

Three-Phase Induction Motor Controller

EECE 496 Final Report



Prepared in partial fulfillment of the requirements for EECE 496

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ABSTRACT

A three-phase induction motor controller system is designed, with an emphasis on hardware, to be used in traction applications with a focus on electric vehicles. Circuitry is designed and external hardware selected to facilitate the control of a variety of induction motors. Control algorithms in firmware are discussed briefly. A working printed circuit board (PCB) is designed and fabricated and preliminary firmware permits the basic operation of a low power motor for proof of concept purposes.

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GLOSSARY

Baud A bitrate (measured in bits per second) used in communication terminology.

Field-Oriented Control A control algorithm for AC induction motors where the torque producing and magnetizing currents are decoupled and controlled independently, allowing precise torque control under varying load conditions.

LIST OF ABBREVIATIONS

AC	Alternating Current
ANSI	American National Standards Institute
DC	Direct Current
kHz	Kilohertz
kW	Kilowatt
IC	Integrated Circuit
IGBT	Insulated-Gate Bipolar Transistor
IO	Input/Outputs
LED	Light Emitting Diode
LQFP	Low-Profile Quad Flat Pack Package
MHz	Megahertz
PCB	Printed Circuit Board
PWM	Pulse Width Modulation
USD	United States Dollars
V/Hz	Volts per Hertz

1 INTRODUCTION

This report details the development of a three-phase induction motor controller intended for use in electric vehicle applications. It presents an investigation into the challenges associated with developing hardware and software for real time motor control applications, and the development of a low cost, modular and scalable motor control system.

The objectives of this project are to develop a hardware and software system capable of driving a low power (approximately $\frac{1}{2}$ horsepower) alternating-current (AC) induction motor at variable speed. The design should be modular so as to allow the eventual scaling of output power to levels more consistent with typical electric vehicles (25kW and higher). Notable project tasks include the design, fabrication and testing of a printed circuit board (PCB), microcontroller firmware, and supporting electronics to form a complete and working system.

The significance of this project is related to the diminishing of fossil fuel sources and environmental concerns about ever-increasing greenhouse gas levels. As a clean and efficient method of personal transportation, electric vehicles are becoming a promising solution for a more environmentally friendly future. One of the major components for an electric vehicle is the motor controller, whose operation is integral to the overall performance of the vehicle. The controller is typically a complex and often expensive subsystem, and developing a non-

commercial but economical controller would be an excellent testament to the feasibility of electric vehicle development. For reference, a 37 kW inverter¹ for electric vehicles has a manufacturer suggested retail price of approximately \$4300 USD. The inverter developed in this EECE 496 project was completed at a budget of well under \$1000 USD and should be capable of driving similar output power levels.

The project began development in late 2012 during which time general research began and feasibility studies were performed. Basic system components were picked during this time, which allowed for accelerated hardware development during the term. A high level hardware and firmware design was also completed in preparation for the bulk of the work. The project began from scratch and has evolved into a working prototype over the period of approximately six months.

The project focusses primarily on the development of the electronics and to a lesser extent firmware to support the operation of an induction motor. To limit the project to reasonable goals given the timeframe, an enclosure was not produced and the appropriate waterproofing, vibration testing, etc. that would be required of a proper electric vehicle motor controller were neglected. Included in the report will be the relevant details of the design with a focus on the control electronics.

¹ http://www.ewwest.com/catalog/product_info.php?cPath=1&products_id=103

The report is comprised of the following primary sections: design overview, system integration, results and conclusion.

2 DESIGN OVERVIEW

In this section, the various designs created in this project are documented and described in moderate detail. An emphasis is placed on the circuit design as the project was intended mostly as an exercise in electronics development. The design overview is broken into sections focussing on the circuit design, PCB design and firmware design.

2.1 Circuit Design

The circuit design was broken into subsections, designated the power supplies, microcontroller, current sensing, input and outputs (IO) and output drivers. A diagram taken from the schematics depicting the interconnections may be seen below in Figure 1.

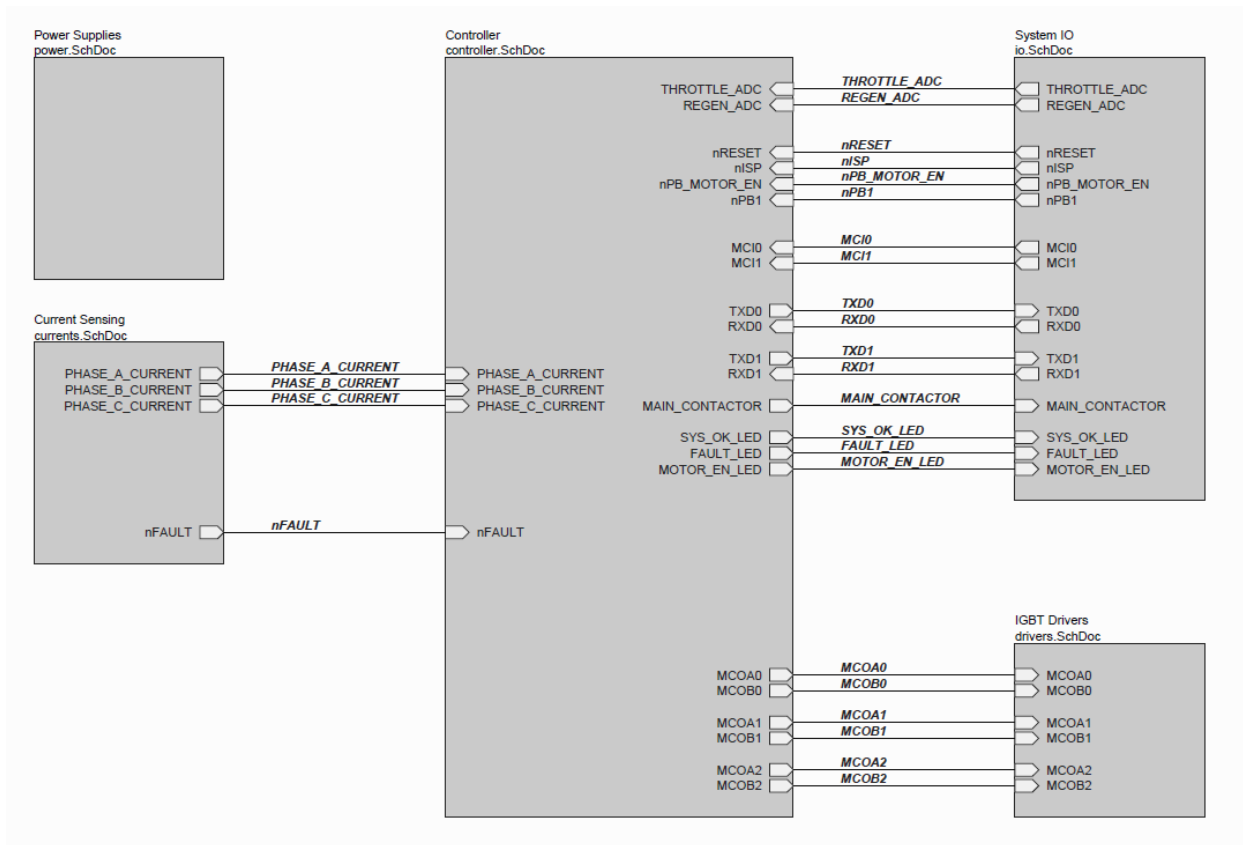


Figure 1: A diagram depicting the interconnections between the circuit subsections

