sensors are positioned so that they are never all three in position 1 or in position 0. This produces a table of switching (Table 1).

Table 1

Switcing table for hall sensor method.

Position	Sensor 1	Sensor 2	Sensor 3	Coil A	Coil B	Coil C
1	1	0	1		Low	High
2	1	0	0	High	Low	
3	1	1	0	High		Low
4	0	1	0		High	Low
5	0	1	1	Low	High	
6	0	0	1	Low		High

The sensors are positioned to switch from one row to another at the time of phase switching. This allows to determine in which of the 6 steps the magnetic rotor vector is located and so activate the correct two windings.

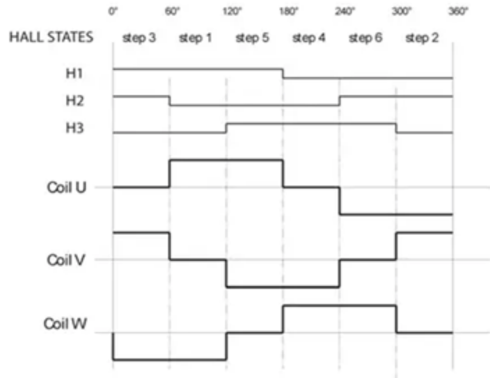

Fig.4. Operation of hall method.

The disadvantage of the method is the presence of additional sensors and their additional wiring and structure and the need for calibration of their position at the moment of commutation as well as the temperature dependence of the sensors.

3.1.1 Sensored method use 360 degree digital angle sensor

The method is similar to the Hall effect, but here a IC sensor (for example, TLE5012B) is used that detects the orientation of the magic field at 360 degrees. This is achieved by measuring sin and cos through elements using iGMR (integrated Giant Magneto Resistance). The raw signal is processed internally, and the final irrigation signal is output. It can be accessed by micro controller (MC) via I2C, SPI and PWM, depending on the characteristics of the specific IC.

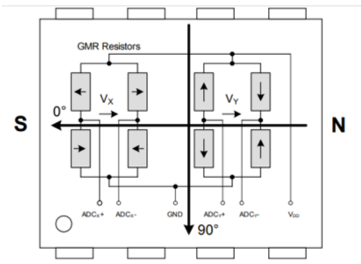

Fig.5. iGMR sensor.

These GMR elements change their resistance depending on the direction of the external magnetic field. 4 indivual components are connected, which reads one of the magnetic field components. Accordingly Vx and Vy components are measured. If the outer magnetic field is parallel to the element, their resistance is minimal and if outer magnetic field is perpendicular - to the maximum. So the output is within 180 degrees. To get a full 360 degrees we add another set of 4 elements rotated to 90 degrees. The arctan2 function calculates the output of the IC.

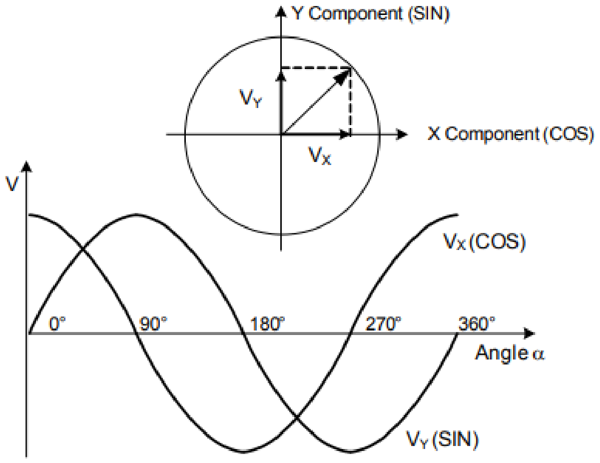

Fig.6. Calculating sensor output.

