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DESIGN OF WIDE RANGE INPUT BLDC MOTOR DRIVE BASED ON TRAPEZOIDAL CONTROL

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ABSTRACT

This paper deals with the design and development of wide range input Brushless DC (BLDC) motor drive based on trapezoidal control. The proposed drive is designed for a three-phase brushless DC motor to drive in power tool applications, operating from a voltage from 8V to 21V. The design uses a discrete MOSFET-based three-phase inverter, which deliver rms continuous winding current, without the need of external cooling or heat sink and it is proved by the simulation done by LTspice

Keywords: BLDC drive, Motor Drives, PM BLDC, Three phase Brushless Motor, Trapezoidal Control.

I.INTRODUCTION

Power tools are used in various industrial and household applications such as drilling, grinding, cutting, polishing, driving fasteners, various garden tools, and more. The most common types of power tools use electric motors while some use internal combustion engines, steam engines, or compressed air. Power tools can be either corded or cordless (battery powered). Corded power tools use the mains power to power up the AC or DC motors. The cordless tools use battery power to drive DC motors [8]. The brushless motors are more efficient and have less maintenance, low noise, and a longer life. Power tools have requirements on form factor and thermal performance, therefore, high-efficient power stages with a compact size are required to drive the power tool motor.

Conventional DC motors have many attractive properties such as high efficiency and linear torque-speed characteristics.

II.BASIC BLOCK DIAGRAM

Fig. No. 2.1 shows the basic block diagram of wide range input BLDC motor drive based on trapezoidal control. This drive for a three-phase brushless DC (BLDC) motor that can be used in power tools. The design will be compact that implements sensor-based trapezoidal control [9]. The design uses a discrete, compact MOSFET-based three-phase inverter that delivers a continuous winding current without external cooling or heat sink. The cycle-by-cycle overcurrent protection feature protects the power stage from large currents [9].

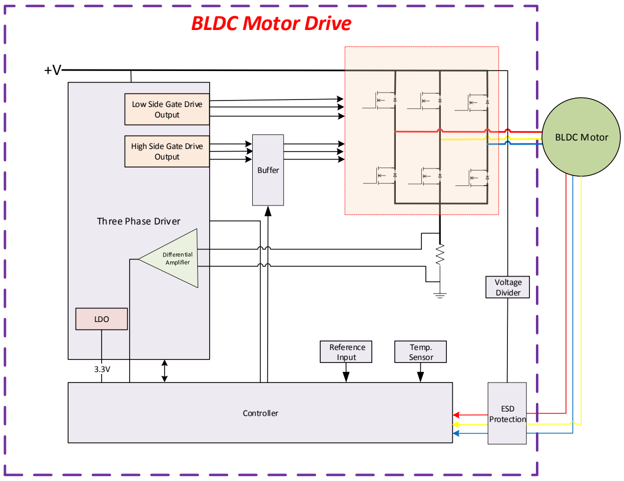

Fig. No.2.1 Basic block diagram

III.CONVENTIONAL BRUSHED DC MOTOR

Designers used brushed DC motors instead of brushless DC motors in past. Conventional DC motors have many attractive properties such as high efficiency and linear torque-speed characteristics. The control of DC motor is also simple and does not require complex hardware. However, the main drawback of DC motor is the need of periodic maintenance [2]. The brushes of the mechanical commutator eventually wear out and need to be replaced. The commutator has other undesirable effects such as sparks, noise and carbon particles coming from brushes. BLDC motor can in many cases replace conventional dc motor. They are driven by DC voltage but current commutation is done by solid state switches [3].