2.1.1 Power Supplies

There are a total of four power supplies utilized for the control board and six isolated power supplies for the driver stages – one for each individual IGBT. The input power supplied to the PCB is intended to be an automotive 12VDC supply (usually around 13.8V nominal). The control board electronics, including the microcontroller and other discrete integrated circuits (ICs) operate on +3.3V. The motor shaft encoder operates on +5.0V and the current sensors require +/- 15V for operation. Each IGBT driver uses a 12V input to 24V output isolated converter and

generates +15V and -8.4V. These two voltages are used to rapidly turn the IGBTs on and off respectively. The power supply topology may be seen below in Figure 2.

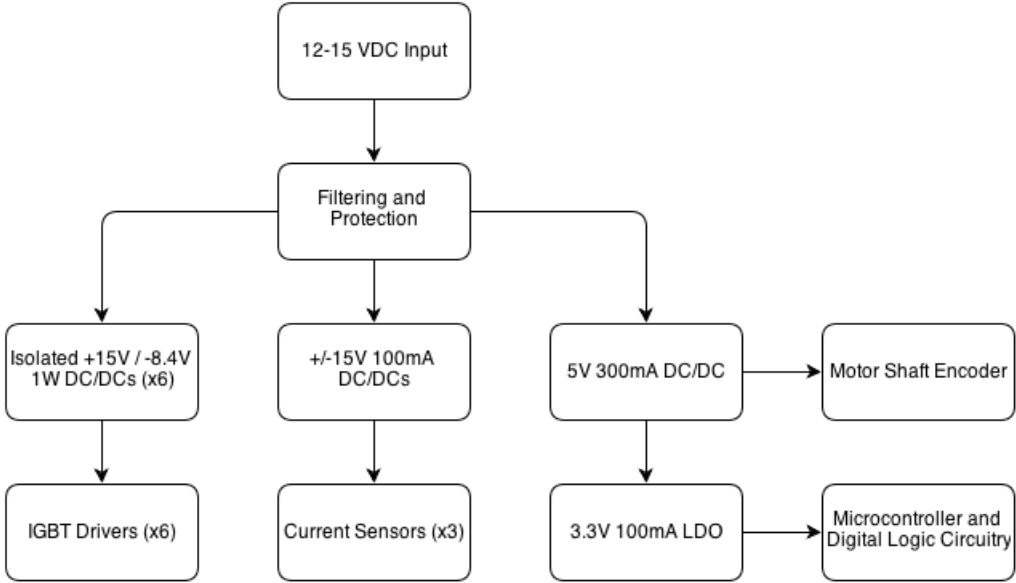


Figure 2: A diagram depicting the power supply topology

Power supply requirements for the +5.0V and +3.3V rail are exclusively logic and should each be well under 100mA. For this reason, 500mA and 300mA supplies were chosen respectively for the +5.0V and +3.3V rails to provide headroom for additional test circuitry. The requirements for the positive and negative 15.0V supplies were 25mA per current sensor per rail, totalling 75mA each. The supplies were designed to handle 100mA accordingly. The IGBT driver supplies were required to be able to drive large IGBTs at switching frequencies up to approximately 15kHz. The current required to do this is calculated using equations from [1] as follows:

$$I_{gate} = Q_G * f_{sw}$$

$$I_{gate} = 15nC * 15kHz$$

$$I_{gate} = 225\mu A$$

Since we are using one power supply per IGBT, and the IGBT selected has a relatively small gate charge Q_G , our average gate current requirements are very small. To utilize off-the-shelf components, the VLA106-15242 isolated DC/DC converter was chosen as it can provide an ample 100mA of output current at +15V and -8.2V.

2.1.2 Microcontroller

The microcontroller for this project had several key requirements:

- Dedicated three-phase hardware PWM outputs
- A fast (75MHz or higher) processor core
- Good ANSI C support and a large online community
- Sufficient (at least five) analog-to-digital converters

To meet all of these requirements, an NXP LPC1769 120MHz microcontroller was selected. This 32-bit ARM Cortex-M3 based microcontroller has a wide variety of peripherals in addition to

the aforementioned required ones – including Ethernet, USB and a wide selection of communication protocols. The device is an integrated circuit (IC) available in a 100-LQFP surface-mount package. For more device information, see the product webpage².

2.1.3 Current Sensing

For purposes of fault protection and use in advanced control algorithms (including Field-Oriented Control), it was decided to employ current measurements on each of the three motor phases. This was implemented using hall-effect sensors, specifically the LEM HAL 300-S series of isolated -300 to +300A sensors. The three sensors with custom wiring harnesses may be seen below in Figure 3.

² http://www.nxp.com/products/microcontrollers/cortex_m3/LPC1769FBD100.html



Figure 3: The HAL 300-S current sensors

The interface circuitry consists of a level shifter to convert the -4 to +4V linear output from the sensors to a microcontroller-compatible 0 to 3.3V, followed by an RC low-pass filter for light noise filtering. The schematic diagram of the interface circuit may be seen below in Figure 4.

