DSP Based Closed Loop Position Control of BLDC Motor

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***Abstract:-* This paper presents the design of digital controller for a BLDC motor to control the speed and position control using Digital Signal Processor (DSP) TMS320LF 2407 which is used in an Electromechanical Actuator. Brushless D.C motor (BLDC) are one of the motor types rapidly gaining popularity. This motor offer a simple and rugged motor Solution for many variable speed drive application. Rotation of the BLDC is achieved by energizing the stator phases in a sequence, which depends on the rotor position. A rotor position sensor is required to obtain information about the rotor position. Three Hall sensors are used for this purpose.**

The main objective of the usage of DSP is to commutate the switches of the inverter based on hall sensors signal, and for speed and position control of motor by generating PWM signal of different duty ratio.

***Index Terms* – Brushless DC Motor, DSP**

I Introduction

The motor is simple and rugged when compared, for example with DC, Induction machines. The inverter for the BLDC motor is same as that of any other three phase machine for example induction or synchronous machine. But here only two phases are energized at a time unlike three for synchronous and induction machine. Hence the losses in the inverter circuit for BLDC motor is less compared to the conventional machines. The BLDC motor can operate at high speeds in excess of other motor types, and can operate in hostile environments. It has significant performance advantage over other motors particularly in its torque production and stability at high speeds.

However, the impact of this technology has been delayed for various reasons. With the advent of powerful permanent magnets and fast switching devices like Mosfets and a better appreciation of the control requirements have led to major improvement in the brushless DC drive technology, particularly in the last 10 years. There has been significant activity in the areas of aerospace (actuators, robots, fans and blowers) industry (machine tool drives, general variable speed drives, floppy and plotter drives) domestic (washing machine and food mixer drives) automotive (blower) applications.

The overall objective of this paper is to present a simple and robust controller for the BLDC motor which performs the following.

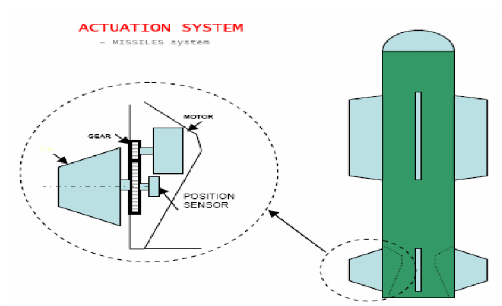
1. Commutate the inverter switches based on the rotor position
2. Speed control of the motor using the PWM signal.
3. And control the position of the motor

Key Activities involved are

- Develop a logic table for the BLDC motor for different rotor position, based on which the inverter switches are commutated.
- Develop an algorithm to generate PWM pulses from TMS320LF2407 DSP chip.
- Develop a program, which includes commutation algorithm and PWM Peripheral configuration by which the motor speed can be controlled.
- Design of converter circuit for the motor.
- Integration of the digital controller, power electronics and motor

Actuators are used in aerospace, military and industrial applications for control purposes Actuators are devices, which impose a state on a system, hopefully independent of the load applied to them. There are different types of actuators, which are frequently used, in aerospace applications. They are electro hydraulic actuators and electromechanical actuators

Electromechanical Actuators shown in the figure below contains an electric motor; generally the motor will be a brushed DC motor, brushless DC motor, stepper motor or switch reluctance motor. The motor is controlled using analog controller or a digital controller.



In this paper an electromechanical actuator having brushless DC motor with DSP based digital controller is used. The Electromechanical Actuators employing BLDC motors requires controllers of complex circuitry and logic. The Electromechanical actuators used in Aerospace applications required to be flexible in terms of control performance as the mission may demand certain changes in control parameters when required by the application. Analog controllers will not provide any flexibility in terms of control performance as the control parameters can not be changed with out hardware replacement which is not reliable. Digital controllers provide the flexibility in changing the control parameters as demanded by the mission.

The BLDC motor employed in electromechanical actuator is similar to a brushed DC motor in terms of speed torque characteristics. The control of BLDC motor is complex when compared to that of Brushed motor. The commutation of BLDC motor is through electronics circuit which makes it little complex than Brushed motor. Many motion control DSP's are available which includes all the on chip functions to implement a reliable and efficient digital controller.