3.2. Sensorless methods

3.2.1 Using back EMF

Since only two of the motor windings are fed at a given time in the third non-fed coil, back EMF is induced. Back EMF is proportional to the rotation speed and is zero at rest, this results in a large amount of noise in the useful signal and requires the use of various techniques for filtering noise and amplifying the useful signal. Approaches using bEMF measurement are suitable for fast-on-field systems and are not suitable for slow moving and precision systems.

- Direct Terminal Voltage Sensing

  This is the simplest method using bEMF. It is based on measuring the time interval between two bEMF crossings across zero of the non-powered coil. And the use of a reverse counter of this time to count the switching moment. The commutation moment has been shifted by 30 degrees at the zero point. Low pass filters are used to eliminate high-harmonic interference caused by commutation. The time delay of these filters may affect the maximum motor speed.
- Using of third harmonic (Voltage Integrator)

This method uses the third harmonic of the back EMF to determine the switching moment. It is based on the fact that in symmetric three-phase motors connected in a star the sum of the three voltages in stator winding eliminates all polyphase and all components of 5, 7, etc. And therefore, in this amount, the third harmonic, which retains its shape at any load and speed, is predominant.

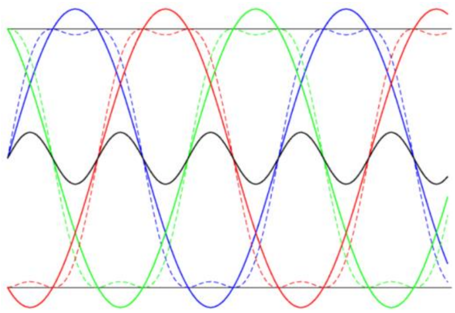

Fig.7. Three phase and the third harmonic.

Correct processing of the third harmonic makes it possible to predict the position of the rotor vector and to produce a proper control signal. Unlike direct measurement of bEMF here, we do not need complex filters. This method can be used for both high speed and slow moving systems. However, at low speeds it is possible to observe problems related to the integration process and to make errors that increase with the flow of time.

- Integration method

  This approach integrates silent phase back EMF. The main point here is that the area of integration is almost the same for all speeds. The integration starts when the silent phase back EMF becomes zero and continues to a predetermined limit corresponding to the switching point. This method is considerably more resistant to switching noise but is not suitable for low speeds because of the possibility of an integration error.

3.2.2 Using PWM

BLDC control can be achieved by using Pulse Width Modulation (PWM). By selecting the appropriate fill of each of the control signals of each phase, the required switching can be achieved - two fed phases at one time and a third in floating states. It can be seen in FIG. below. By changing the duty-cycle of modulation we can control the motor speed and by reverse the step order we can control the motor direction (Fig.8).

An extremely simple method that provides low loss of switching invertor, but generates a large amount of high harmonics. This results in an increase in motor losses.

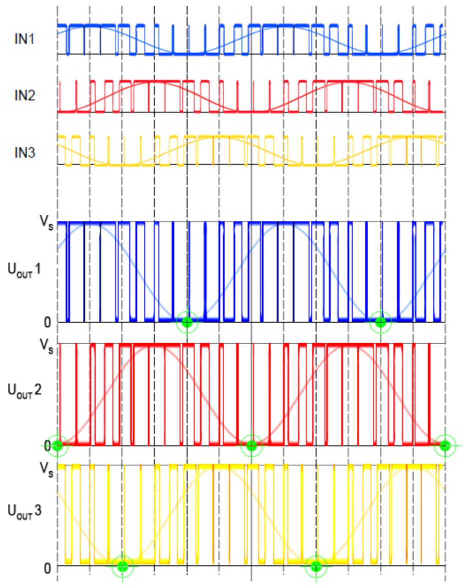

Fig.8. PWM control of BLDC.

4. EXPERIMENTAL SETUP

We build a setup for experimenting with control of BLDC. We use two BLDC motors with stator size 2208 and 12 pole and 14 magnets. One of the motors is equipped with hall sensor ring. We choose BLDC driver IC DRV8313 for 3 stage ½ H-bridge operation. The driver is controlled by Atmega32u4 powered board.