3.1DRAWBACKS

- A Brush DC Motor is less reliable in control at lowest speeds
- A Brush DC Motor is physically larger than other motors producing equivalent torque
- A Brush DC Motor is considered high-maintenance, which is not true of brushless DC motors
- A Brush DC Motor are vulnerable to dust which decreases performance

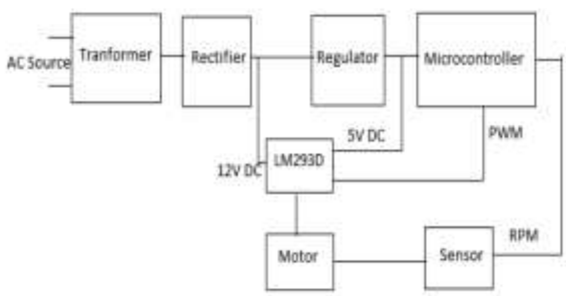

Fig. No. 3.1 Block Diagram for DC motor Speed control

IV.PROPOSED METHOD

The proposed architecture mainly has one power stage, one MCU and one gate driver section. Compared to their brushed-motor counterpart, permanent magnet brushless motors are gaining importance because of their high efficiency, high torque-to-weight ratio, low maintenance, high reliability, low rotor inertia, and more. A brushless permanent-magnet synchronous motor (PMSM) has a wound stator and a permanent magnet rotor assembly [3]. These motors generally use internal or external devices to sense the rotor position. The sensing devices provide position information for electronically switching the stator windings in the proper sequence to maintain rotation of the magnet assembly. The electronic drive is required to control the stator currents in a brushless permanent magnet motor [2]. The electronic drive has the following parts:

- Power stage with a three-phase inverter that has the required power capability
- MCU to implement the motor-control algorithm
- Position sensor for accurate motor-current commutation
- Gate driver for driving the three-phase inverter
- Power supply to power the MCU.

4.1SYSTEM DESCRIPTION

Power tools are used in various industrial and household applications such as drilling, grinding, cutting, polishing, driving fasteners, various garden tools, and more. The most common types of power tools use electric motors while some use internal combustion engines, steam engines, or compressed air. Power tools can be either corded or cordless (battery powered). Corded power tools use the mains power (the grid power) to power up the AC or DC motors. The cordless tools use battery power to drive DC motors. Most of the cordless tools use lithium-ion batteries, the most advanced in the industry [3]. Lithium-ion batteries have high energy density, low weight, and greater life. These batteries have relatively low self-discharge (less than half that of nickel-based batteries) and can provide a very high current for applications like power tools. Cordless tools use brushed or BLDC motors. The brushless motors are more efficient and have less maintenance, low noise, and a longer life. Power tools have requirements on form factor and thermal performance, therefore, high-efficient power stages with a compact size are required to drive the power tool motor [4]. The small form factor of the power stage enables flexible mounting, better PCB layout performance, and a low-cost design. High efficiency provides maximum battery duration and reduces cooling efforts. The high-efficiency requirement must have switching devices with a low drain-to-source resistance (RDS_ON). The power stage should also take care of protections like motor stall or any other chances of high current. The three-phase gate-driver DRV8305 will be used to drive the three-phase MOSFET bridge, which can operate from 4.5 V to 45 V and support a programmable gate current with a maximum setting of 1.25-A sink and 1-A source. The DRV8305 includes three current shunt amplifiers for accurate current measurements that support bi-directional current sensing with an adjustable gain. The DRV8305 has an integrated voltage regulator and controller to support a microcontroller (MCU) or additional system power needs. The SPI provides detailed fault reporting and flexible parameter settings such as gain options for the current shunt amplifier, slew rate control of the gate drivers, and various protection features.

The MSP430G2553 micro controller planning to use for this design. The MSP430G2553 MCU implements the control algorithm in this design. The cycle-by-cycle (CBC) overcurrent protection uses the internal comparator of the MSP430G2553 and external buffer. The test report shows the RMS current capability, peak current capability, and thermal performance of the board and overcurrent protection features such as cycle-by-cycle control and latch control of the DRV8305 [9]. The test results also show the improved RMS current capability of the board with a different air flow