Power Bridge:

Basically the inverter of BLDC motor can operate in the following two modes.

1.2π/3 angle switch on mode

2. Voltage and current control PWM mode.

1. 2π /3 angle switch on mode- The six switches (S1- S6) of the inverter shown in Fig 2 operate in such a way so as to place the input DC current symmetrically for 2 π /3 angle at the centre of each phase voltage wave. It can be seen that at any instant, two switches are on, one in the upper group and another in the lower group. As seen from figure 3 each switch conducts for 120 degrees and conduction pattern changes every 60 degrees. The rotor position sensor dictates the switching or commutation of the devices at the precise instants of the wave.

2. Voltage and current control PWM mode- In the above method the inverter switches were controlled to give commutator function only. In addition to the commutator function it is possible to control the switches in the PWM chopping mode for controlling voltage and current continuously at the machine terminal.

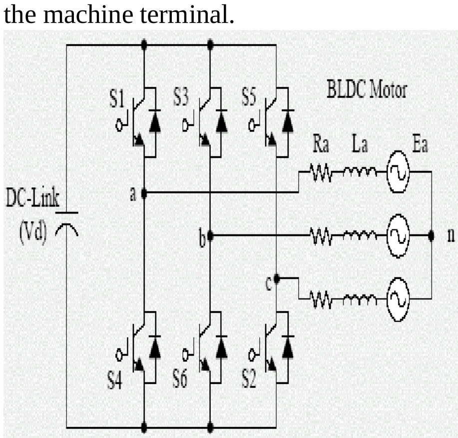


Fig 2 inverter circuit

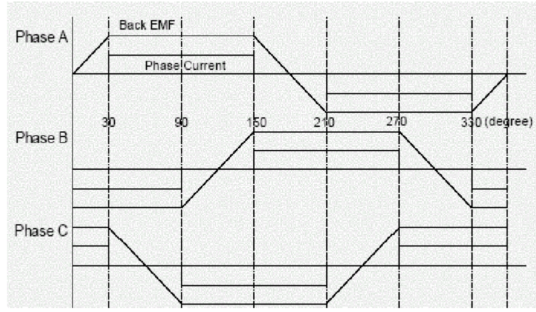


Fig 3 Stator phase voltage and current waveform

Commutation Process

Unlike a brushed DC motor, the commutation of a BLDC motor is controlled electronically. To rotate the BLDC motor, the stator windings should be energized in a sequence. It is important to know the rotor position in order to understand which winding will be energized and following the energizing sequence.

Rotor position is sensed using Hall Effect sensors embedded into the stator. Whenever the rotor magnetic poles pass near the Hall sensors, they give a high or low signal, indicating the N or S pole is passing near the sensors.

Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined. Table 1 shows the switching sequence that should be followed with respect to the Hall sensors. Every 60 electrical degrees of rotation, one of the Hall sensors changes the state. Given this, it takes six steps to complete an electrical cycle. In synchronous, with every 60 electrical degrees, the phase current switching should be updated. However, one electrical cycle may not correspond to a complete mechanical revolution of the rotor. The number of electrical cycles to be repeated to complete a mechanical rotation is determined by the rotor pole pairs. For each rotor pole pairs, one electrical cycle is completed. So, the number of electrical cycles/rotations equals the rotor pole pairs.

ROTOR POSITION	HALL SENSOR SIGNAL			INVERTER SWITCHES					
	Ha	Hb	Hc	S1	S3	S5	S4	S6	S2
0 – 60	1	0	0	1	0	0	0	0	1
60 – 120	1	1	0	0	1	0	0	0	1
120 - 180	0	1	0	0	1	0	1	0	0
180 – 240	0	1	1	0	0	1	1	0	0
240 – 300	0	0	1	0	0	1	0	1	0
300 – 360	1	0	1	1	0	0	0	1	0

Table 1 Commutation Table for Three Phases of BLDC motor.

Three hall sensors are present in the stator of BLDC motor at an angle of 120 deg Electrical. The three hall sensors signals will be coming at an angle of 120 deg electrical. Each hall sensor will give high signal for 180 deg electrical.

There are three hall sensors correspond to three phases of the motor. Let H1, H2, H3 corresponds to phase A, phase B, phase C of Motor respectively. The following figure no 4 show's below the back E.m.f wave forms and hall sensor signals which helps in deriving the commutation logic for driving the BLDC motor.