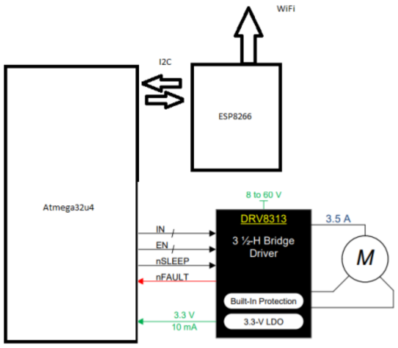

Fig.9. Shematic of experimental setup.

The main idea is to build standalone BLDC driver module which is controlling one motor. This module will receive command by I^{2}C for enable the motor and control of speed and direction of motor. This command can be produce by main MCU of the future system.

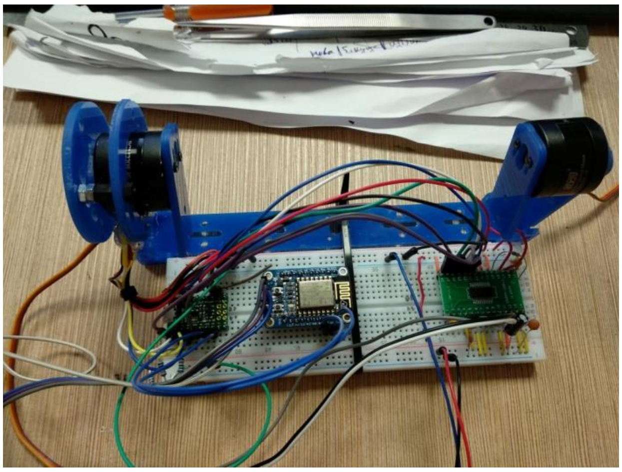

Fig.10. Experimental setup.

For this particular experiment we decide to build web portal with one Wi-Fi ESP8266 module that will send command to BLDC driver module thought Wi-Fi/Internet.

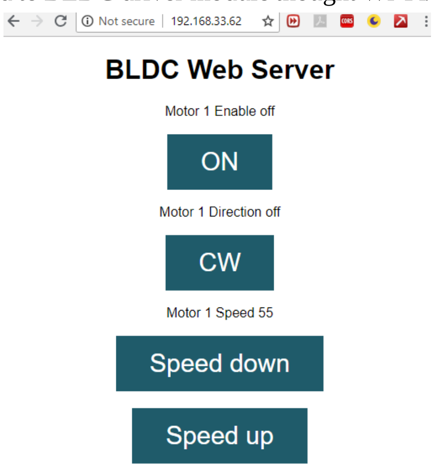

Fig.11. Web Portal.

4.1. Setup Hall effect method

To investigate this method, we build a special ring by SolidWorks. It take 3 Hall sensors by 30 degree each other and put them in s little space gap to the rotor magnets. We cut it by a CNC milling machine.

We use digital Hall sensors, which at have only 0 or 1 as output, depending on the magnetic field passing by them. Each output signal has to be placed with a 10KOmh pull-up resistor before being connected to the MC.

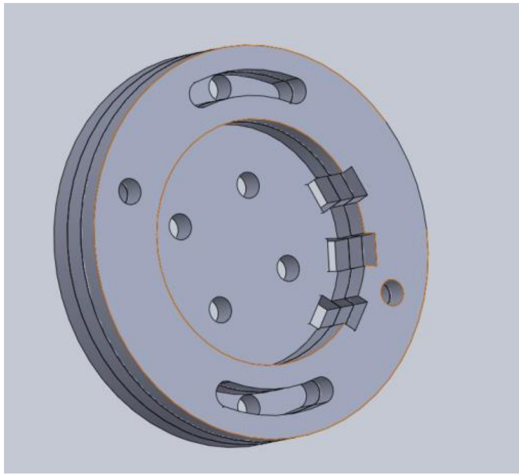

Fig.12. 3D prototype of hall ring.