4.2BRUSHLESS PERMANENT MAGNET MOTORS

Permanent magnet motors can be classified according to Back-EMF (BEMF) profiles: a BLDC motor and a PMSM. Both BLDC motors and PMSMs have permanent magnets on the rotor but have different flux distributions and BEMF profiles. In a BLDC motor the BEMF that is induced in the stator is trapezoidal, and in a PMSM the BEMF that is induced in the stator is sinusoidal. Implementing an appropriate control strategy is required to obtain the maximum performance from each type of motor [2]. The BLDC motor or the trapezoidal BEMF motor has the ampere conductor distribution of the stator, which should remain constant and fixed in space for a fixed interval (commutation interval). For a three-phase winding, the commutation interval is 60° electrical [6]. At the end of each commutation interval, the ampere conductors are commutated to the next position. These motors use a two-phase ON control, where two phases of the motor energize at a time and the third winding will open. The principle of the BLDC motor is, at all times, to energize the phase pair that can produce the highest torque. The combination of a direct current with a trapezoidal BEMF makes it theoretically possible to produce a constant torque [4]. In practice, the current cannot be established instantaneously in a motor phase; because of this, the torque ripple is present at each 60° phase commutation. Fig. No. 4.1 shows the electrical waveforms in the BLDC motor in the two phases ON operation.

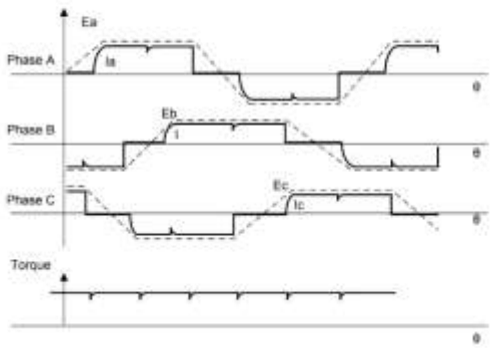

Fig. No. 4.1 Electrical Waveforms in Two-Phase ON Control of BLDC Motor and Torque Ripple

A trapezoidal control has the following advantages:

- Only one current at a time needs to be controlled.
- Only one current sensor is required (or none for speed loop only).
- The positioning of the current sensor allows the use of low-cost sensors as a shunt.

V.BLDC MOTOR-CONTROL INTRODUCTION

The Brushless DC motors have gained increasing popularity in the recent years. BLDC motors have permanent magnets that rotate (rotor) and a fixed armature (stator). An electronic controller is used for motor commutation instead of the brushed commutation used in the brushed DC motors. BLDC motors offer many advantages over the brushed DC motors, which include increased speed vs torque efficiency, longer life (as no brushes are used), noiseless operation, and increased efficiency in converting electrical power to mechanical power (especially because there are no electrical and frictional losses due to brushed commutation). The motor commutation in BLDC motors is implemented by an electronic controller and, to determine the rotor position and to know when to commutate, either Hall sensors (sensored commutation) or the back EMF generated in the stator windings of the motor (sensorless commutation) are used [5]. Sensorless controllers have challenges during motor start-up, as no back EMF is present when the motor is stationary; this is worked around by starting the motor from an arbitrary position; however, this can cause the motor to briefly jerk or even rotate backward during start-up. Hall sensor based controllers are simpler to implement compared to the sensorless control and are used in applications that require good starting torque and that require the motors to run at lower speeds. The sensored motor solutions are especially critical for applications that operate in noisy electrical systems [6]. This application report discusses a Hall sensored commutation control that uses an MSP430 microcontroller as the motor controller. Depending on the number of windings on the stator, BLDC motors are available in 1-phase, 2-phase, and 3-phase configurations. This application report discusses the 3-phase BLDC motor control in both open loop and closed-loop control configurations.

5.1OPEN-LOOP CONTROL

Open-loop control is a simple control system in which the system does not track the output of the process it is controlling. In other words, open-loop control does not use feedback to determine if the output has achieved the intended goal of the input [8]. This type of control is used in systems in which the relationship between input and the resultant state is well-defined and the feedback is not critical. The key advantages of this control system are:

- Simplicity in designing the control system
- Lower cost as the feedback signal chain is not required

5.2BLOCK DIAGRAM

In motor control applications, open-loop control is used to control the speed of the motor by directly controlling the duty cycle of the PWM signal that directs the motor-drive circuitry. The duty cycle of the PWM signal controls the ON time of the power FETs in the half bridges of the motor-drive circuit and this in turn controls the average voltage supplied across the motor windings.