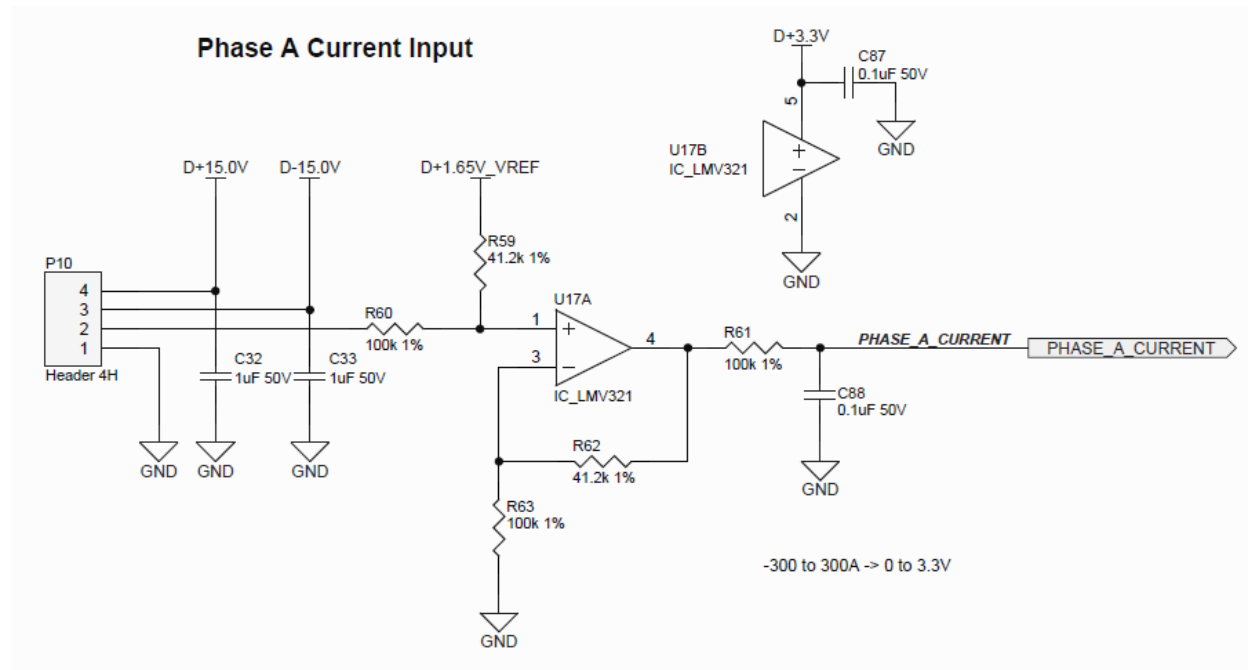


Figure 4: Current sensor interface circuitry

There is also an overcurrent protection circuit designed to shut down the output drivers in the event of an external fault. If any of the phase currents is measured over a set threshold, the microcontroller receives a signal to immediately turn off the motor PWM. The overcurrent trip level is set using the potentiometer R71 (see the schematics in the Appendix B).

2.1.4 Inputs and Outputs

The PCB features several inputs and outputs, namely:

- Inputs

- +12VDC input power supply
- Throttle and regeneration potentiometers
- Four pushbuttons (reset, program, motor enable, and auxiliary input)
- Three current sensor inputs
- A motor shaft encoder input
- Outputs
 - Main contactor control (to control main breaker to motor)
 - Four LEDs for debugging purposes
 - Six IGBT gate signals

The board also has a Bluetooth serial module³ facilitating two way communications with a host computer for remote microcontroller programming, debugging and diagnostic purposes. It communicates using the standard serial protocol at 115200 baud with 8 parity bits and 1 stop bit.

2.1.5 Output Drivers

The output driver circuitry consists of six independent drivers, each including an isolated power supply, low-side driver IC, and basic transient spike protection for the IGBT gate. The IGBT gates

³ <https://dx.com/p/jy-mcu-arduino-bluetooth-wireless-serial-port-module-104299>

are each switched on and off using +15V and -8.2V respectively through a 12A low-side gate driver IC, the MIC4451⁴. The drivers may be seen on page 3 of the schematics in Appendix B.

2.2 PCB Design

To combine the required circuits onto a compact and reliable medium, a PCB was designed and manufactured. It features a 0.062" thickness, 0.006" minimum trace width and spacing, 0.015" diameter via holes and solid top and bottom ground planes. The PCB is a two-layer design and measures 7.00" by 5.85". The completed PCB may be seen below in Figure 5.

⁴ <http://www.micrel.com/PDF/mic4451.pdf>

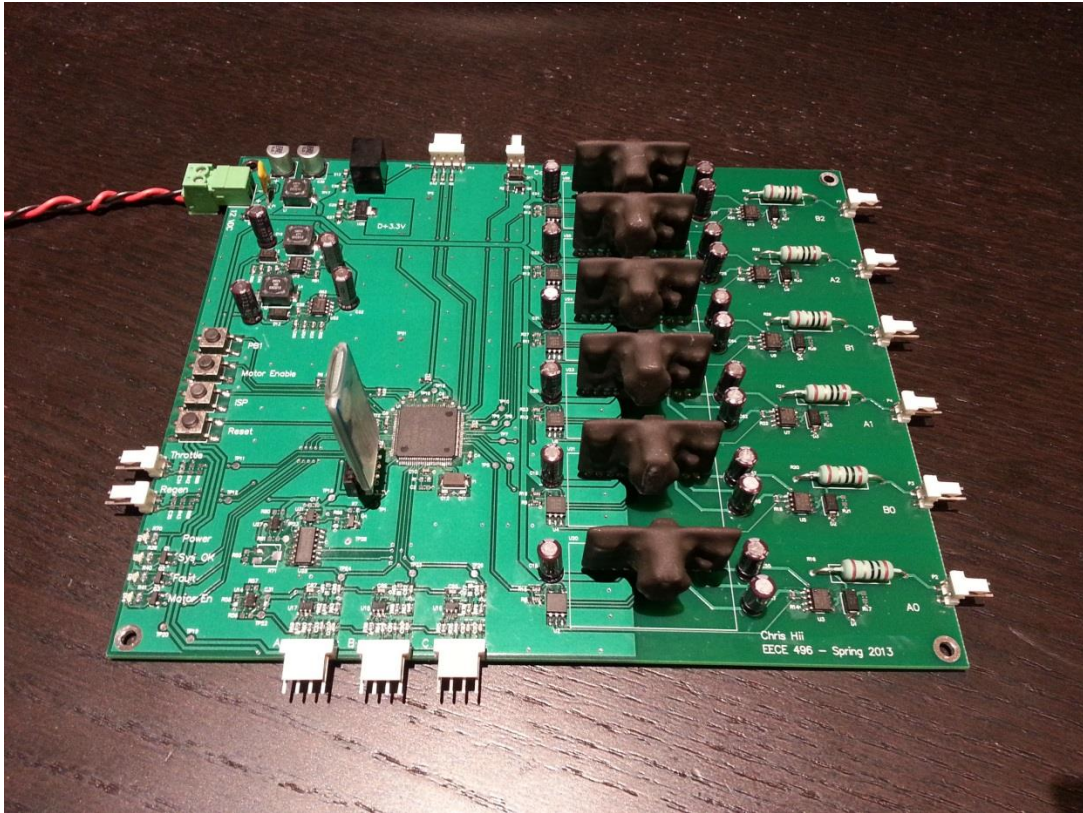


Figure 5: The completed PCB

The left side of the PCB is dedicated to the microcontroller and non-isolated power supplies. The pushbutton inputs, throttle and regeneration potentiometer inputs are also interfaced on the left side of the PCB. The right side of the PCB contains the individual IGBT drivers, each referenced to their own local (isolated) ground plane. The top side of the PCB contains the motor shaft encoder input connector and the main contactor control output connector. The six isolated DC/DC converters may be seen running vertically approximately down the center. This topology provides good analog noise resilience, low noise coupling from the drivers to the logic section, simple routing and ease of external connections.