Back E.m.f wave forms and hall sensor wave forms are given below from which the commutation logic can be built up. Hall sensor will be on if a north pole comes under it. And it will be off if a south pole comes under it. The BLDC motor rotates by the interaction between PM Field of rotor and stator field.

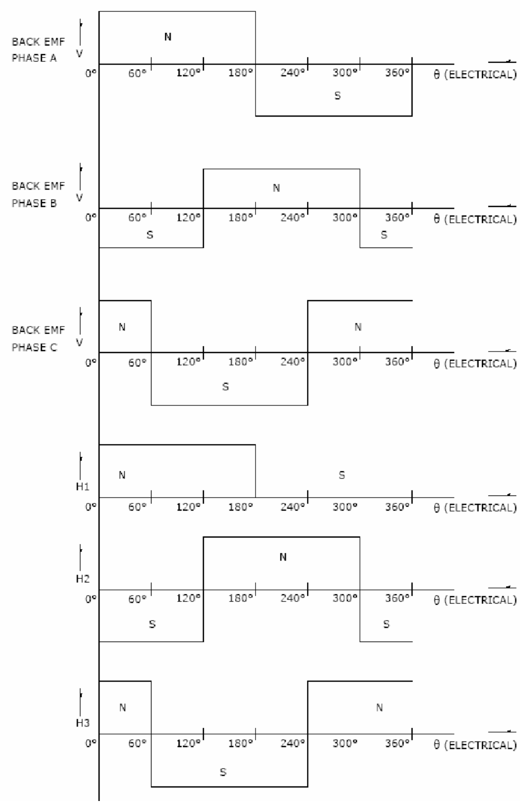


FIG: - 4 BACK E.M.F WAVEFORM

Speed control of a Brushless D.C machine –

BLDC motors are a type of synchronous motor. This means the magnetic field generated by the stator and the magnetic field generated by the rotor rotates at the same frequency. With variable frequency control the synchronous motor may operate in two modes

1.True synchronous mode
2. Self controlled mode.

1) True synchronous mode -

In this mode the supply frequency is controlled from an independent oscillator, as in the case of induction machine. For a given frequency setting, the machine runs at a fixed speed, independent of the variation in load supply voltage and field current. Hence the speed can be controlled precisely in open loop by precisely controlling the frequency.

2) Self control mode –

A permanent magnet motor is generally operated in this mode. A self controlled variable speed drive have number of advantages which make then superior to induction and DC motor variable speed drive. The advantage is that the operation of a BLDC motor in the self controlled mode eliminates hunting and stability problems, and permits the realization of versatile control characteristics of a DC motor without the limitation associated with commutator and brushes, such as limits on the maximum speed, voltage and power, frequent maintenance, inability to operate in contaminated and explosive environment and so on. The self controlled BLDC motor has been built for speeds approaching 20000 rpm, which are beyond the capability of the DC an induction drive.

Operating Principle of BLDC motor.

In self control of BLDC motor as the rotor speed changes, the armature supply frequency is also changed proportionately so the armature field always moves at the same speed as the rotor. This ensures that the armature and rotor fields move in synchronism for all operating points. The accurate tracking of speed by frequency is realized with the help of a rotor position sensor. The switches of the inverter, feeding the motor are fired based on the rotor position. The frequency of the voltage induced in the armature is proportional to the speed.

II **IMPLEMENTATION**

TMS320LF2407 DSP CHIP

Motor drives are traditionally designed with relatively inexpensive analog components. The weaknesses of analog systems are their susceptibility to temperature variations and component aging. Another drawback is the difficulty of upgrading these systems. Digital control structures eliminate drifts and, by using a programmable processor, the upgrades can be easily accomplished by software. Digital Signal Processors go further. Their high performance allows them to perform high resolution control and minimize control loop delays. These efficient controls make it possible to reduce torque ripples and harmonics, and to improve dynamic behavior in all speed ranges. The motor design is optimized due to lower vibrations and lower power losses such as harmonic losses in the rotor. Smooth waveforms allow an optimization of power elements and input filters. Overall, these improvements result in a reduction of system cost and better reliability.

