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Velocity Estimation from Hall Sensors using Digital Signal Processor and Modelling and Simulation of Electro-Mechanical Actuator

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Abstract

Objective: Electromechanical actuators convert rotary motion to linear motion. The electromechanical actuation system considered in this paper is a position servo system. In overall the entire work involved in this paper may be outlined into modelling and simulation of Electro-Mechanical Actuator in frequency domain in Matlab software and Velocity estimation from the hall sensor signals using digital signal controller. **Method:** The scope of the project is to evaluate the speed of the rotor using the hall sensor signals. Generally a tacho winding in the motor is used for speed of the motor. The EMF generated on the winding is proportional to speed of the rotation of the motor. By decoding the signal from the tacho winding speed of the rotor is determined. This results in the addition of necessary circuitry to decode the signals from the tacho windings. **Findings:** So on usage of hall sensor signals to determine the speed of the rotor will avoid the usage of tacho winding and its associated circuitry. Hence, increases the efficiency along with the reliability of the motor. **Application:** This method is used in flight control systems of aircrafts, missiles in aerospace industries.

Keywords: Brushless DC Motor, Digital Signal Processor, Electro-Mechanical Actuator, Hall Sensors, Velocity Estimation

1. Introduction

Electro Mechanical Actuation System consists of two Electro Mechanical Actuators (EMAs) (one main and one mirror actuators) and one Dual Channel Digital Controller composed of one single processor module with two Driver Electronics Modules as shown in Figure 1.

The actuation system contains velocity Feedback Transducer, Tachometer to provide stabilization, a position feedback sensor which is a Linear Variable Differential Transformer (LVDT) and a mirror sensor. The current sensor sensing the motor current is used for shutting off the motor in case of any abnormal current drawn by the motor. BLDC motor is used in the Electro-Mechanical actuators. When we need to control the position of an object then that system is called servomechanism. Servomotors are used to convert an electrical signal (control voltage) applied to them into an angular displacement of shaft in aerospace applications.

DC Servomotors are advantageous compared to AC servomotors as their linear characteristics are achieved easily, light weight and inertia and low inductance armature that can respond quickly to commands for change in position or speed. BLDC motor is a type of DC servomotor and BLDC motor is used in aerospace applications because of its advantages like it is simple and more reliable motor because the field power supply is not required, has high efficiency due to absence of field losses, less heating, making it possible to totally enclose the motor[1–2].

Control architecture of EMA is usually implemented based on cascaded position, velocity and current loop. The modelling and simulation of EMA with position, velocity and current loop. Previously used technology in industry is usage of tacho winding or three phase alternator wound on the stator and excited by three magnets on the rotor forms the basic measurement block. Hall sensor data is also used for demodulating the alternator output. The direction of rotation of the motor is also derived

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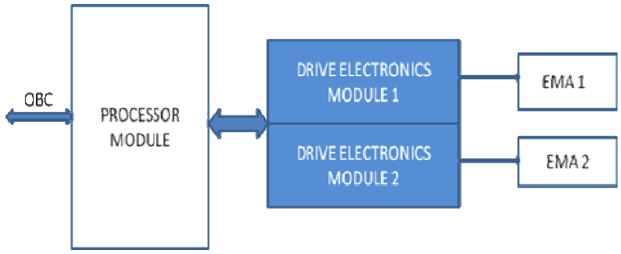

Figure 1. Block Diagram of EMA.

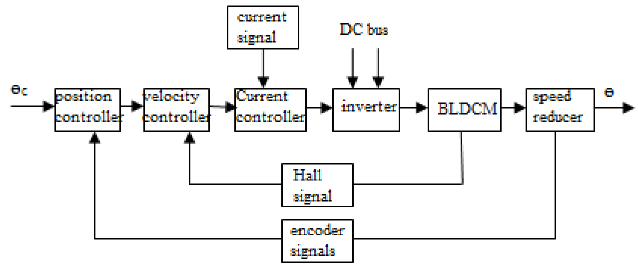

Figure 2. Block diagram of position servo BLDCM.

from the hall sensor data. Precision rectifier circuits with filtering circuits will give DC signal proportional to velocity of the rotor. This DC voltage proportional to the motor velocity is used in the servo loop for feedback. This results in the addition of tacho processing circuitry and other necessary circuitry to decode the signals from the tacho windings. So on usage of hall sensor data itself for velocity estimation will avoid the usage of tacho winding and its associated circuitry. Hence, increases the efficiency along with the reliability of the motor.