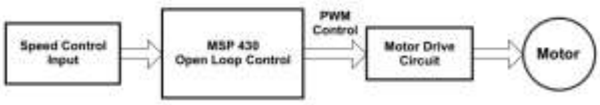

Fig. No. 5.1 Open-Loop Control – Basic Block Diagram

The Speed Control Input unit provides the motor-speed input to the control system [1]. This input can either be analog or digital. Depending on the speed-control input, the open-loop control system implemented in the MSP430 either increases or decreases the PWM duty cycle, which in turn increases or decreases the average voltage or current applied to the motor via the motor-drive circuitry and controls the motor speed accordingly.

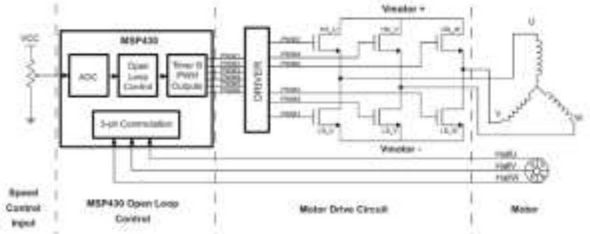

Fig. No. 5.2 Open-Loop Control – MSP430-Based Implementation

1.1. 3-PHASE BLDC MOTOR COMMUTATION

The PWM outputs of the MSP430 are used to control the 3-phase motor commutation, and its duty cycle is used to control the current through the power FETs and motor windings and, in turn, the speed of the motor. In the Hall sensored solution, Hall sensors mounted on the motor reflect the motor position. These Hall sensor signals from the motor are input to the MSP430 to close the commutation loop. The Hall sensor signals are connected to the GPIO input pins with the respective interrupts enabled. On capturing a Hall sensor state change event, the PWM outputs that control the motor-drive circuit are updated according to the commutation sequence [8]. The below table show the 3-phase BLDC motor commutation sequence in accordance with the standard 120˚ commutation using Hall sensors.

State	HALL INPUTS		Active PWMs
	Direction = CW	Direction = CCW	
1	001	110	PWM4, PWM5
2	011	100	PWM2, PWM5
3	010	101	PWM2, PWM3
4	110	001	PWM6, PWM3
5	100	011	PWM6, PWM1
6	101	010	PWM4, PWM1

Table 5.1 Hall Sensor Based Motor Commutation Sequence

1.2. CLOSED-LOOP CONTROL

Closed-loop controls are used in applications that require more accurate and adaptive control of the system. These controls use feedback to direct the output states of a dynamic system. Closed-loop controls overcome the drawbacks of open-loop control to provide compensation for disturbances in the system, stability in unstable processes, and reduced sensitivity to parameter variations (dynamic load variation). A PID controller is a closed-loop control implementation that is widely used and is most commonly used as a feedback controller [3].

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VI.POWER STAGE DESIGN

6.1POWER INPUT TO BOARD

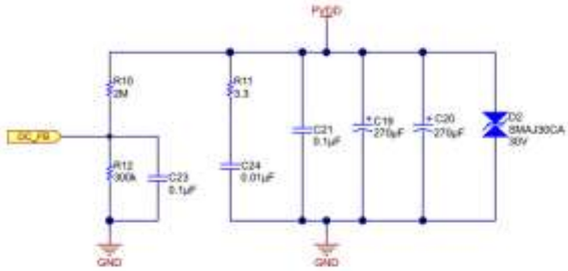


Fig. No. 6.1 Schematic of Battery-Power Input Section

The battery-power input schematic is shown in Fig. No. 6.1. The input bulk-aluminum electrolytic capacitors (C19 and C20) provide the ripple current and the voltage rating is derated by 50% for better life [9]. These capacitors are rated to carry high ripple current. Capacitors C21 and C24 are used as bypass capacitors to GND. D2 is the transient voltage suppression (TVS) that has to be a breakdown voltage of 30 V and a maximum supply voltage of 30 V.