As the first DSP optimized for digital motor control, the TMS320LF2407 is a single chip solution based on a 30 MIPS 16-bit fixed-point DSP core associated with several micro-controller peripherals such as a Pulse Width Modulation (PWM) generator and Analog to Digital Converters (ADC). The block diagram for closed loop position control of BLDC motor is shown in the figure no 6

Open loop speed control of BLDC motor:

The Compare values of Timers and PWM's are implemented in software as shown in above table. This allows the motor to commutate and rotate in the direction as written in the software. The open loop speed control of the motor can be obtained by varying the duty ratio i.e. by varying the values of Timer compares and PWM compares. The motor speed is varied from zero to max by varying the duty ratio in the software.

Closed loop Position control of BLDC motor:

The BLDC motor will be used in electromechanical actuator in the final application. The electromechanical actuator should be controlled in closed loop where only position loop is to be closed in this application. The rotary potentiometer is used as feedback element for closing the position loop.

For implementing closed loop operation two ADC channels of DSP EVM are utilized. Two channels of ADC module are activated and configured through software. Position command is given to one channel and the potentiometer feedback is given to another channel. The digital values of two channels are subtracted in the software to calculate the error. Using a proper proportional gain the error is amplified and duty cycle is modified to drive the motor to desired position until the error becomes zero. The relation between error and duty ratio is

Duty ratio=error*Kp

Where Kp= proportional gain

. The error magnitude determines the duty ratio and error direction will determine the motor direction (reverse or forward). The flow chart for closed loop control is show in the fig 5

Commutation logic implementation in DSP:

From the Commutation table derived above the logic is implemented in the software. The three hall sensors are hard wired to three capture units of DSP EVM. The capture units are configured in the software. The CAPCON register, CAPFIFO register are configured in the Software. The CAPFIFO register is read in the software which gives the status of capture units which gives the status of hall sensors. The table no 2 below gives the different values of CAPFIFO register for different hall sensor status.

S. No	CAPFIFO	Phase Conducting Direction (forward)	Phase Conducting Dir (reverse)	Mosfets to be ON (forward)	Mosfet's to be ON (reverse)
1	256	**AC**	**CA**	Q1+Q6	Q3+Q4
2	4352	**BC**	**CB**	Q2+Q6	Q3+Q5
3	1280	**BA**	**AB**	Q2+Q4	Q1+Q5
4	5120	**CA**	**AC**	Q3+Q4	Q1+Q6
5	4096	**CB**	**BC**	Q3+Q5	Q2+Q6
6	1024	**AB**	**BA**	Q1+Q5	Q2+Q4
7	5376	**Fault Condition**	**Fault condition**	All are off	All are off
8	**90**	**Fault Condition**	**Fault condition**	All are off	All are off

Table no 2

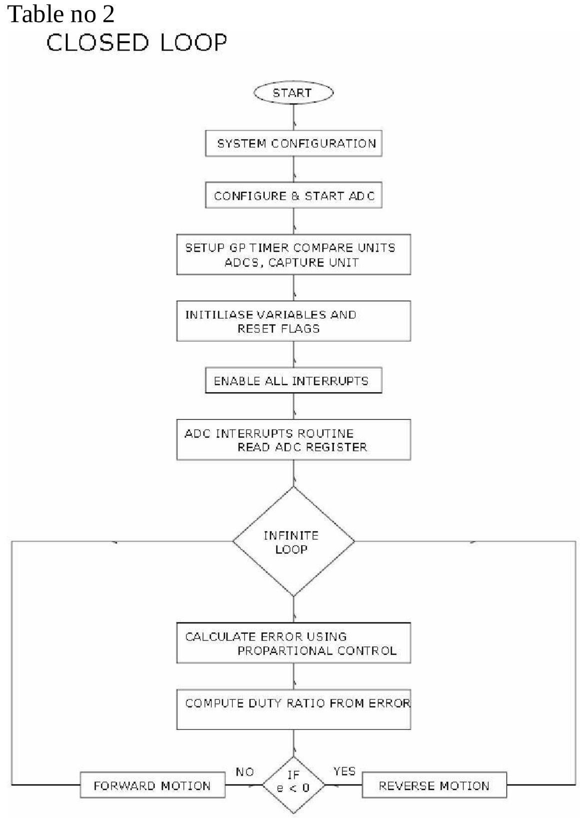


Fig 5 Flow chart of closed loop position control of BLDC motor

Generation of PWM signal:

PWM signals can be generated from GP timers and also from Compare units.