2. Modelling and Simulation of EMA

The model of BLDCM position servo system consists of BLDCM, speed reducer, controller, signal detection unit, inverter etc as shown Figure 2. Design requirements are maximum rotation angle of the load is 50°. The frequency response of this model should be 6Hz, when the rotation angle is 8°. And the position error should be less than 0.1°[3].

According to the frequency response requirement of the position loop, the frequency responses of the velocity loop and current loop can be obtained and a frequency domain method is used to design the PID controllers The deceleration ratio of speed reducer is i = 80:1. The transfer function of BLDC motor is as below:

$$\frac{n}{V} = \frac{K_T}{2(L_s + R)J_s + J_s + K_e K_T}$$

The model of BLDC motor is given in Figure 3.

2.1 Current Loop Design

The Current loop is designed with a proportional controller. The frequency response of this loop is 10 times greater than velocity loop, so the inverter can be considered as a proportional unit. The gain of the proportional unit is:

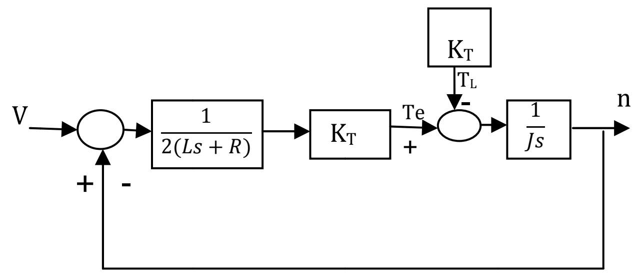

Figure 3. Block diagram of BLDC motor.

Table 1. The motor parameters are as follows

Phase resistance	**0.52ohm**
Phase equivalent inductance	16mH
Constant of torque (k_T)	1099Nm/A
Constant of back emf(k_e)	1099 v/rpm
The moment of inertia	2330 kg-m^2
Nominal power	350W
Nominal torque	1.85 N
Nominal speed	2000rpm

$$K_{PWM} = 70 / 2.5 = 28$$

The closed loop equation is given as

$$\varnothing_c = \frac{K_{PC} K_{PWM}}{2L_s + 2R + K_{PC} K_{PWM}}$$

From the definition of bandwidth we have

$$\mathrm{K_{pc}} = \frac{4L\Pi F1 - 2R}{Kpwm} = 0.680$$

Then closed loop transfer function of current loop is

$$\varnothing_c = \frac{19.04}{3.2\times10^{-3}s + 20.08} \approx \frac{1}{0.16\times10^{-4}s + 1}$$

The open loop transfer function is

$$\varnothing_c = \frac{1}{0.16\times10^{-4}s}$$

2.2 Velocity Loop Design

The velocity loop also consists of proportional controller with gain Kpv. The block diagram of the velocity loop is as shown below Figure 5. It consists of a delay unit and current loop. The two units in series are equivalent to one low inertia unit. And the equivalent time constant is:

$$T = 0.001 + 0.16 \times 10^{-3} = 1.16 \times 10^{-3} sec$$

The equivalent inertial unit is

$$\mathrm{G} = \frac{1}{1.16 \times 10^{-3}\mathrm{s} + 1}$$

The closed loop transfer function of velocity loop is given as

$$\varnothing_V = \frac{2 \times 10^6 K_{PV}}{s^2 + 862.37s + 2 \times 10^6 K_{PV}}$$

According to the definition of bandwidth, K_{PV} is:

$$K_{PV} = 8.50 \times 10^{-2}$$

Then closed loop transfer function is given as

$$\varphi_V = \frac{170 \times 10^3}{s^2 + 862.37s + 170 \times 10^3}$$

The open loop transfer function of velocity loop is

$$\varphi_V = \frac{170 \times 10^3}{s^2 + 862.37s}$$

2.3 Position Loop Design

The position loop consists of a PI controller to eliminate the steady state error.

