Overcurrent Protection: Reference Design & Study

Sponsor: Texas Instruments

Project Contact: Pete Semig

Michigan State University
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Executive Summary

This project's purpose is to design, test, and document multiple real-world over-current protection application circuits. Designs will focus on placing Texas Instrument components on a printed circuit board to demonstrate the application of theory. The project is a complete engineering design cycle, from receiving specifications to final documentation of findings, and qualifies for participation in Texas Instrument's Analog Design Competition.

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Introduction

The use of overcurrent protection (OCP) is a common practice in designing electrical circuits, and several common methods currently exist, such as; circuit breakers, fuses, and ground fault circuit interrupts. However, these traditional methods do not always meet the design criteria; portable, low-power devices, sensitive to even the slightest (dozens of mA) level of overcurrent, could become inoperable if the power is not removed in a very short time. Although OCP devices are designed to restrict the excessive flow of current, most of the traditional methods cannot effectively detect the low current levels in portable electronics in order to remove power before circuit components are damaged. The solution to this problem is to use integrated circuit systems, which can detect current levels in the micro amp range, and make logical decisions to control a switch that can respond several orders of magnitude faster than mechanical systems. In addition to the fast system response time, the integrated systems will not suffer from wear and can be used to protect a circuit multiple times without service, unlike a fuse.

Texas Instruments (TI) is a company that specializes in various electrical systems, and is in need of a reference design for electrical OCP systems. TI has requested that two different applications be designed and implemented for a tablet PC and cellphone OCP system. For the tablet PC application, as soon as any excess current draw is detected, power to the system is removed and the system is shutdown, this is done by monitoring the supply current. In the cellphone application, the load current of the cellphone will be accurately monitored, and decisions made only on certain levels of current draw. For both designs, select TI components from a large portfolio will be utilized, including the MSP430 microcontroller and operational amplifiers, and current shunt monitors.

Design Specifications

The following specifications were given by TI Analog Application Engineer, Pete Semig:

Design a Tablet-PC OCP system that shuts down the supply current if excess current is drawn.

- Assume battery is Li-polymer with 3.6 V, 6.75 A-hr.
- Use 1A for the trip current.
- Design a test fixture that emulates three different scenarios:
  - Normal Load (750 mA, should not cause shutdown)
  - High Current Load (draws current greater than 1A, trips shutdown)
  - Variable Load that trips at a random time (Example: A Thermistor will trip if it exceeds a certain temperature.)
- The priorities for this application are as follows:
  - Low Power
  - Small Size
  - Low Cost
  - Speed of Shutoff
  - Accuracy

Design a Cellphone OCP system that monitors load current of a cellphone.

- Accurate power consumption monitoring is critical
- Required precision between 7-192.5 mA
- Assume supply voltage is 3.0 V regulated
- Load requires 2.7-3.3V
- The priorities for this application are as follows:
  - Minimal System Impact
  - Accuracy
  - Small Size

The following deliverables are also required:

- Block Diagrams
- Component Selection and Justification
- Design Studies and testing
- Circuit Diagrams and PCB layouts
- Results and Demonstrations

Current Sensing Background Information

Several current sensing methods are in existence today: R_{ds} MOSFET sensing, Hall-effect, current transformers, resistive shunts, and more exotic methods. Choosing an appropriate method for the given design requirements requires some knowledge on how each procedure may affect system performance.

R_{ds} MOSFET sensing uses the characteristic impedance between the drain and source of the MOSFET (if used as a switch) in a power supply and the voltage at the switch to infer the current flowing through the circuit. This method is not useful in solving the giving design requirements because it requires a MOSFET switch, which would not exist when running the current sensing application using a battery. [1]

Hall-effect current sensing is a common solution, which does not suffer from insertion losses that reduce useful battery life. The main concept is to focus a flux field using a toroid such that current flow through a conductor placed within the toroid induces a magnetic field. By observing the generated magnetic flux density, one may figure the amount of current flow. However, this method is undesirable because of the increased PCB real estate usage and increased cost for the components required by this process. [2]

Current transformers, like Hall-effect current sensing, allow for circuit isolation and zero insertion losses. This method also has zero offset voltage and requires no external power. The concept is basic transformer theory, running current through an inductor (winding) allows for coupling to another inductor, with current proportional to the number of turns in each winding. Also like the Hall-effect method, current transformers are expensive and require large amounts of PCB real estate, but perhaps most debilitating is that this method requires AC current and the design specifications call for current sensing on batteries, which are inherently DC. [2]