The input supply voltage (PVDD) is scaled using the resistive divider network that consists of R10, R12, C23, and is fed to the MCU. Considering the maximum voltage for the MCU ADC input is 3.3 V. The maximum measurable amount of DC input voltage is calculated by using

$$\mathbf{VDCmax = VADC_{DCmax}\ x\ \frac{(300k\Omega+2000k\Omega)}{300k\Omega}} \qquad \textbf{(1)}$$

$$\mathbf{= 3.3\ x\ \frac{(300k\Omega+2000k\Omega)}{300k\Omega} = 25.3V}$$

Considering a 20% headroom for this value according to above equation, the maximum recommended voltage input to the system is 25.3 × 0.8 = 20.25. For a power stage with a maximum operating voltage of 21 V, this voltage feedback-resistor divider is ideal. Also, this choice of feedback-resistor values gives optimal ADC resolution for a system operating from 5 V to 21 V. The three-phase inverter circuit is shown in Fig. No. 6.1. The current-sensor resistors (R5 and R18) mounted on the DC bus return path measure the DC bus current. Power dissipation in sense resistors and the input-offset error voltage of the op amps are important in selecting the sense-resistance values [9]. The sense resistors carry a total nominal RMS current of 18 A with a peak current of 60 A for 1 second. A high sense resistance value increases the power loss in the resistors. If the current-sense amplifier is used without offset calibration, select the sense resistor so the sense voltage across the resistor is sufficiently higher than the offset error voltage to reduce the effect of the offset error. Select a 0.5-mΩ resistor as the sense resistor and use the below equation to calculate the power loss in the resistor at 18 ARMS.

$$\mathbf{Power\ loss\ in\ the\ resistor = \ IRMS^2\ x\ R_{SENE}} \qquad \textbf{(2)}$$

$$= 18^2 \text{ x } 0.0005$$

$$= 0.162 \text{ W}$$

Fig. No. 6.1 Schematic of Three-Phase MOSFET Inverter

6.2DRV8305 GATE DRIVER

Capacitors C1 and C3 are the AVDD and DVDD decoupling capacitors that must be placed close to the IC. PVDD is the DC supply input; in this case, it is the battery voltage of 10.8 V. A 4.7-µF capacitor (C5) is the PVDD capacitor in this design. Capacitors C12 and C15 are charge pump capacitors for the high-side and low-side gate drivers. The EN_GATE pin of DRV8305 is connected to the MCU and is pulled down by R32. The MCU can enable or disable the gate drive outputs of the DRV8305. Capacitors C2 and C4 are the flying capacitors for charge pumps [9]. The WAKE pin of the DRV8305 is tied to 3.3 V. To control the WAKE pin through the MCU, connect the pin to any digital I/O of the MCU.

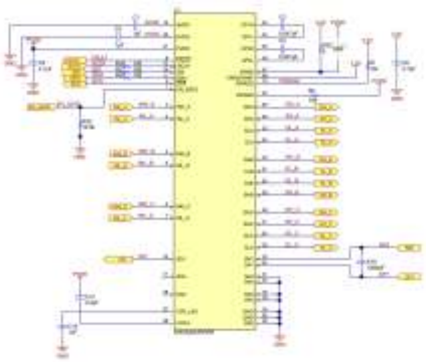
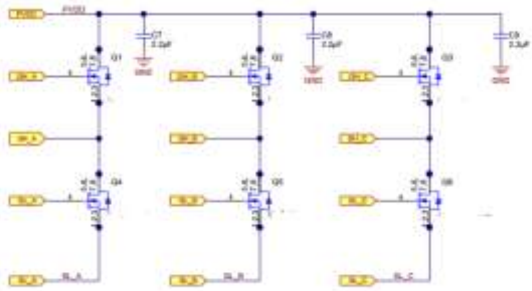


Fig. No. 6.2 Schematic of the DRV8305 gate drive

The DRV8305 gate driver uses a complimentary push-pull topology for the high-side and the low-side gate drivers. The high side (GHx to SHx) and the low side (GLx to SLx) are floating gate drivers that tolerate switching transients from the half-bridges.

6.4HIGH-SIDE GATE SUPPLY

The DRV8305 uses a charge pump to generate the proper gate to source voltage bias for the high-side N channel MOSFETs. Similar to the commonly used bootstrap architecture, the charge pump generates a floating supply voltage that enables the MOSFET [9]. To support low-voltage operation, a regulated triple charge pump scheme is used to create a sufficient VGS to drive standard and logic level MOSFETs during the low-voltage transient. The charge pump regulates the voltage in a tripler mode from 4.4 V to 18 V. Beyond 18 V and up to the maximum operating voltage, the charge pump switches over to a doubler mode to improve efficiency. The charge pump is continuously monitored for under voltage and overvoltage conditions to prevent under driven or over driven MOSFET scenarios.