K_{PP} - gain of the PI controller

K_{IP} - integral coefficient.

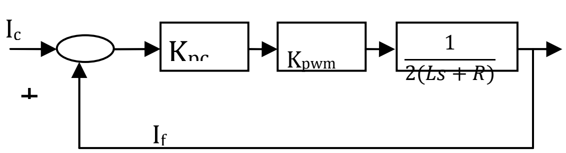

Figure 4. Block diagram of current loop.

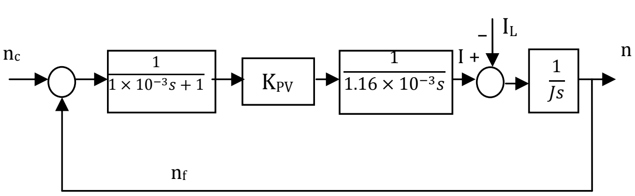

Figure 5. Block diagram of velocity loop.

By ignoring the higher order terms in velocity loop the closed loop transfer function is obtained as

$$\frac{n}{n_c} = \frac{170 \times 10^3}{862.37s + 170 \times 10^3} = \frac{1}{5.072 \times 10^{-3} s + 1}$$

Block diagram of position loop is given in Figure 6.

The closed loop transfer function of position loop is:

$$\varnothing_P = \frac{K_{PP}s + K_{IP}}{5.072 \times 10^{-3} s^3 + 80s^2 + K_{PP}s + K_{IP}}$$

According to definition of bandwidth , the following is obtained:

$$\frac{\sqrt{K_{PP}^2 \omega_b^2 + K_{IP}^2}}{\sqrt{\left(K_{IP} - 80\omega_b^2\right)^2 + \left(K_{PP}\omega_b - 5.072 \times 10^{-3}\omega_b^3\right)^2}} = \frac{1}{\sqrt{2}}$$

Where

$$\omega_b = 2 \times 6 \times \pi = 37.70 rad/\sec$$

The open loop transfer function of position loop is given as

$$\varphi_p = \frac{K_{PP}s + K_{IP}}{80s^2\left(5.072 \times 10^{-3}s + 1\right)}$$

The phase margin is greater than Π/4 , then:

$$\frac{\sqrt{k_{PP}^2 \omega_{CP}^2 + K_{IP}^2}}{80\omega_{CP}^2\sqrt{\left(5.072 \times 10^{-3}\right)^2 \omega_{CP}^2 + 1}} = 1$$

$$arctg\frac{K_{PP}\omega_{CP}}{K_{IP}} - arctg 5.072 \times 10^{-3}\omega_{CP} > \frac{\pi}{4}$$

Where ω_{CP} is cut off frequency of position loop. From above three equations we have

$$K_{PP} = 2050$$

$$K_{IP} = 150$$

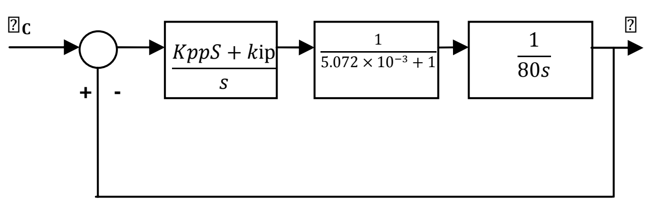

Figure 6. Block diagram of position loop.

The transfer function of the position controller is

$$P = 2050 + \frac{150}{s}$$

The closed loop transfer function of position loop is

$$\phi_P = \frac{404.2\times10^3 s + 29.6\times10^3}{s^3 + 15.8\times10^3 s^2 + 404.2\times10^3 s + 29.6\times10^3}$$

The open loop transfer function of position loop is

$$\varphi_P = \frac{404.2\times10^3 s + 29.6\times10^3}{s^3 + 4.44\times10^2 s^2}$$

Thus the design of curent, velocity and position loops is completed and all parameters of the controllers are given based on the design requirement of frquency response.