2.3 Firmware Design

The firmware requirements for an AC motor controller are typically complex. In this case, ideal firmware would provide smooth operation of the motor at speeds from standstill to the motor's maximum rated speed. The motor torque would be controlled to be directly proportional to the desired throttle setting, using a control algorithm known as Field-Oriented Vector Control as described in the Texas Instruments application note [2]. This control algorithm allows precise control of both the motor torque producing current and magnetizing current by using the phase currents and motor speed (as reported by the shaft encoder) as inputs. Many implementations of Field-Oriented Control exist for microcontroller platforms, and a Texas Instruments reference [3] was used in the development of the firmware for this project. An alternative form of control, known as scalar control or Volts per Hertz (V/Hz), simply controls the target speed of the motor without directly controlling the torque. It maintains a fixed ratio between applied voltage and frequency to maintain approximately equal motor flux at different speeds. Due to time constraints, the latter form of control was adopted for the purposes of evaluating the hardware. To illustrate the difference in complexity, see Figure 6 (borrowed from [2]) and Figure 7 for control scheme illustrations of Field-Oriented Control and scalar control respectively.

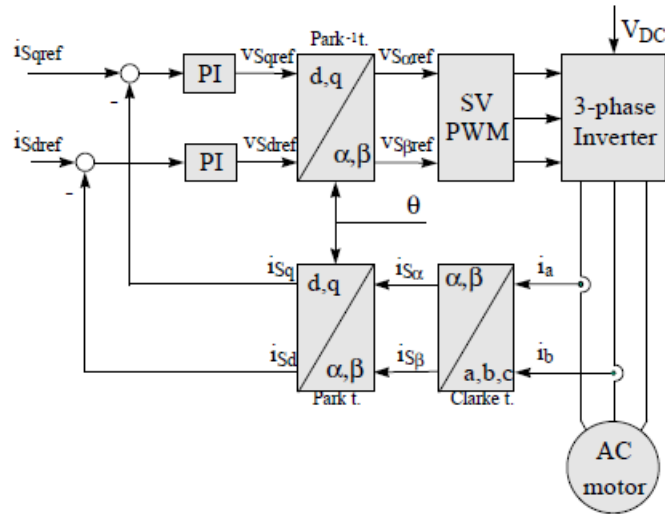


Figure 6: Control scheme for Field-Oriented Control algorithm

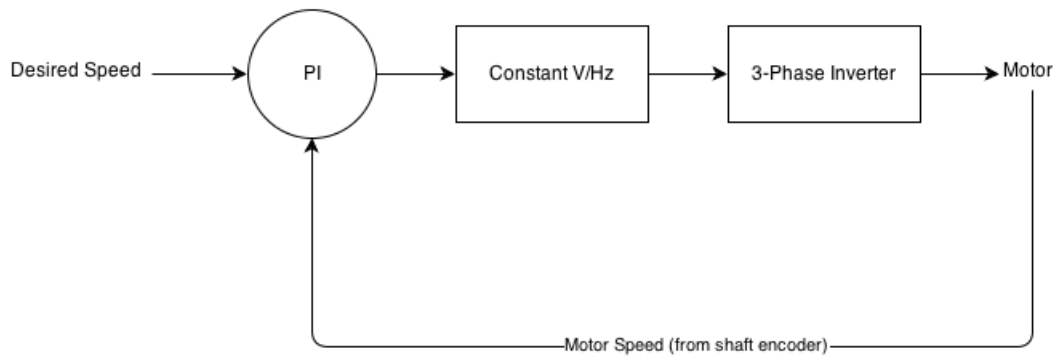


Figure 7: Control scheme for scalar control algorithm

Unfortunately, due to the amount of time required to complete the hardware portion the firmware remains incomplete and features only basic on/off control of the motor at a fixed speed for evaluation purposes.

3 SYSTEM INTEGRATION

The motor controller required custom hardware to be developed in order to meet the project requirements. The circuitry described in Section 2.1 was designed onto a printed circuit board (PCB). A power stage was selected and utilized externally from the PCB. Basic firmware was employed for system testing. A laboratory power supply and some miscellaneous protective devices (such as fuses) were also used. A system diagram and description of the power stage are presented below.

3.1 System Diagram

A high level drawing of the system may be seen below in Figure 8.

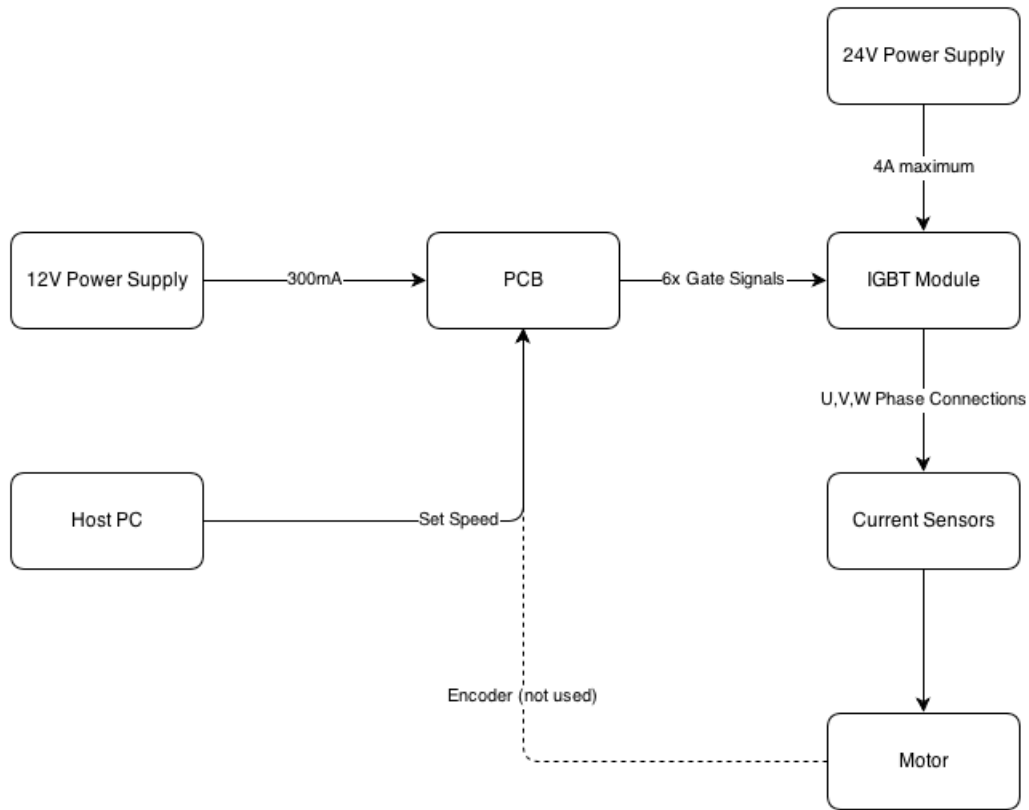


Figure 8: A high level system diagram of the motor controller

The PCB may be considered the center of the system and was connected to a 12V power supply, a host PC for controlling the system, the current sensors, and the IGBT module. For testing and safety purposes a laptop 24V power supply was used to power the motor as it was current limited to approximately 4A. The phase currents were measured for fault protection only and not used in the motor control algorithm. A motor shaft encoder was not used.