6.5LOW-SIDE GATE SUPPLY

The DRV8305 uses a linear regulator to generate the proper gate-to-source voltage for the low side N-channel MOSFETs. The Linear regulator generates a fixed 10-V supply voltage with respect to GND. To support low-voltage operation, the input voltage for the VCP_LSD linear regulator is taken from the VCPH charge pump; this allows the DRV8305 to provide a sufficient VGS to drive standard and logic level MOSFETs during the low-voltage transient [9]. The VCP_LSD regulator is continuously monitored of under voltage conditions.

6.6CURRENT SHUNT AMPLIFIER

The DRV8305 includes three high-performance, low-side current-shunt amplifiers for accurate current measurement using low-side shunt resistors in the external half-bridges [8]. The current-shunt amplifiers are commonly used to measure the motor phase current to implement overcurrent protection, external torque control, or external commutation control through the application MCU [1]. The current shunt amplifiers have the following features:

- Can be programmed and calibrated independently
- Can provide output bias up to 2.5 V to support bidirectional current sensing • May be used for either individual or total current shunt sensing
- Four programmable gain settings through SPI registers.
- Programmable output bias scaling. The scaling factor k can be programmed through SPI registers.
- Programmable blanking time of the amplifier outputs
- Minimizes DC offset and drift through temperature with DC calibrating through SPI register.
- Calculate the output of the current-shunt amplifier by using below equation

$$\boldsymbol{Vo = \frac{VREF}{K} - G\,x\,(SN_X - SP_X)} \qquad \textbf{(3)}$$

where

VREF is the reference voltage from the VREG pin
G is the gain setting of the amplifier
k = 2 or 4
SNX and SPX are the inputs of channel x

6.7MOSFET OVERCURRENT PROTECTION

To protect the system and external MOSFET from damage because of high current events, VDS overcurrent monitors are implemented in the DRV8305. The VDS sensing is implemented for both the high side and low-side MOSFETs through the following pins:

- High-side MOSFET: VDS measured between VDRAIN and SHx pins
- Low-side MOSFET: VDS measured between SHx and SLx pins

Based on the RDS_ON of the power MOSFETs and the maximum allowed IDS a voltage threshold can be calculated and, when exceeded, triggers the VDS overcurrent protection feature. The voltage threshold level is programmable through the SPI VDS_LEVEL setting. The VDS overcurrent monitors implement adjustable blanking and deglitching times to prevent false trips because of switching voltage transients. The different VDS sensing protection modes are:

- VDS Latched Shutdown Mode: When a VDS overcurrent event occurs, the device pulls all gate drive outputs low and reports through nFAULT and SPI registers.
- VDS Report Only Mode: When the overcurrent event is detected, the device does not take action related to the gate drivers and reports through nFAULT and SPI registers.
- VDS Disabled Mode: The device ignores VDS overcurrent-event detections and does not report them.

VII.MICROCONTROLLER MSP430

Fig. No. 7.1 shows the schematic for configuring the MSP430G2553 MCU. Capacitors C16 and C17 are the decoupling capacitors. Resistor R8 is used to limit the dv/dt at the supply pin of the MSP430G2553. TI recommends using a 4.7-µF capacitor (minimum) at the DVCC pin. This design uses a 10-µF capacitor at the DVCC pin. A 0.1-µF capacitor has been added to obtain the best performance at a high frequency. Timer A of the MCU is used for PWM generation [2]. This instance of the timer and the corresponding pins are mapped to the high-side switch PWM. This instance of the timer and the corresponding pins are mapped to the low-side switch PWM. This design uses unipolar, trapezoidal BLDC control where the high-side switches switching at a high frequency. The low side switches at the electrical frequency of the motor current that is much lower, and the same side switches at a high frequency (complimentary to high-side switch) during the freewheeling period to enable active freewheeling and low losses [8]. All of the feedback signal voltages including the DC bus voltage, current sense amplifier output, potentiometer voltage for speed control, and temperature sensor output are interfaced to the 10-bit successive approximation (SAR) ADC channels of the MCU.