3. Simulation of EMA

The simulink model of Electro-Mechanical Actuator is as shown in Figure 7.

The simulink results are as shown in Figure 8.

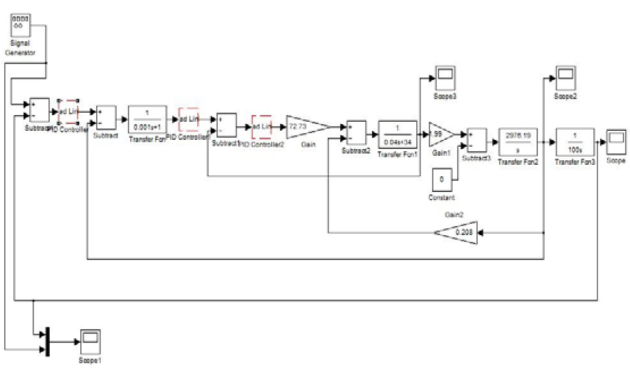

Figure 7. Block diagram of simulation.

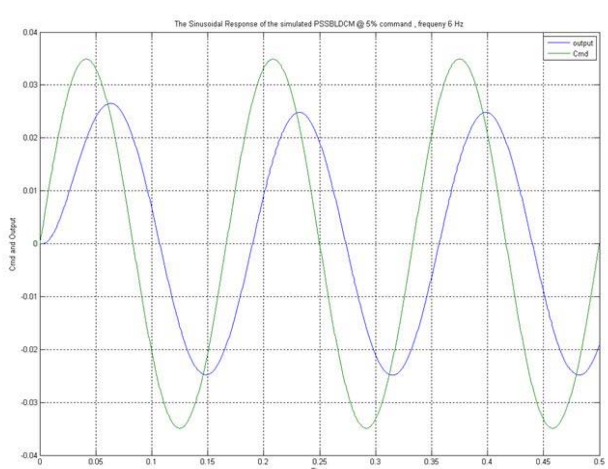

Figure 8. Sinusoidal response for frequency 3Hz.

4. Velocity Estimation from Hall Sensors

In the Brushless DC motor which is taken here each hall sensor is placed 120 degrees electrically apart. To determine the velocity we have to calculate the mechanical angle. The relationship is given as

Electrical revolutions made = mechanical revolutions made * pole pairs

Therefore, **Electrical angle = pole pairs * mechanical angle.**

So from the above formula we can say that the mechanical angle depends mainly on the pole pairs and electrical angle is equal to mechanical angle for a single pole pair. Since the hall sensors are mounted electrically 120 deg apart, the mechanical angle can be calculated based on the pole pairs which is equal to 8 for the motor used here.

4.1 Placement of Hall Sensors

The formula required for the conversion of electrical angle to the mechanical angle is

Electrical angle = pole pairs * mechanical angle

From the above

Electrical angle =120 degree = 2*pi/3

Pole pairs = 8

Let us assume mechanical angle as theta.

On substituting the above data in the formula as follows

Electrical angle = pole pairs* Mechanical angle

2*pi/3 = 8 * theta

Theta = pi/12

Now, **Theta =15 deg (mechanical angle between hall sensors).**

Thus the hall sensors are placed 15 degrees mechanically apart.

4.2 Evaluation of Velocity

Each hall sensor is typically placed 120 degrees apart (mechanical angle of 15 degrees) and produces '**high**' whenever it faces North Pole of rotor and '**low**' when it faces South Pole of rotor. On every hall event, only one bit changes. The general hall sensor pattern we get when hall sensors are placed electrically 120 degree apart is as shown below Table 2.

The above pattern will repeat in any order throughout the rotation of motor. For every hall pattern the

Table 2. Hall sensor pattern at 120 degree apart

Sl. No.	H_a	H_b	H_c
1	0	1	1
2	0	1	0
3	1	1	0
4	1	0	0
5	1	0	1
6	0	0	1

mechanical angle remains same. On the other side the time period changes for every change in the hall event.

