



Design Document

BLDC Drive for ECE431

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Abstract:

In 2003, drives and dynos were built to demonstrate brushless dc (BLDC) motors for ECE431 (Electric Machinery) laboratory experiments. They had a number of problems and were not very rugged. A new system was designed in late 2003/early 2004 to replace them. The result is a rugged drive capable of being used for a variety of experiments, and particularly convenient for use with a rugged dynamometer composed of a BLDC motor coupled to a dc permanent-magnet motor.

Document Revision History

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1. Introduction

This project involves a simple three-phase inverter capable of being used for a number of experiments, with a primary emphasis on a BLDC dynamometer. The dynamometer was designed by Scott McDonald and built in the ECE Machine Shop. The drive was designed entirely by Jonathan Kimball. Boards were fabricated by Advanced Circuits; sheet metal was fabricated by eMachineShop, finished by the ECE Machine Shop and silkscreened by the ECE Electronics Shop. Final assembly was performed by Alicia Shepherd, Nathan Brown, and Yongxiang Chen. Troubleshooting instructions were developed by Dustin Kramer.

1.1 Scope

The primary end use of the boxes is for ECE431 (formerly ECE333) use. Therefore, it must be rugged and reliable in an undergraduate lab setting. It must also be easy to debug and repair.

In addition, it is desirable to provide capabilities for use outside the lab in demonstrations and simple experiments. To that end, switching frequency should not be limited to commutation frequency.

The inverter stage is composed of six IRFIZ48N MOSFETs.

1.2 Definitions

BLDC: brushless dc, a type of motor closely related to a permanent magnet synchronous machine. The only difference is the way it is driven (square wave voltage vs. sine wave voltage).

1.3 References

Schematics: SK0014 rev 2

Layouts: PB0014 rev B

Drawings: [PJ0005 rev B](#)



2. Control Design

2.1 Motor Signals

The motor has “Hall effect” outputs spaced 120° electrically. The falling edge of a given Hall signal is aligned to the peak of some line-to-neutral voltage. This is highly inconvenient, since what is desired is alignment to line-to-line voltage.

There is an encoder as well. However, it is 500 pulses per revolution (500 ppr). This is not evenly divisible by three, so it would not be convenient to use for commutation.

The decision was to accept the phase error and synchronize switching events to the Hall effects directly. This means that the inverter output voltage leads the speed voltage by 30° electrical. Some would argue that this is even preferable at high speeds to compensate for inductive effects. Signals were found such that something we call “Hall U” corresponds to the low side of phase 1 being turned on.

2.2 Start-Up

The gate drive used is an IR2130 with the high sides powered by bootstrap. There was previously a problem at start-up. In a switchmode converter, the low-side switch is always turned on eventually. In a motor drive commutated by Hall tracks, there is no guarantee that the low-side switch will ever turn on. To ensure that the bootstrap capacitors get charged, an enable switch was added.

For complete logic, see the schematic (SK0014 rev 2). Essentially, when the enable switch is off, all three low-side switches are turned on. When the enable switch is on, the drive commutates according to the Hall tracks.

2.3 Protection

The IR2130 has built-in overcurrent shutdown. To enable it, a $50\text{ m}\Omega$ current sensing resistor was used in the negative bus. The overcurrent threshold was set at 12 Apk, corresponding to 8.5 Arms, a thermally safe current.

Both power inputs are diode protected. This prevents regeneration, but more importantly protects against reverse polarity power.

2.4 User Interface

For convenience, some signals are brought out to the front panel through BNC jacks. The bus current, as sensed by the overcurrent sensing resistor, is brought out. Scopes should be set on high impedance, 10X probe, and then current will be read directly.

Also, the bus voltage is provided after the protection diode. Again, if the scope is set on high impedance, 10X probe, the bus voltage will be read directly.

The three Hall effects are buffered and brought out to BNCs. This allows students to see the relationship between switching and phase currents.