3.2 Power Stage

The system was designed to accommodate a wide variety of IGBTs so as to allow scalability. The IGBT pack chosen for testing is a FUJI 600V 100A six-in-one module (part number: 6MBI 100L-060) containing three high-side and three low-side drivers in one physical package. This allows for a simpler physical layout during testing. The IGBT module may be seen below in Figure 9, with its schematic is shown in Figure 10.



Figure 9: The FUJI IGBT module

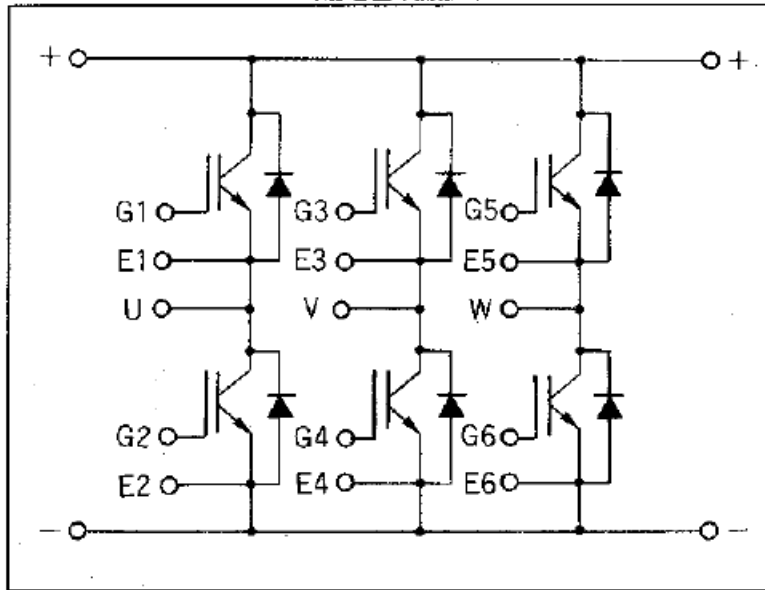


Figure 10: Schematic diagram of the FUJI IGBT module

4 RESULTS

During the course of this project there were many realizations of the various challenges in developing real-time motor control hardware and software. The system evaluation, tasks completed and not completed, problems faced, and recommendations for future developments are discussed below.

4.1 System Evaluation

From a system evaluation standpoint a rudimentary system has been completed. The hardware produced is functional and capable of driving a wide range of motors, but the firmware is limited to operation at fixed speeds. The control electronics, under normal operating conditions, run at 12V input voltage drawing approximately 300mA. This indicates an operating power consumption of 4W – very low when compared to other typical car loads such as headlights (approximately 55W each). A proper system evaluation would be required after completion of more capable firmware to document the performance of the motor under varying load conditions. At present the system can only operate a motor at a fixed speed, making performance measurements unavailable.

Budget-wise all the necessary components were purchased and the PCBs fabricated at a grand total cost of \$555.70 CAD, well under the estimated \$1000. See Appendix A for the project budget.

4.2 Tasks Completed

During the course of the term, the largest accomplishment was the design and fabrication of the circuits and PCB. The PCB in conjunction with the external hardware facilitates the operation of a range of electric motors, currently restricted only by firmware limitations. The selection of external hardware (current sensors and IGBTs) was also a major task completed. Communication with the microcontroller, sensing of the motor phase currents, hardware overcurrent protection and proper driving of the IGBT drivers have all been completed. Rudimentary working firmware was completed to allow operation of a motor at fixed speeds.

4.3 Tasks Not Completed

The complete algorithm for Field-Oriented Control was written but is not functional at the time of writing. The largest task that remains to be completed is the development of firmware capable of controlling the motor torque directly (Field-Oriented Control).

A suitable motor shaft encoder also needs to be sourced, as it will be required for utilization of the Field-Oriented Control algorithm.

4.4 **Problems Faced**

It was found during the course of this project that the firmware design and development presented the largest challenges. Due in part to my past experience with hardware design and unfamiliarity with fast, floating-point math operations in a microcontroller environment I found the hardware development to be much more straightforward.

The only major problem faced in hardware development was the necessary removal and replacement of the microcontroller due to incorrect orientation during initial soldering. Lacking the tools to professionally reflow the 100-pin surface mount IC, I used a candle and a jig to hold the PCB above the flame, heating the board underneath the microcontroller until the solder melted and I was able to remove the IC.

The largest problem faced in firmware development was the inability to debug the system due to its real time nature. A conventional approach of stopping throughout the program and

inspecting variables is unfeasible in a motor control application as the firmware must constantly update whilst the motor is spinning. This severely slowed firmware development to the point where only rudimentary firmware was able to be produced.

4.5 Future Development

The hardware platform combined with larger IGBT modules should allow for much scalability in terms of output power. Two recommended additions to the hardware design are the implementation of temperature sensing (for the IGBT module and motor) for safety purposes. This would allow an over-temperature condition to be detected and the output drivers to be disabled to prevent damage to the components or fire.

Much firmware development is needed, namely completion of the Field-Oriented Control algorithm and tuning of the parameters for smooth operation. The lack of proper firmware is certainly the limiting factor of this system at the present, and much stands to be gained from further development.

5 CONCLUSION

The design of a three-phase motor control system has been documented with design details, integration information and results discussed. Designs were produced for the required circuitry to operate a three-phase motor and implemented on a working PCB. Rudimentary working firmware was developed for purposes of hardware evaluation, with much of the required source code for Field-Oriented Control written but not completed. It has been shown that a low-cost, modular and scalable motor control system can be developed in a period of less than a year at a cost of well under \$1000 USD, with the exception of complete firmware. Given further development with a heavy emphasis on firmware, I believe this system is proof-of-concept for an affordable electric car motor controller.