The formula to determine the velocity is

Velocity = mechanical angle / time period

For example let us consider two hall sensor patterns 011 (H_a, H_b, H_c) and the next pattern 010 (H_a, H_b, H_c). We can observe that only one bit is changed. Let the time period at this instance is t1. As we have 8 pole pairs=16 poles, the mechanical angle between each pole of the rotor is given as 360degrees/16= 22.5 degree. The velocity estimation can be done by considering one hall sensor. Therefore the velocity at this instant can be calculated as follows

Velocity = 22.5/t1

4.3 Detection of Direction of Rotation of the Motor

The detection of change in the direction of rotation of the motor can be fulfilled by using D- flip flops. These give one clock time delay. So they are called Delay flip flops.

The general mechanism of D-type flip flops is shown in Figure 9.

Clk means Clock

The input D and Q remains in the same state for a given clk unless there is a change in the input D. When clk becomes low and input D changes the output is equal to previous output.

The circuit determining the direction of rotation of motor is given below Figure 10.

The above circuit which determines the change in the direction of rotation of motor employs three D- flip flops. The hall pattern is given as inputs to the flip flops. The circuit comprises gates like AND, OR, XOR. The AND and OR gates are connected as inputs to the XOR gate. The inputs to the AND and OR GATES are the outputs of the three D-type flip-flops. The XOR gate' output determines the direction of rotation. When the outputs of AND and

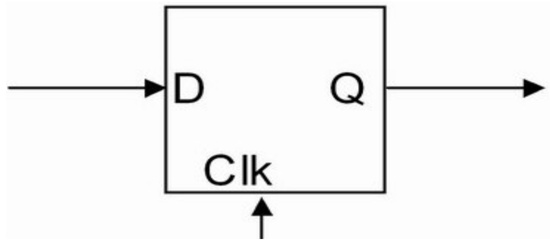

Figure 9. General mechanism of D flips flop.

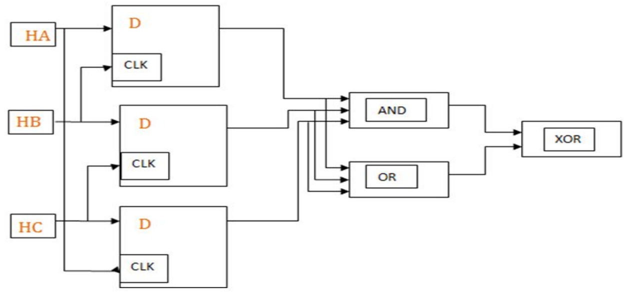

Figure 10. Logic for detection of direction of rotation.

OR gates are identical (when the motor rotates in one direction) then the XOR output is low state[2]. Upon the change in the direction of rotation the outputs of the AND and OR gates differ in their states. Then the XOR output assumes to be high state. Therefore this circuit determines the change in direction[4].

The above logic circuit is replaced by the software logic and implemented for finding the direction of motor. So whenever there is a change in states we consider it as a direction change of motor.

5. Algorithm for Velocity Estimation

The angular rate of motor can be calculated using the hall sensor of BLDC motor as follows[3]. The velocity estimation concept can be explained by below Figure 11.

Let the rising edge and falling edge times as shown in Figure 12, that is event driven times be **t1** and **t2**, and the in-between angle as θ, then we can get following relations

.$\Delta t = t1 - t2$[5].

$\Theta = 360^o/\text{no. of poles}$

$\quad = 360^o/16 = 22.5^o$

The velocity is given as

$\omega = \Theta/\Delta t$

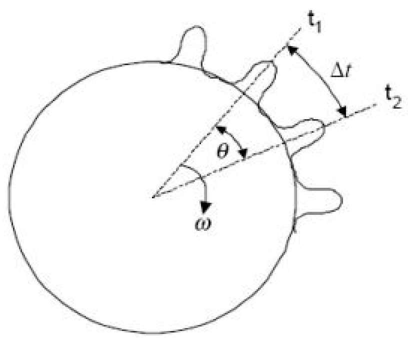

Figure 11. Velocity estimation concept.