The ring is designed to be easy to modify for any size and type of motors.

A key point in this method of control is the calibration of the motor-sensor ring system to match the moment of commutation of phases. A calibration procedure can be done using both an oscilloscope and manual. The ring has production holes for calibrating.

Fig.13. Real hall ring.

- Calibrating using oscilloscope

On one oscilloscope channel, we measure the back EMF of the coils, and on the other channel we hook the output of middle Hall sensor. Our aim is to orient the ring in such a way that the low-to-high-level switching time of the Hall sensor coincides with the moment when the bEMF passes through the zero point (Fig. 14). To be able to measure the bEMF we have to rotate the motor by external source and it is desirable to rotate at constant speeds.

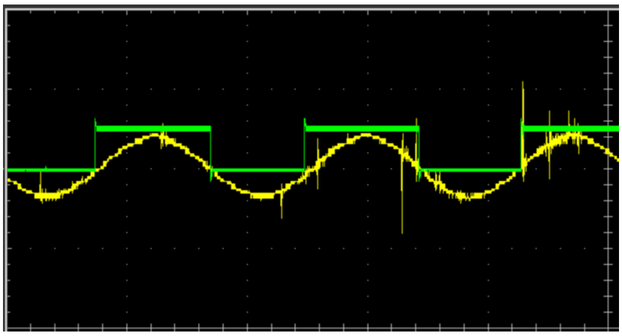

Fig.14. Oscilloscope calibrating.

The reason for switching right at this point is that our desire is to keep the motor torque as high as possible at all times. The bEMF is proportional to the torque and each commutation occurs when it changes its sign.

- Manual calibrating

The method is also a good exercise to understand how BLDC works. If we connect the coil A (to +) and the coil B (to -) to a DC voltage source, the motor will rotate slightly and will stop. Now, if we move the negative end of the C coil, the motor will move a bit longer and stop. Then, if we move the positive end of the coil supply B, it will spin a little more, and so on. When doing this, the motor always stops at the point where the torque is zero or the position from the upper figure where the signal crosses the X axis. It should be noted that the zero of the third combination corresponds to the commutation of the first two combinations. That's why the zero-coupled position of the B-C pair is where we want to put sensor 2 (the moment it switches).

After that we achieve smooth work of the motor, how we can see on Fig15.

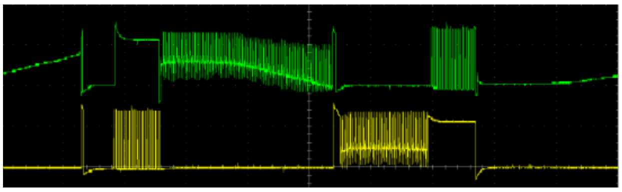

Fig.15. 2 Phases of BLDC motor driven by Hall sensors.

4.2. Setup PWM method

For controlling one BLDC, we need 3 PWM output pins and three enable pins. We also want to use an I^2C bus for communication between modules. Looking at the diagram with the pins of our micro controller (Fig.16), we notice that it supports 6 PWM channels.

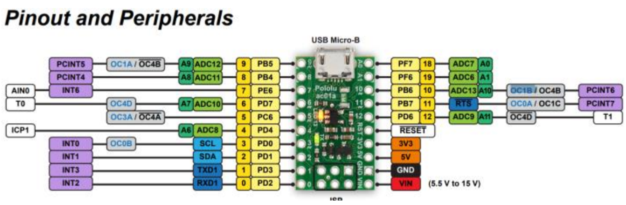

Fig.16. Atmega32u4 pinout.