Six PWM channels, 3 Capture units of DSP EVM are used for this purpose.

Hall sensors are hard wired to three capture pins of DSP EVM.

H1 to CAP1

H2 to CAP2

H3 to CAP3

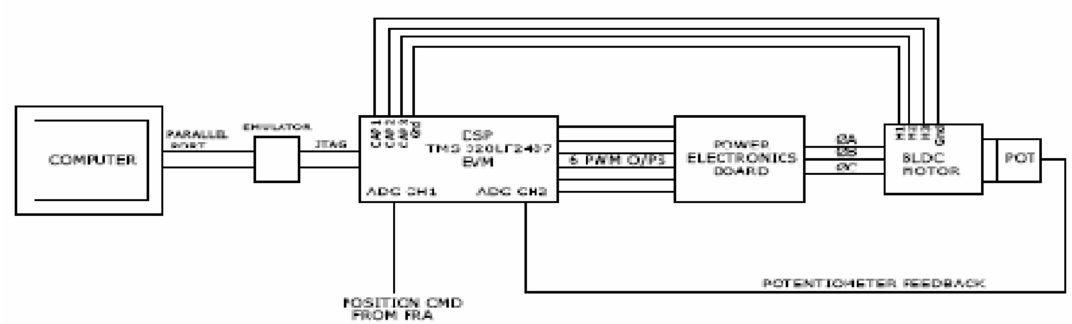


Fig 6 Block diagram of Position control of BLDC Motor

The capture units are configured in the Software to store the events of transitions in CAPFIFO register whenever a transition occurs on the capture pin.

Based on the CAPFIFO register value the state of hall sensor will be determined. Based on the state of hall Sensors the gate signals to the Mosfets are given by DSP in PWM fashion controlled by software. It is explained as follows with the table no 3 below

S.No	CAPFIFO	PHASE Conducting Dir (forward)	PHASE Conducting Dir (reverse)	PWM signals Dir FWD	PWM signals Dir REV
1	256	AC	CA	Cmp1,T3CMP	Cmp3,T1CMP
2	4352	AB	BA	Cmp1,T2CMP	Cmp2,T1CMP
3	1280	BC	CB	Cmp2,T3CMP	Cmp3,T2CMP
4	5120	CA	AC	Cmp3,T1CMP	Cmp1,T3CMP
5	4096	CB	BC	Cmp3,T2CMP	Cmp2,T3CMP
6	1024	BA	AB	Cmp2,T1CMP	Cmp1,T2CMP
7	5376	Fault	Fault	All gates off	All gates off
8	90	Fault	Fault	All gates off	All gates off

Table no 3 commutation table showing CAPFIFO

Speed Control:

The speed control of motor is done by varying the voltage applied to the motor phase winding. The voltage is varied in PWM fashion. The PWM signals are generated by configuring PWM register through software. We are using 3 timers to generate three PWM signals to drive 3 bottom Mosfets and 3 Compare PWM's to drive 3 top Mosfets.

The voltage applied to motor is varied by varying the duty ratio.

III .RESULTS AND DISCUSSION

The digital controller for the BLDC motor has been designed and integrated with the power electronic circuit, motor and tested.

PWM waveform of variable duty cycle has been recorded and shown in the figure. The voltage across phase AB, BC and CA has been recorded.