2.5 Use as a General Inverter



To use the drive as a generic inverter, it is necessary to provide PWM commands. J17 is a DB9 intended for connection to the BLDC motor in the dyno. Complete pin-out is given in the schematic (SK0014 rev 2). Pins 1 and 2 are 5V and ground, respectively, available to run a small external circuit. Pins 7, 8, and 9 are HALLW, HALLU, and HALLV, respectively. As stated above, HALLU high → phase A is low, and similarly HALLV high → phase B low, HALLW high → phase C low.

There are no inherent frequency limitations, although the IR2130 inserts a deadtime of 2.5 μs . If this is a problem, a drop-in replacement, IR2132, is available with a deadtime of 0.8 μs . These drivers also have an inherent delay, see datasheet for complete details. Voltage is limited to the rating of the bootstrap diodes (75 V), the rating of the MOSFETs (55 V), and the rating of the bus capacitors (63 V). To avoid damaging overshoots, the bus voltage should not exceed 40 Vdc.



3. Power Design

3.1 Gate Drive

The gate drive is an IR2130. The circuit is very simple, straight from the data sheet. The biggest detail is the bootstrap supply. The isolation diodes are 1N4148, which are fast but only rated to 75 V continuous.

3.2 Inverter Bridge

The inverter bridge is composed of six IRFIZ48N MOSFETs. These are 55 V, 16 mΩ MOSFETs in a TO-220 Fullpak (fully isolated). Rated θ_{JC} is 3.6 °C/W. These represent a significant step forward in the newer design; the previous version used FETs with approximately 6x the on-state resistance.

3.3 Thermal Design

The best explanation for the failures of the previous version was inadequate thermal design. It was thought that the motor only required a few hundred milliamps. In fact, the motor is rated 2.5 Arms. In light of the higher current requirement, it is obvious that the MOSFETs require some sort of heat sink.

The total power dissipation in the bridge is:

$$P_{tot} = 3I_{rms}^2 R_{ds(on)} + (1.37I_{rms})^2 R_{sense} \quad (1.1)$$

The 1.37 factor accounts for the rectifier action of the control scheme implemented. With the devices used, the approximate power dissipation is:

$$P_{tot} = 0.142 I_{rms}^2 \quad (1.2)$$

The heat sink chosen is the same one used in the FET box (see DD00003, FET Box 2003), an Aavid 62200 extrusion cut to 3.75". Given natural convection, it can dissipate 10 W at a 35°C rise. This calculates to an RMS current limit of 8.4 A, which has been implemented as a peak current limit of 12 A. In this situation, the MOSFET junction temperature rise over the sink temperature is only 2°C, so the current limit yields a steady-state junction temperature of approximately 60°C in the laboratory, an extremely conservative figure.



4. Troubleshooting

Always complete a visual scan over the entire circuit and PCB to look for any visual signs of damage. Look for overheated or burnt components; look for cracked solder joints and bad connections. Check to make sure all snap mounts are securely fastened to PCB jacks.

The motor drive takes a 12V dc input to provide voltage to the numerous IC's in the circuit. VSOURCE in the schematic is 11.0V-12.0V dc, and VCC is a 5V dc supply to power logic IC's and LED's. The 0-24V dc input is to provide voltage to the 3 phase output.

Proper motor drive operation will produce an output waveform like Fig. 1 using the differential probe. BNC outputs U, V and W provide an output of the Hall Effect sensors located in the Brushless DC motor. They should be square waves with their frequency proportional to the speed of the motor.