The MC has 4 timers (0,1,3,4) providing the operation of the 6 PWM pins. Pin 3 and pin 11 use timer 0, but pin 3 is used for the SCL signal of the I^2C bus. We have a timer of 1,3 and 4. Looking at the MC datasheet, we notice that timers 1 and 3 are 16 bits . So we select pins 5,9 and 10 to control the PWM outputs to the driver (IN1-3), and 11, 18 and 19 for enable pins (EN1-3).

It is desirable to choose a frequency for PWM beyond the audible range (> 20KHz).

Mode	WGMn3	WGMn2 (CTCn)	WGMn1 (PWMn1)	WGMn0 (PWMn0)	Timer/Counter Mode of Operation	TOP	Update of OCRnx at	TOVn Flag Set on
0	0	0	0	0	Normal	0xFFFF	Immediate	MAX
1	0	0	0	1	PWM, Phase Correct, 8-bit	0x00FF	TOP	BOTTOM
2	0	0	1	0	PWM, Phase Correct, 9-bit	0x01FF	TOP	BOTTOM
3	0	0	1	1	PWM, Phase Correct, 10-bit	0x03FF	TOP	BOTTOM
4	0	1	0	0	CTC	OCRnA	Immediate	MAX
5	0	1	0	1	Fast PWM, 8-bit	0x00FF	TOP	TOP
6	0	1	1	0	Fast PWM, 9-bit	0x01FF	TOP	TOP
7	0	1	1	1	Fast PWM, 10-bit	0x03FF	TOP	TOP
8	1	0	0	0	PWM, Phase and Frequency Correct	ICRn	BOTTOM	BOTTOM
9	1	0	0	1	PWM, Phase and Frequency Correct	OCRnA	BOTTOM	BOTTOM
10	1	0	1	0	PWM, Phase Correct	ICRn	TOP	BOTTOM
11	1	0	1	1	PWM, Phase Correct	OCRnA	TOP	BOTTOM
12	1	1	0	0	CTC	ICRn	Immediate	MAX
13	1	1	0	1	(Reserved)	–	–	–
14	1	1	1	0	Fast PWM	ICRn	TOP	TOP
15	1	1	1	1	Fast PWM	OCRnA	TOP	TOP

Fig.17. Atmega32u4 PWM mode bits.

According to the manufacturer's datasheet, we have several possible PWM timer options. Most suitable for our purposes is Phase Correct PWM mode with OCRnA upper limit register. By setting an upper limit, we can control duty-cycle.

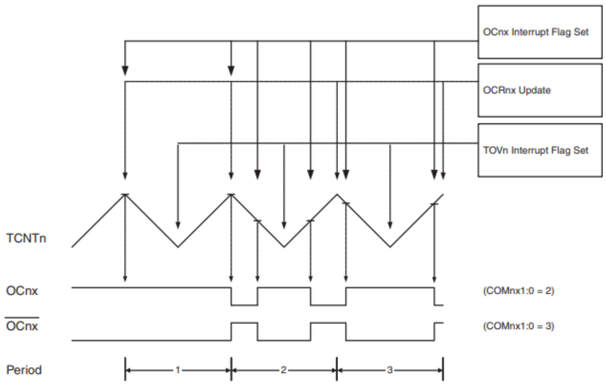

Fig.18. Phase Correct PWM Mode, Timing diagram

By equation 1 we can calculate the PWM frequency ($f_{OCnxPCPWM}$). We use a 16MHz external source for the MC operation frequency ($f_{clki/o}$). N is a prescale factor, which can be 1,8,64,256,1024.

$$f_{OCnxPCPWM} = \frac{f_{clki/o}}{2.N.Top} \quad (1)$$

Only one possible prescale factor is N = 1 and fpwm = 31372Hz when Top is 255.