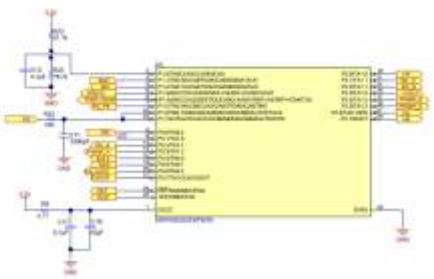


Fig. No. 7.1 MSP430G2553 Schematic

7.1PWM SHUTOFF USING SN74LVC126A

The SN74LVC126A, a quadruple bus buffer gate, features independent line drivers with three state outputs. Each output is disabled when the associated output enable (OE) input is low. To ensure the high impedance state during power up or power down, OE should be tied to GND through a pulldown resistor; the minimum value of the resistor is determined by the current-sourcing capability of the driver. Inputs can be driven from either 3.3-V or 5-V devices. In this design, all of the high-side PWM signals are connected through the buffer [9]. Whenever a current limit happens, all of the high-side PWMs shut off by pulling down the OE of the buffer. The OE of the buffer is connected to the comparator output through a diode (D5) and the current limiting resistor (R26). When the DC bus current reaches the set current limit reference, the comparator output goes low and causes capacitor C30 to discharge through resistor R26 and D5. Once the capacitor discharges below the VIL of buffer, all the buffer outputs will tristate [8]. This means all the high-side PWMs are off and the current falls down. As the current goes below the overcurrent reference threshold, the comparator output goes high (3.3 V), and as the OE voltage is lower, diode D5 will be reverse biased. Next, capacitor C30 charges through resistor R25. When capacitor C30 reaches the VIH of the buffer, the buffer output enables and the high-side PWMs go high [9]. The value of C30 and R25 are designed so the next enable occurs after approximately 50 µs once the OE is disabled. The value of C30 has to be low to ensure that C30 discharges immediately through R26, and this affects the response time of the current limit action.

VIII.SIMULATION RESULTS AND DISCUSSIONS

LTSpice is a high-performance tool for electronics simulation. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. In this chapter, the LTSpice simulation results of conventional and proposed methods were provided and detailed analysis were carried out.

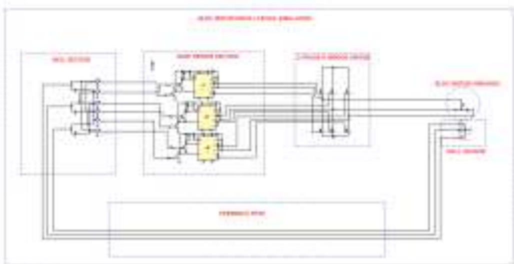


Fig. No. 8.1 Simulation Circuit for BLDC Motor Drive

8.1GATE DRIVER SECTION

For simulating gate driver section, we have selected three half bridge driver ICs and connected accordingly for the H Bridge requirements. This will be replaced be a single IC in actual board. Each driver ICs have boot strap

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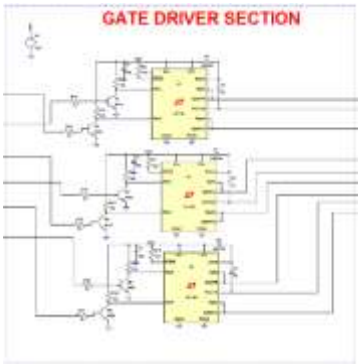

circuits for driving high side section and dead rime protection inbuilt.

Fig. No. 8.2 Gate Driver section

8.2THREE PHASE H BRIDGE

There are six MOSFETs, each one will be driven from the gate driver section. The output of these MOSFETs are going to the motor windings directly.