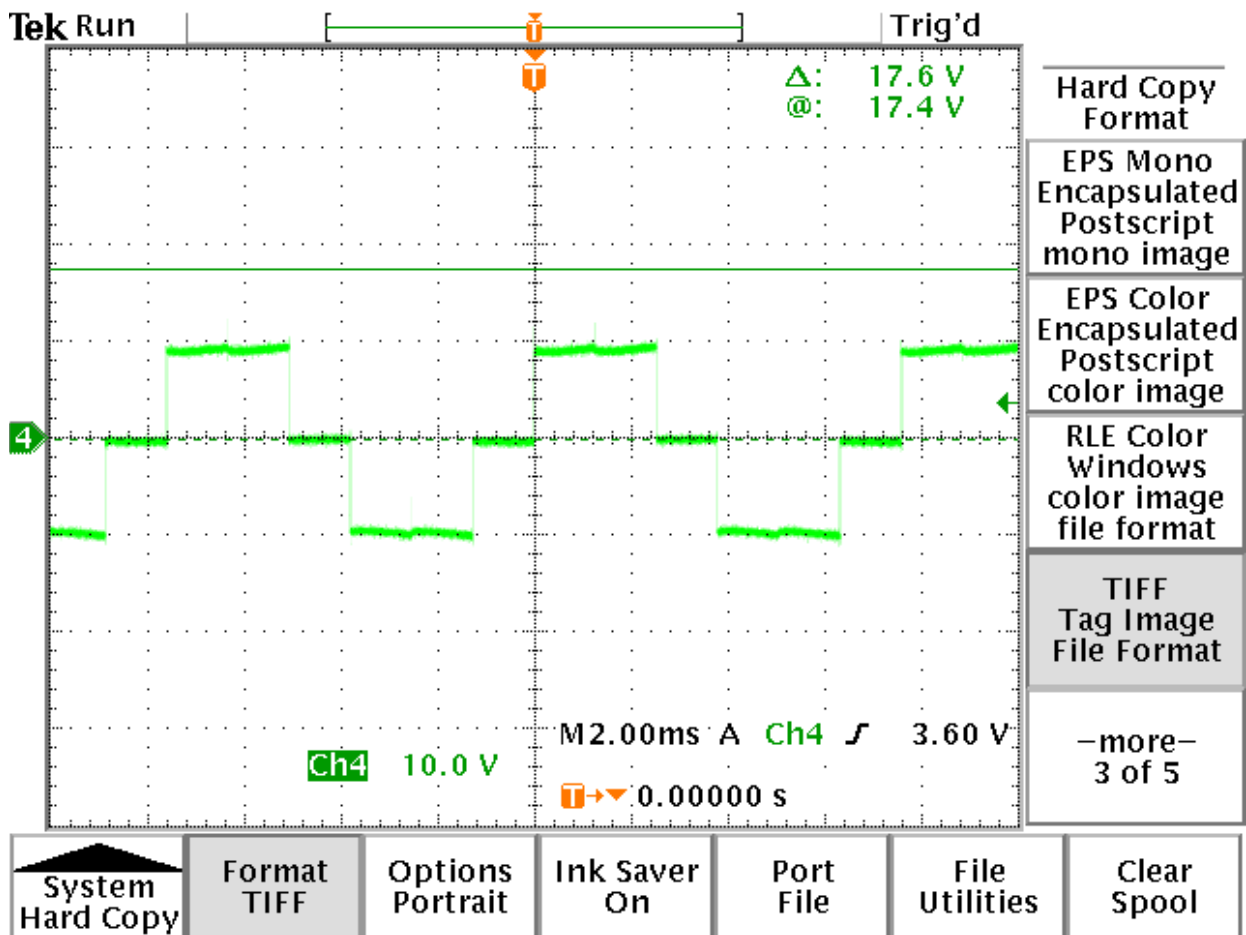


Figure 1: Typical Voltage Waveform, measured with differential probe



4.1 Troubleshooting Flowchart

I. Motor Does Not Operate

1. Is the switch above the green enable LED in the up position?
 - Yes:** Move to number 2
 - No:** Move the switch in the up position and start with number 1.
2. Is a 12V dc supply present at the input terminals labeled 12V?
 - Yes:** Move to number 3
 - No:** Apply 12V dc to input terminals and start with number 1.
3. Is a 0-24 V dc supply present at the input terminals labeled 0-24 V?
 - Yes:** Move to number 4
 - No:** Apply 0-24V dc to input terminals and start with number 2.