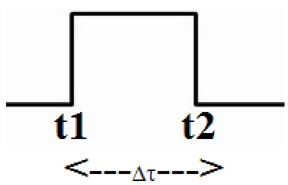

Figure 12. Rising and falling edge times.

6. Software Logic Implementation for Velocity Estimation

The above algorithm of velocity estimation can be put into a logic which is implemented in software programming to get required output. For this purpose we need to calculate the time instants at the rising edge and the falling edges i.e., t1 and t2 respectively as shown in below figure and calculate the velocity by putting ω= Θ/Δt.

Velocity estimation is done in both offline and online analysis. Offline analysis means velocity estimation is done using hall data file about hall sensor pattern is available. The hall data file is obtained by running the motor and taking the hall pattern data in the recorder for particular frequency. Here we have obtained hall pattern data is taken for 1.5 Hz frequency. Using this data file offline analysis logic for velocity estimation is programmed in MATLAB with the logic described above. The obtained for results for velocity estimation are shown in Figure 13.

By considering the direction logic which is discussed above along with the velocity estimation code gives the following result as shown in Figure 14.

7. SHARC Processor ADSP21062

SHARC processor ADSP21062 is used for software programming purpose. The above algorithm discussed in

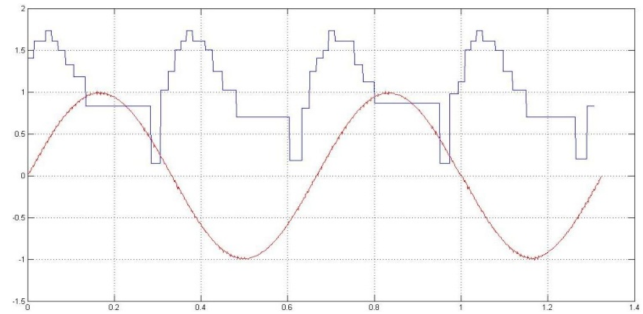

Figure 13. Velocity estimation in offline analysis.

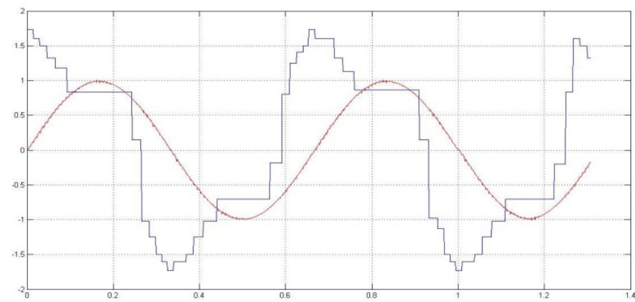

Figure 14. Velocity along with direction in offline analysis.

the flow chart is implemented in the SHARC processor as shown in Figure 15. High performance processors called the SHARC processors are used for medical imaging, communications, military, motor control, imaging and many other applications. Advantages of SHARC processor are: It performs fast, flexible arithmetic operations, unconstrained data flow, efficient programming sequence, and dual address generators. SHARC processors are 32/40 bit processors.

The interrupt timer is programmed to generate the interrupt at every 100us. The interrupt in turn calls for subroutine. The subroutine contains reading of ADC's channels through which hall sensor signals are being read. The timer interrupt also keep track of the time elapsed. Any bit pattern change in the hall sensor signals are being detected by the logic provided and hence gives the information of the displacement (in degree). Hence it gives the velocity information when divided by time. All the logics are programmed in the SHARC processor. The velocity extracted can be fed back to the control loop for providing the damping. A separate logic is implemented for detecting the direction and enclosed in the implementation part. The graph for velocity estimation in online analysis is shown in Figure 16.