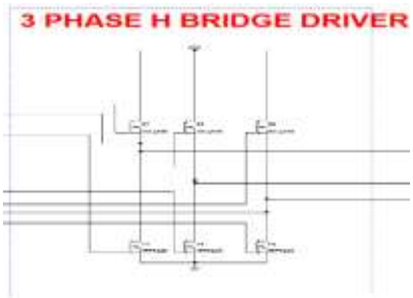

Fig. No. 8.3 3 Phase H Bridge

8.3HALL EFFECT SENSOR

This will give the information which will use to decide which PWM need to enable in next cycle as per Table 1. This decision will be taken by micro controller. Here we have considered three volatge pulse sources for three signals. And PWM pulse width considred only 50%.

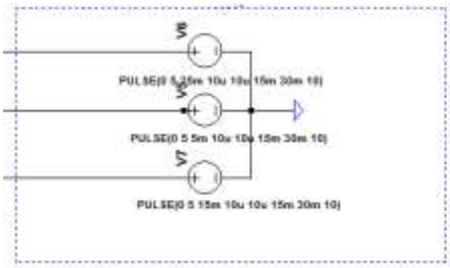

Fig. No. 8.4 Hall Sensor Simulation

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8.4WAVEFORM FOR HALL EFFECT SENOR

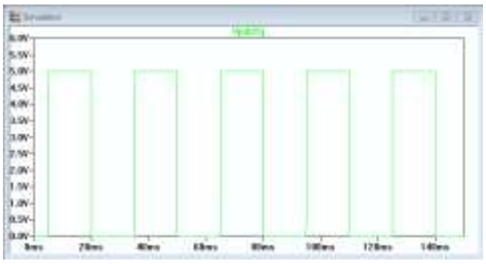

Fig. No.8.5 Hall Sensor winding A output

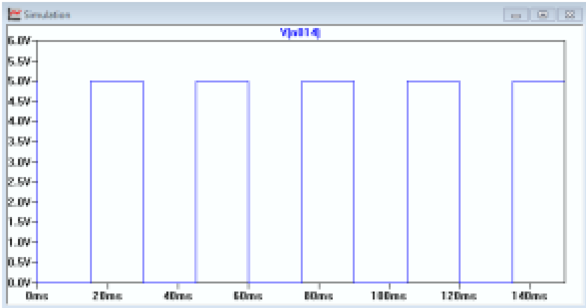

Fig. No.8.6 Hall Sensor winding B output

Fig. No. 8.7 Hall Sensor winding C output

8.5WAVEFORM ACROSS MOTOR WINDINGS

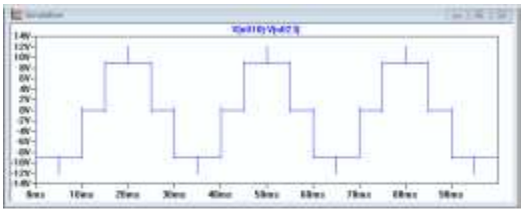

Fig. No. 8.8 Voltage across Winding A

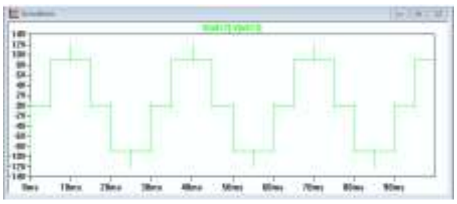

Fig. No. 8.9 Voltage across Winding B

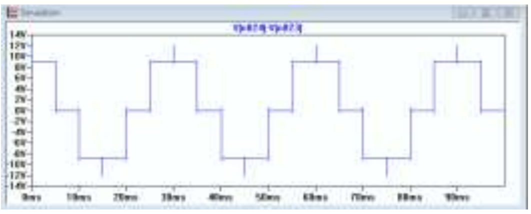

Fig. No. 8.10 Voltage across Winding C

IX.CONCLUSION

In this paper, a method of controlling BLDC motor using an MCU has been discussed. The implementation technique is used to develop an algorithm for motor speed controlling bysensing the position of the motor using a Hall Effect sensor. The BLDC motor will offer more reliability than conventional DC motor. The efficiency of BLDC motor will be higher than a DC motor. So, this will save energy usage than DC motor. There will be an option to adjust the speed of the motor by user. In future, It is planned to make this as a pluggable off the shelf part for industrial and commercial application and the hardware implementation of this paper will be done.

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