II. Faulty Motor Drive Output Voltage. (See Figure 1)

4. Check TP5; is the voltage applied to the input terminals labeled 0-24 V present?
 - Yes:** Move to number 5
 - No:** Is the voltage applied to the input terminals labeled 0-24 V present at J10?
 - Yes:** Check diode D5 (*replace if faulty*)
 - No:** Check the input voltage.
5. Check TP6 is there a square wave with voltage amplitude approximately equal to the input terminals labeled 0-24 V?
 - Yes:** Move to number 6
 - No:** Move to number 8
6. Check TP8 is there a square wave with voltage amplitude approximately equal to the input terminals labeled 0-24 V?
 - Yes:** Move to number 7
 - No:** Move to number 9
7. Check TP10 is there a square wave with voltage amplitude approximately equal to the input terminals labeled 0-24 V?
 - Yes:** Check the Brushless DC Motor.
 - No:** Move to number 10
8. Check TP1 and TP7 is there two out of phase square waves?
 - Yes:** Is resistor R2 and/or R3 open?
 - Yes:** Replace faulty resistor(s)
 - No:** Check transistors Q1 and/or Q4 (*replace if faulty*)
 - No:** Move to number 11
9. Check TP3 and TP9 is there two out of phase square waves?
 - Yes:** Is resistor R4 and/or R5 open?
 - Yes:** Replace faulty resistor(s)
 - No:** Check transistors Q2 and/or Q5 (*replace if faulty*)



- No:** Move to number 12
10. Check TP4 and TP11 is there two out of phase square waves?
Yes: Is resistor R6 and/or R7 open?
Yes: Replace faulty resistor(s)
No: Check transistors Q3 and/or Q6 (*replace if faulty*)
No: Move to number 13.
11. Check pin 2 and pin 5 on IC U1; are pin 2 and pin 5 a pair of out of phase 5V square waves?
Yes: Check the voltage between pin 1 and pin 12 on IC U1; is there approximately 11V dc?
Yes: Replace IC U1.
No: Check diode D4.
No: Move to number 14
12. Check pin 3 and pin 6 on IC U1; are pin 2 and pin 5 a pair of out of phase 5V square waves?
Yes: Check the voltage between pin 1 and pin 12 on IC U1; is there approximately 11V dc?
Yes: Replace IC U1.
No: Check diode D4.
No: Move to number 15
13. Check pin 4 and pin 7 on IC U1; are pin 2 and pin 5 a pair of out of phase 5V square waves?
Yes: Check the voltage between pin 1 and pin 12 on IC U1; is there approximately 11V dc?
Yes: Replace IC U1.
No: Check diode D4.
No: Move to number 16
14. Check pin 5 on logic IC U4; is there a 5V square wave?
Yes: Is pin 6 on logic IC U4 at 0V?
Yes: Move to number 17
No: Check J14 and Switch above enable LED.
No: Check J17 and male connection from motor, (*Hall Effect sensors may be faulty*)
15. Check pin 8 on logic IC U4; is there a 5V square wave?
Yes: Is pin 9 on logic IC U4 at 0V?
Yes: Move to number 17
No: Check J14 and Switch above enable LED.
No: Check J17 and male connection from motor, (*Hall Effect sensors may be faulty*)
16. Check pin 11 on logic IC U4; is there a 5V square wave?
Yes: Is pin 12 on logic IC U4 at 0V?
Yes: Move to number 17



- No: Check J14 and Switch above enable LED.
- No:** Check J17 and male connection from motor, (*Hall Effect sensors may be faulty*)
17. Check the voltage between pins 14 and 7 on logic IC's U4 and U3; is there 5V for the logic gates?
- Yes:** Check operation of logic gates in U4 and U3 (*replace if faulty*)
- No:** Move to number 18
18. Check TP17; is 5V dc present?
- Yes:** Check the foil runs to logic IC's U4 and U3 pins 14 and 7
- No:** Check the following components:
- Diode D6
 - IC U2
 - Diode D4