REFERENCES

- [1] M. Hermwille. (2007, October 31). IGBT Driver Calculation (Application Note) [Online]. Available: [http://www.semikron.com/skcompub/en/AN-7004 IGBT Driver Calculation rev00.pdf](http://www.semikron.com/skcompub/en/AN-7004%20IGBT%20Driver%20Calculation%20rev00.pdf)
- [2] Texas Instruments. (1998, January 1). Field Orientated Control of 3-Phase AC-Motors (Application Note) [Online]. Available: <http://www.ti.com/general/docs/litabsmultiplefilelist.tsp?literatureNumber=bpra073>
- [3] Texas Instruments. (1998, March 1). Implementation of a Speed Field Orientated Control of Three Phase AC Induction Motor using TMS320F240 (Application Note) [Online]. Available: <http://www.ti.com/sc/docs/psheets/abstract/apps/bpra076.htm>

APPENDIX A – PROJECT BUDGET

Date	Item	Qty	Price (ea)	Shipping + Tax	Total	Source	Notes
8-Jan-2013	Fuji IGBTs (600V 100A)	2	\$31.00	\$36.31	\$98.31	eBay - aesurplusinc 270926337143	
	LEM HAL-300 current sensors	3			\$30.00		
31-Jan-2013	Digikey Parts for Rev A (mostly PCB components)	1	\$102.66	\$21.28	\$123.94	Digikey	Invoice #40807347
1-Feb-2013	PCB Rev A	2	\$33.00	\$21.14	\$87.14	33each.com - amount in USD	Order #823900
6-Feb-2013	Newark Parts for Rev A (incl. VLA106's, fuses, etc.)	1	\$124.04	\$23.84	\$147.88	Newark	Order #954922832
6-Feb-2013	5uF film capacitors	10	\$1.00	\$6.60	\$16.60	Daniel Hall - through eBay	
12-Mar-2013	Digikey Parts - replacement LPC1769 (x2) and a couple other components	1	\$38.28	\$13.55	\$51.83	Digikey	
				Total:	\$555.70		

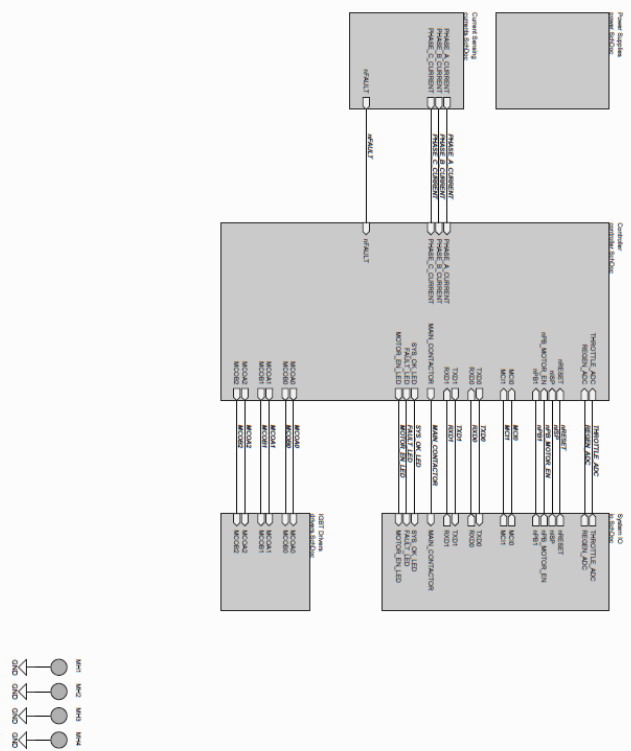
APPENDIX B – SCHEMATICS

AC Induction Motor Controller

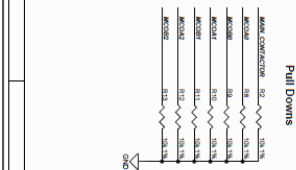
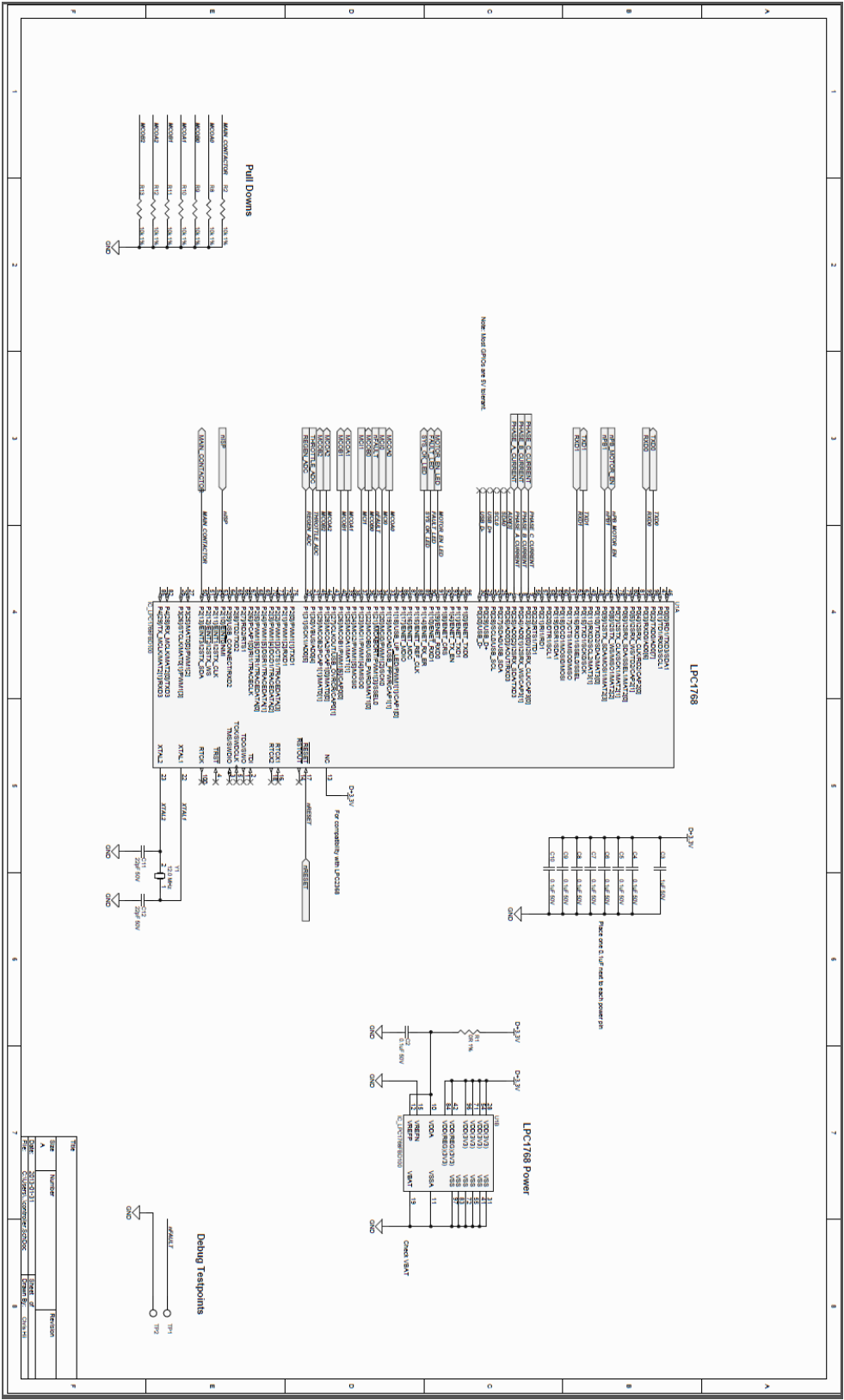
Revision A