Resistive shunts require placing a resistance in series with the power source and the load, and measuring the voltage drop across said resistance to calculate the current flowing through the circuit. This method is low cost, although it suffers from insertion loss and may require signal amplification of the measured voltage. Two distinct uses of the resistive shunt exist; low side current sensing and high side current sensing. Low side current sensing places the resistive shunt between the load and the ground, which allows for easy implementation of current sensing using nothing but an operational amplifier. However, it also adds impedance to the load's line to ground, which may affect system performance. High side current sensing, on the other hand, places its resistive shunt between the power source and the load, which does not add a disturbance to ground. Both methods can be designed for fast, precise, and accurate operation, factors important to meeting the design requirements. Due to low cost, low PCB real estate requirements, and performance capabilities, it is likely that this method will satisfy the design requirements. [3]

Methods that are more exotic are currently beyond consideration, as resistive shunts appear to satisfy design needs, however if resistive shunts do not perform as expected these options will be explored.

Design Concepts

Application One

The purpose of this application is to switch off power to the load of a tablet PC if it draws more than 1A of current from the battery. This involves putting a 25mΩ current shunt resistor in series with the battery and load, with a current shunt monitor across the shunt resistor to sense how much current is being drawn from the battery by measuring the voltage drop across the resistor. The INA138 current shunt monitor is used for this application, which gives the output voltage of: $V_0 = \dfrac{R_s R_L I_s}{R_{CSM}}$

The current shunt resistor (R_s) and output resistor (R_L) were selected such that 1.8V is output if 1A is drawn. The output of the current shunt monitor is sent to the negative input terminal of a comparator. The positive input of the comparator is a constant 1.8V supplied from a voltage divider by the battery. The comparator will output low if the voltage at the negative terminal is higher than the positive terminal. The output of the comparator is connected to the control terminal of a load switch, which opens if a low is input into the control terminal. The block diagram is shown below in Figure 1, along with the schematic shown in Figure 2.