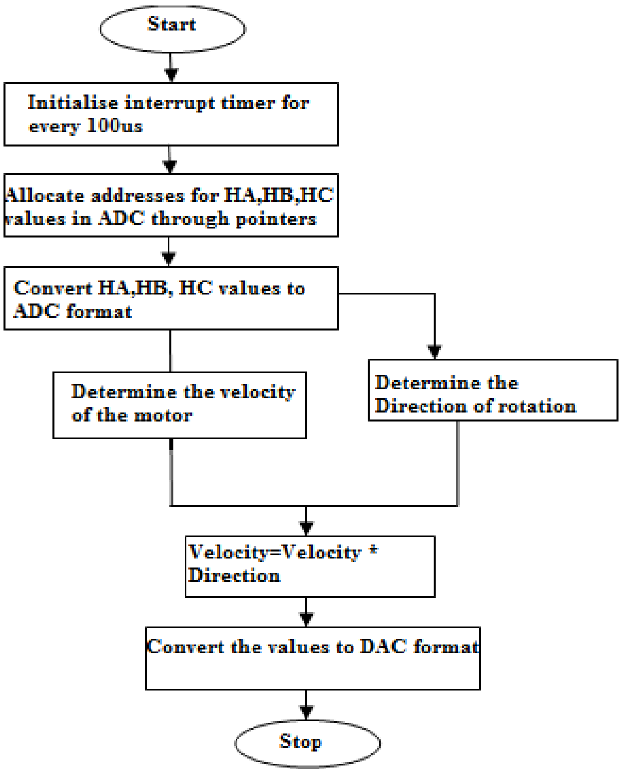

Figure 15. Flow chart determining the process of velocity estimation in online analysis in ADSP 21062.

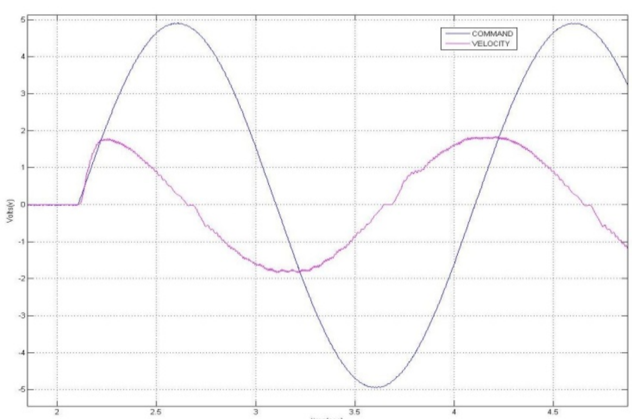

Figure 16. Velocity estimation in online analysis.

8. Conclusion

The logic to estimate the velocity of the BLDC motor and detection of change in direction of BLDC motor using hall sensor signals in digital servo controller unit which has a provision to interface with ADC's and DAC's is developed. This logic enables to evaluate speed at any instance of rotation. The development of logic in offline enables to determine the velocity when there is data file of hall sensor pattern. The development of logic in online analysis enables to determine the velocity while the motor is in rotation at any instance. The speed determined can be given as feedback in the control loop. This technology eliminates the use of tacho winding and its associated circuitry thus increasing the reliability of motor. The modelling and simulation of three loops EMA is also done.

9. References

1. Ko JS, Lee JH, Chung SK, Youn MJ. A robust digital position control of brushless DC motor with dead beat load torque observer. IEEE Transactions on Industrial Electronics. 1993 Oct; 40(5):512–20.
2. Lee YC, Lee HH. A position control of a BLDC motor actuator using time delay control and enhanced time delay observer. Proc of the Eighth International Conference on Electrical Machines and Systems; Nanjing. 2005 Sept 26-29; 2. p. 1692–6.
3. Yu K, Guo H, Wang D, Li L. Design of position servo-system of BLDCM based on frequency domain method. School of Automation Science and Electrical Engineering, Beijing University of Aeronautics and Astronautics; Beijing, China. 100191.
4. Jeong DS, Choi KJ, Woo HW, Kim JG. Controller design of missile actuator using DSP. MSL R&D Centre, LIG Nexl; Yongin, Seoul Korea. 2007 Oct 17-20; p. 2110–3.
5. Pirog BM. A novel speed measurement method for a high-speed BLDC motor based on the signals from the rotor position sensor. Krakow, Poland: Dept of Elecr Drive and Ind Equip. AGH Univ of sci and Technol. 2014 Feb; 10(1):84–91.