Chris Hill

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REV	DESCRIPTION	DATE	BY
1	INITIAL RELEASE	01/15/2010	CHRIS HILL
2	REVISED TO ADD M1-M100	01/15/2010	CHRIS HILL
3	REVISED TO ADD M101-M200	01/15/2010	CHRIS HILL
4	REVISED TO ADD M201-M300	01/15/2010	CHRIS HILL
5	REVISED TO ADD M301-M400	01/15/2010	CHRIS HILL
6	REVISED TO ADD M401-M500	01/15/2010	CHRIS HILL
7	REVISED TO ADD M501-M600	01/15/2010	CHRIS HILL
8	REVISED TO ADD M601-M700	01/15/2010	CHRIS HILL
9	REVISED TO ADD M701-M800	01/15/2010	CHRIS HILL
10	REVISED TO ADD M801-M900	01/15/2010	CHRIS HILL
11	REVISED TO ADD M901-M1000	01/15/2010	CHRIS HILL

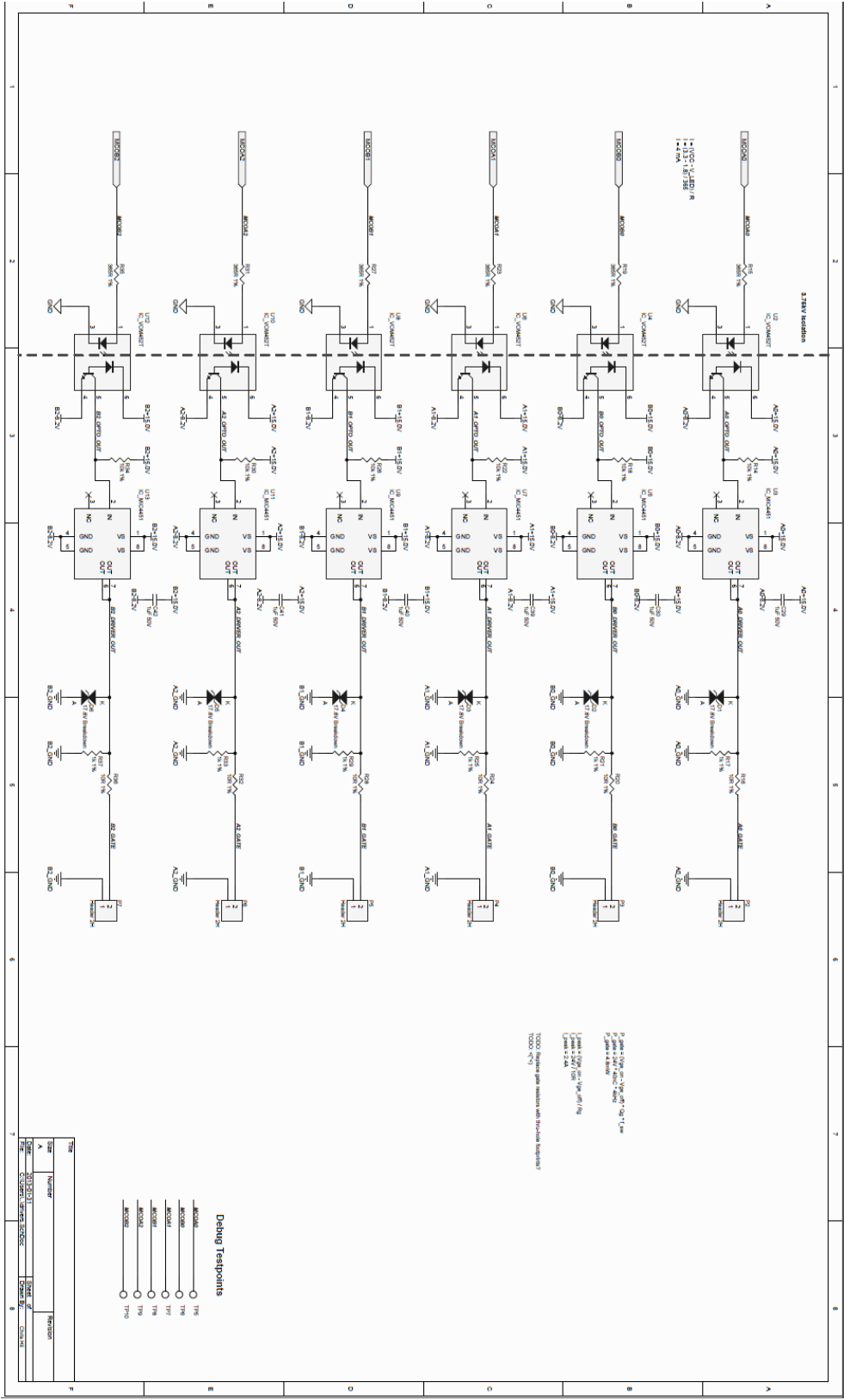


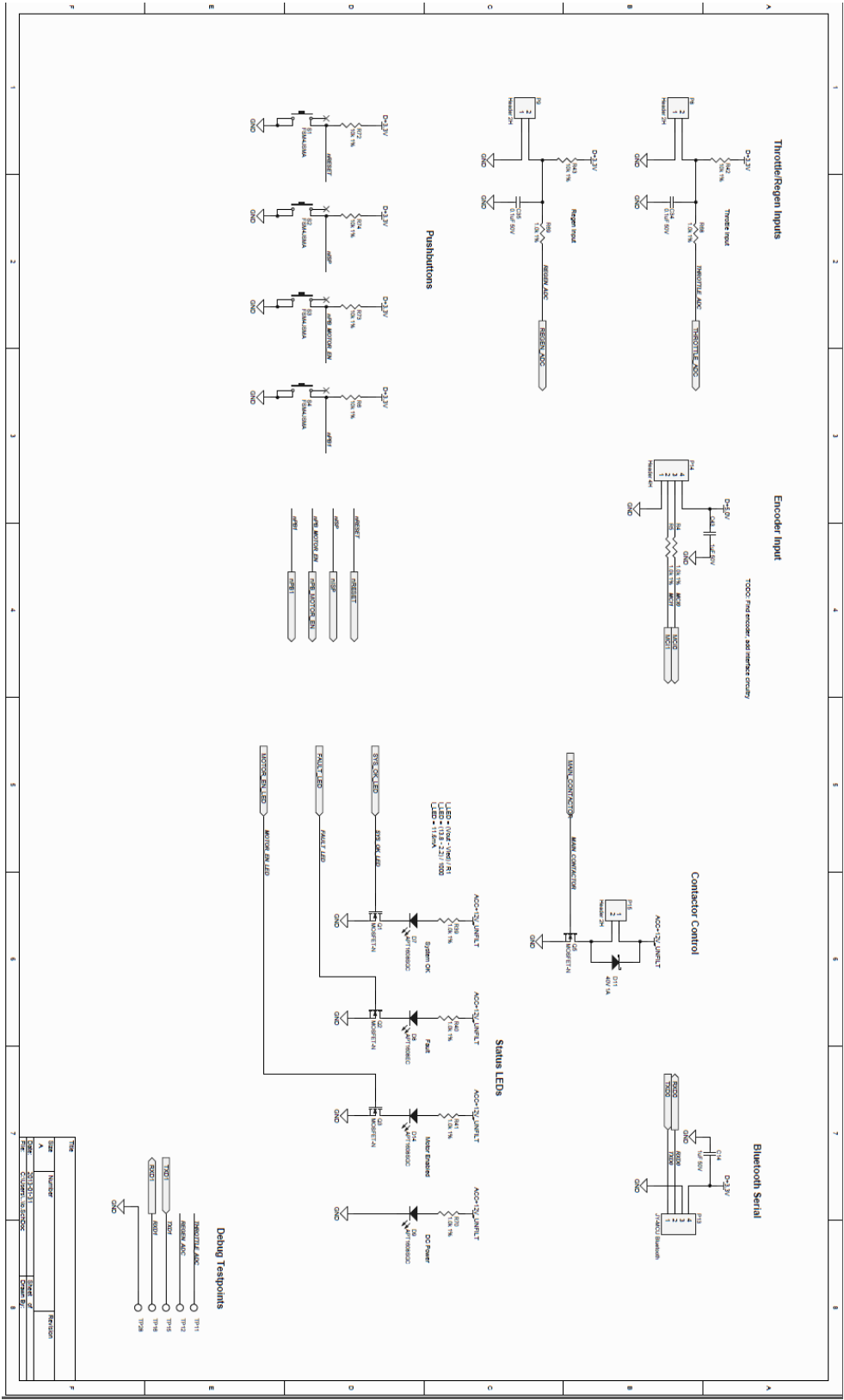
Note: Most devices are SMD devices.

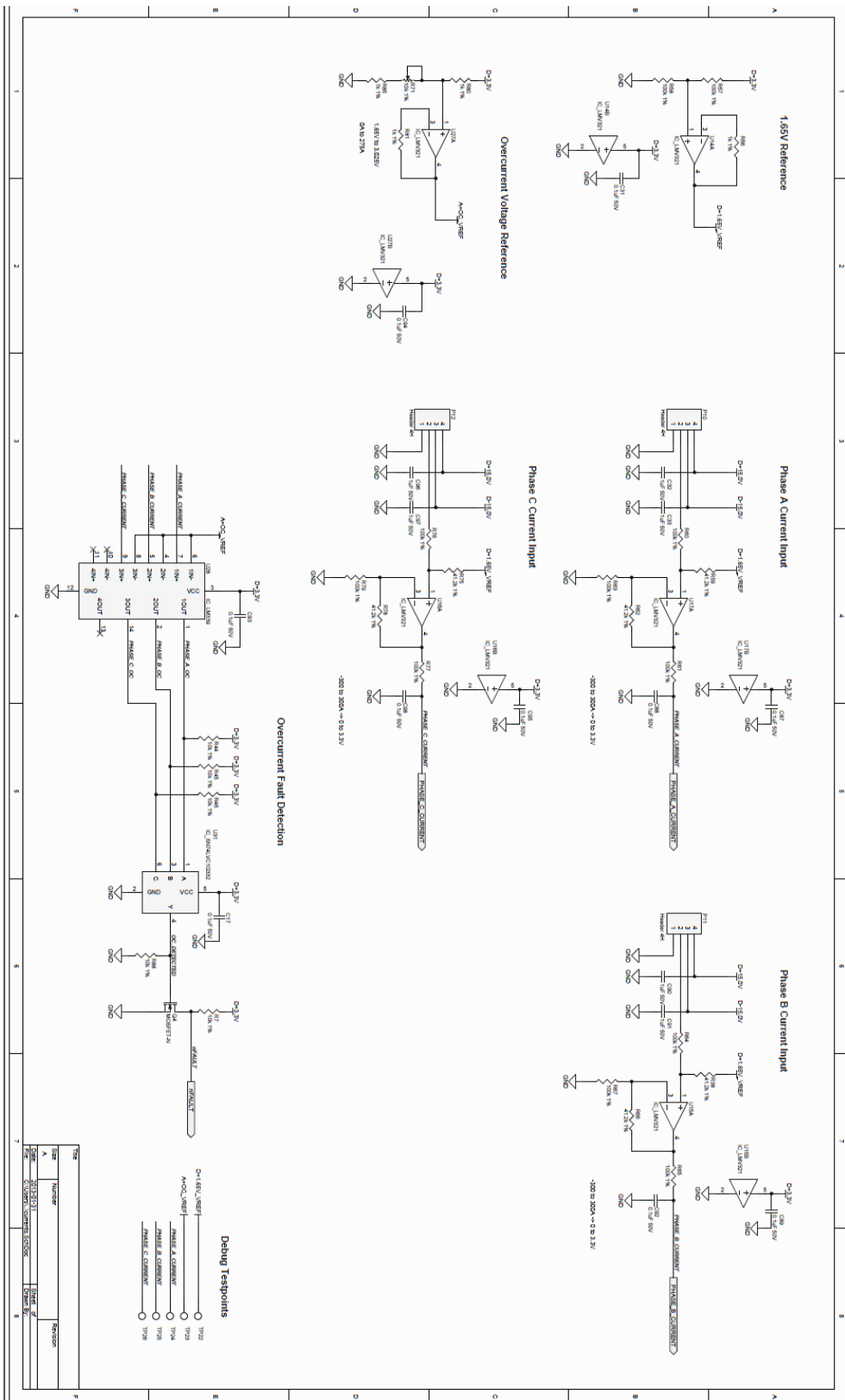
Part	Description	Value	Footprint
U1	LPC1114		QFN-100
U2	3.3V Regulator		SOT-23
C1-C10	Capacitors	100nF	0603
R1-R20	Resistors	10kΩ	0603

Legend

Size	Number	Revision
A	1	1.0







APPENDIX C – SOURCE CODE

Too large for insertion into document, source code is available upon request.