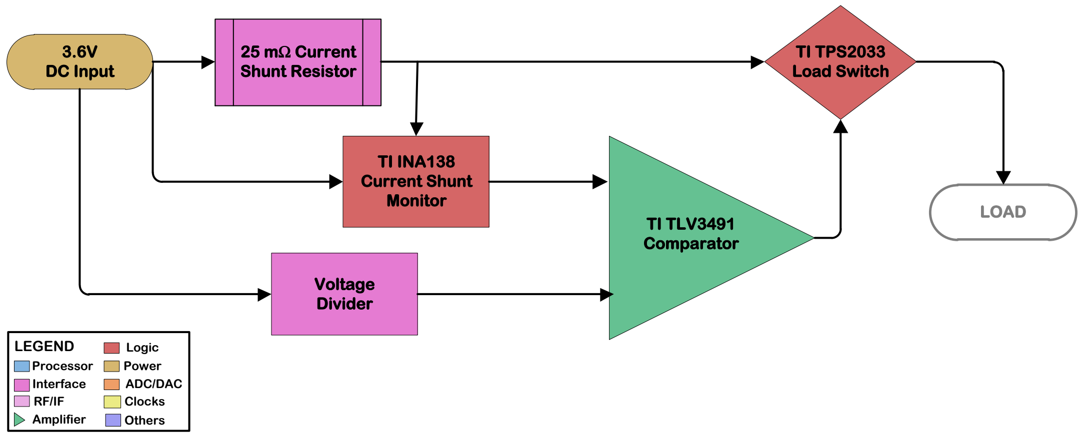

Figure 1: Block Diagram of Application 1

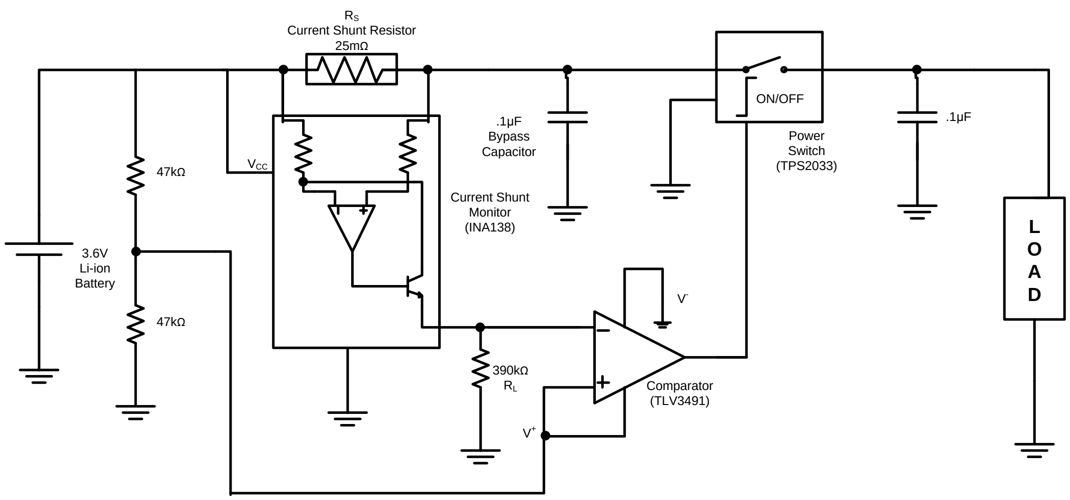

Figure 2: Circuit Schematic for Application 1

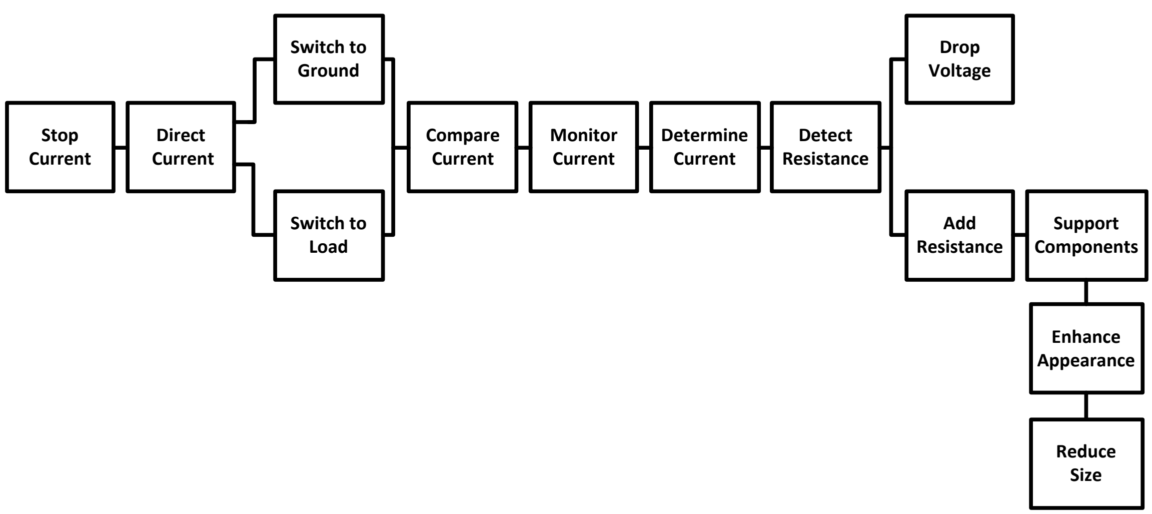

Figure 3: Fast Diagram for Application 1

Application One Part Selection Justification

TI INA138 Current Shunt Monitor

This part was selected because of the flexibility of the output. It can easily be adjusted to obtain any gain from 1 to 100V/V, which will make it very easy to design for a desired voltage for the input of the comparator. One major drawback of this part is the high input offset voltage, which is a max of 1mV and 200µV during typical operation. Once testing of this design is completed, the selection of this part may have to be reconsidered if the input offset voltage has a negative affect on the accuracy of the output.

TI TLV3491 Comparator

This part was selected because it has very low power consumption, drawing at most 1.2µA at 3V, and it also has a very fast response time, no more than 6µs. Also, since this part has rail-to-rail output, this will allow for a more accurate output.

TI TPS2033 Power Switch

This part is a 2.7-5V, active high power switch, with a fall time of 2.8ms. It can easily withstand up to 2A of current, which is well above the expected cutoff level of 1A. [5]

Application Two

This application will monitor the current being input into a cellphone to correctly determine the power being consumed for different applications. The basic method of operation is similar to that of application one, however, this circuit is not required to switch the power off. Instead, the sensed current will be sent to a microcontroller and displayed on an external screen. In practice, the processor in the cellphone would use the sensed current as an input and make decisions accordingly. Since it is not known what ADC capabilities this processor will have, a high resolution ADC is included in the design. The other difference from Application One is the use of the INA333 instead of a current shunt monitor, in order to observe the effects of a low offset voltage on the accuracy and precision of current sensing.