First, you need to set timers 1 and 3 to use Phase Correct mode by changing the WGM10, WGM11, WGM32, and WGM33 bits to the TCCR1B and TCCR3B registers. The next step is to set the prescale factor by the CS10, CS11, CS12, CS30, CS31, and CS33 bits of the TCCR1B and TCCR3B registers. These operations can be put together by:

TCCR1B = TCCR1B & 0b11111000 | 0x01 (2)
TCCR3B = TCCR3B & 0b11111000 | 0x01 (3)

Also, we have to set pin 5,9 and 10 as outputs by changing the DDRC and DDRB registers.
The next step is to set an array of values for each PWM step. There are two approaches to pre-calculate the array and assign it to the MC or calculate it each time on the system initializing. The pre-calculation saves a lot of processing time to calculate the sin function (4), on the other hand, the initialization calculation allows you to change the number of steps and hence the accuracy of control.

$$array[i] = \frac{Top}{2} + \sin\left(\frac{2i}{maxSteps}\pi\right)\frac{Top}{2} \quad (4)$$

Where array[i] is i element of pwm array , Top is the top value of OCRnA and maxSteps is size of array. After that we calculate phase shift :

$$phaseShift = \frac{maxSteps}{3} \quad (5)$$

Now we setup the value for each phase for each system cycle :

$$\begin{aligned} currentStepA &= currentStepA + increment; \\ currentStepB &= currentStepB + increment; \quad (6) \\ currentStepC &= currentStepC + increment; \end{aligned}$$

where currentStepA-C is current step, increment can be plus one or minus one and determines motor’s direction. It is important to keep an eye on reaching the edges of the array (zero and maxSteps) and to change the next value correctly - when zero is reached, the next step will be maxSteps, and when it reaches the maxi will be zero. We can control the rotation speed by adding a delay time after the end of each system cycle. Another approach is to change TOP, but this requires re-initializing the array.
After this setups we can see the output of BLDC driver applied to the motor on Fig.19 .

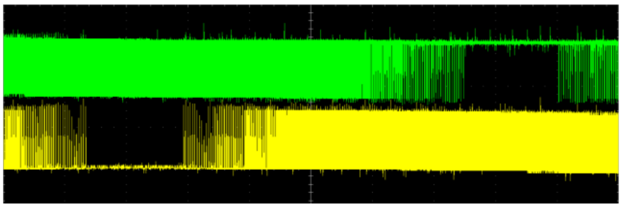

Fig.19. 2 Phases of BLDC motor driven by sine wave PWM.

Till we speak and use sine wave steps in our PWM array. There is another approach to use space vector wave. Space Vector PWM (SVPWM) refers to a special switching sequence of the upper three power transistors of a three-phase power inverter. It has been shown to generate less harmonic distortion in the output voltages and or currents applied to the phases of an motor and toprovide more efficient use of supply voltage compared with sinusoidal modulation technique. We can see the result of SVPWM on Fig.20.

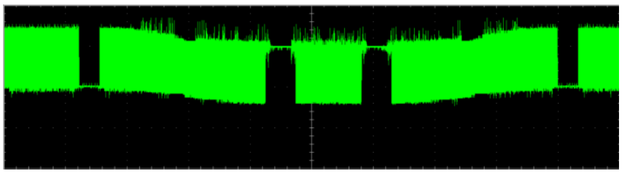

Fig.20. 1 Phases of BLDC motor driven by SVPWM.

5. CONCLUSIONS

Several methods for controlling the BLDC were presented. Two methods were selected, meeting the condition of being able to rob at low speeds and with great precision and not very complex. Studies have been made to compare these methods. From Fig. 15 and Fig. 19 can see the difference in the output signals of Hall using sensor and PWM. Fill of the diagram of PWM method is much larger than the sensored method, which leads to higher energy consumption and possible heat loss. However, as can be seen from Fig.13 sensor method has a much larger structure, multiple cabling, which may be a factor for a possible failure. In the course of the study several times, the ring with Hall sensors is being recalibrated, which breaks the correct engine operation. Due to these facts, we will choose the sensorless method for drive our gimbal, and we will make additional experiment for adjustment of the PWM array for better performans.

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