Fig no 7 Gate wave forms of Q6 Mosfets with 25 % duty ratio

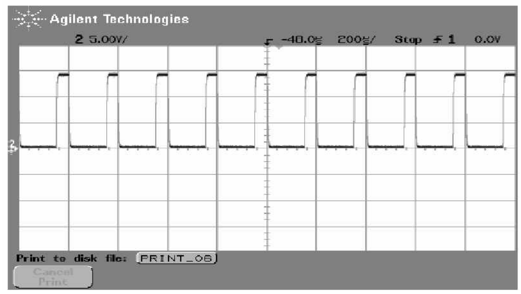


Fig no 8Hall Sensors waveform at different frequency

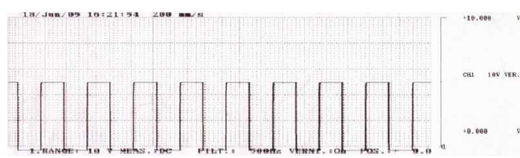


Fig no 9 Voltage across phase AB

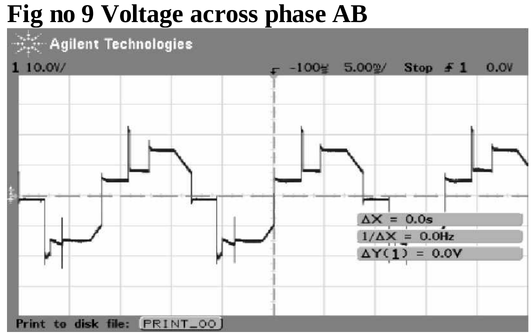


Fig no 10 Voltage across phase BC

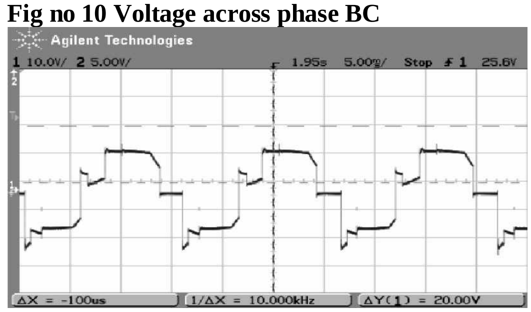
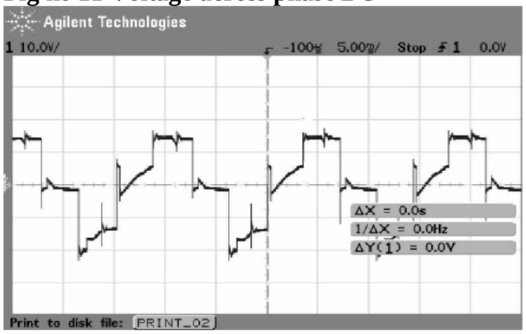


Fig no 11 Voltage across phase BC



Closed loop position commands (triangular waveform) and feedback signals.

Fig no 12 triangular command and its feedback

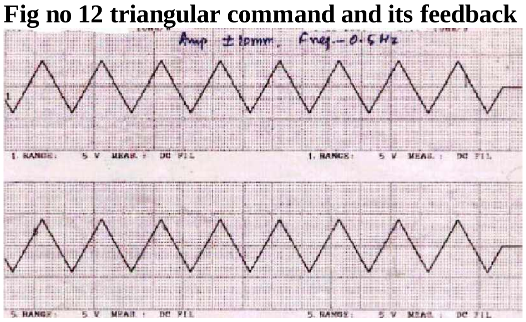


Fig no 13 step command and its feedback

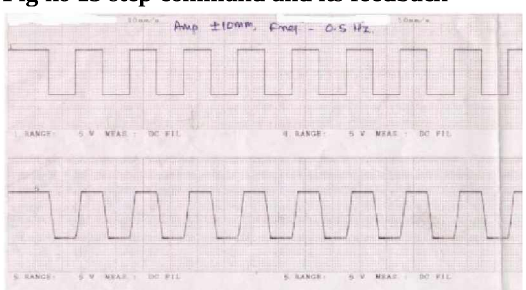
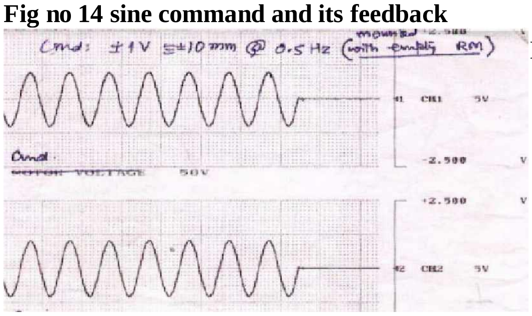


Fig no 14 sine command and its feedback



B.

IV CONCLUSIONS

The design and implementation of a simple, flexible and cost effective digital controller for brush less DC (BLDC) motor has been achieved.

The performance of the machine shows satisfactory performance under no- load and loaded condition.

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