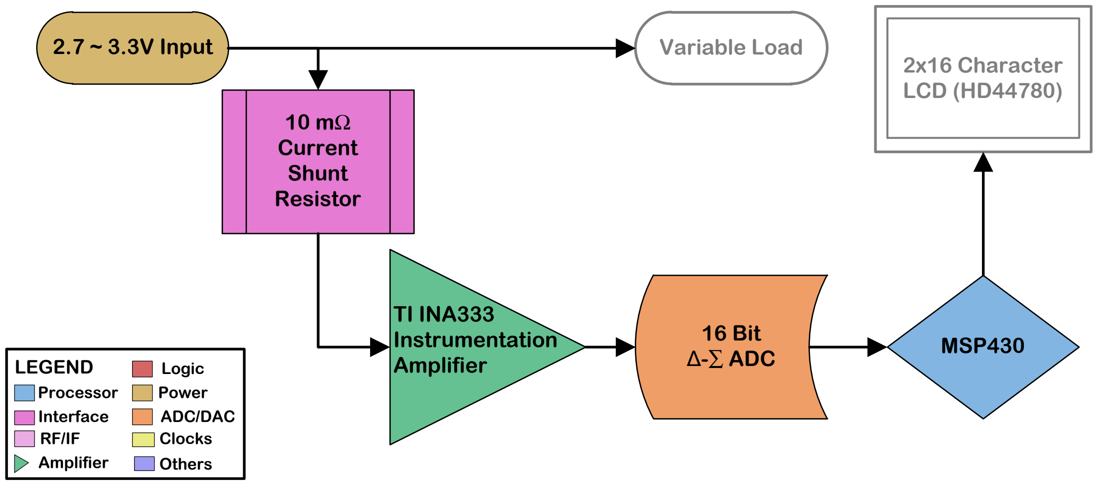

Figure 4: Block Diagram of Application 2

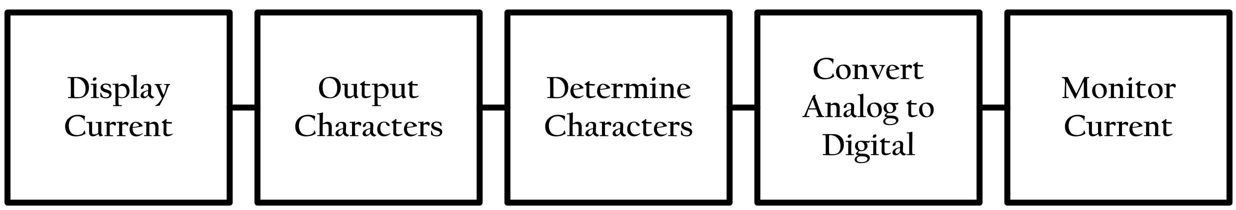

Figure 5: Fast Diagram for Application 2

Application Two Part Selection Justification

TI INA333 Instrumentation Amplifier

This part was selected due to the offset voltage being a max of 25μV, which is considerably lower than the INA138. This should ensure high accuracy of the monitoring.

TI ADS1113 Analog to Digital Converter

This part was selected for its high bit resolution (16-bit), in the event that the analog to digital converter built into the microcontroller does not have a high bit resolution.

TI MSP430F2013 Microcontroller

The MSP430 has an ultra-low power consumption ideal for portable electronics. The F2013 is ideal for this application because it has a built in 16 bit ADC, is low cost, and has a cheap development board (The TI Launchpad).

PCB Design

An important aspect of this project is PCB design. Due to the low power consumption requirements of OCP in portable electronics, sense resistors with very low resistance are required to monitor the current correctly. This low resistance makes testing the OCP designs difficult because traditional testing methods such as vector and proto boards are too inaccurate for the sensing resistor due to the extra resistance they introduce. In addition, part placement and physical trace sizes on the PCB affects the sensing accuracy.

Studies will be performed on a variety of PCB designs in order to determine the optimal size, placement, and performance characteristics. During testing, PCBs will be fabricated independently using chemical etching to save cost and only using professional fabrication services for the final design. PCBs will be initially designed using the Express PCB software; however, if the single-layer designs do not satisfy design criteria, more complex multi-layer fabrications may be required. When designing more complex boards, a more robust design software, such as Eagle, will be incorporated into the design process.

Shown below in Figure 6 is the proposed design in Express PCB. Once the design is complete in Express PCB, the colors must be inverted and then printed on a transparency paper. This is shown in Figure 7. Once printed, the transparency is held to a copper substrate using lamination. The substrate is then exposed to UV light that only flow through the clear portions of the transparency, which are the portions of the PCB designated as copper traces. After this exposure, the board is etched with chemicals that remove copper from the portions of the board that were not illuminated with UV light. The etched PCB for the initial design is shown below in Figure 8.

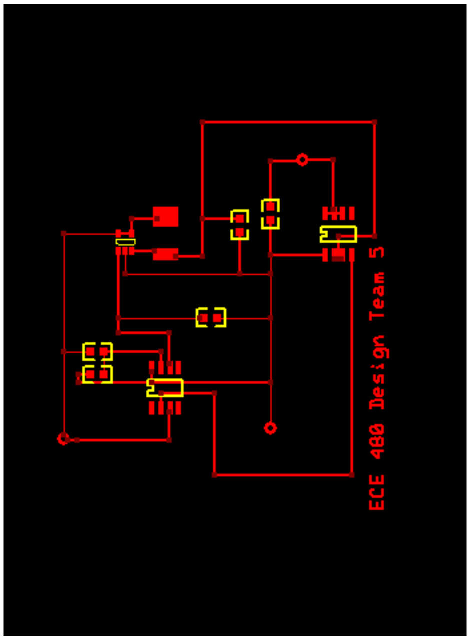

Figure 6: Express PCB Design

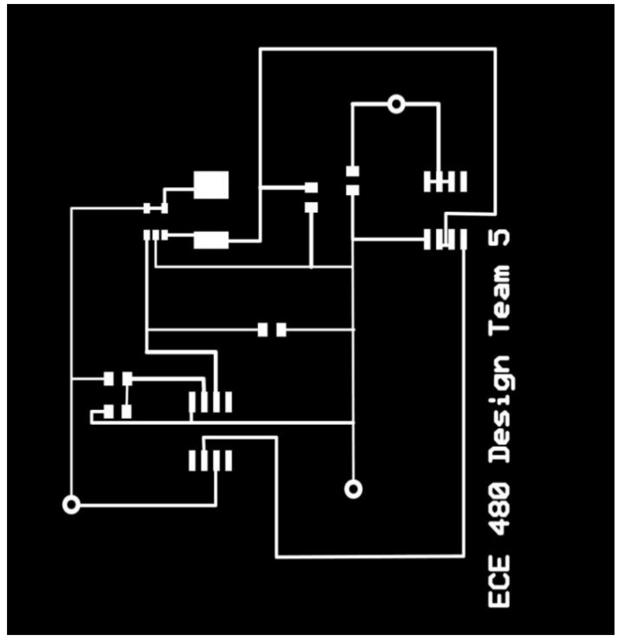

Figure 7: PCB Transparency Mask

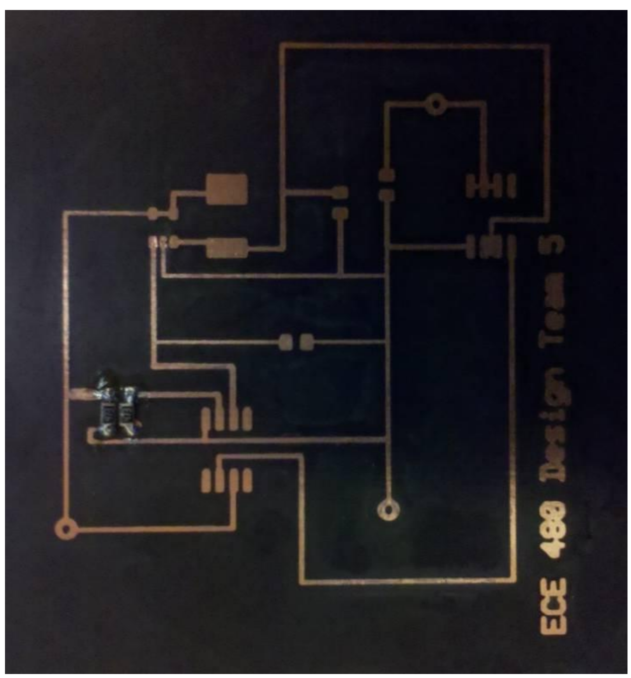

Figure 8: Etched PCB

Team Management

Schedule / Plan

As explained in previous sections, this project includes the design and testing of two over-current protection applications. To begin, preliminary design ideas must be simulated, prototyped, and tested. Based on the results of the testing, alterations will be made to components and other design factors. Texas Instruments has also requested that studies be completed to document which design procedures have the most desirable outcomes. These findings will aid in the designing of a final prototype. There is ample time left before Design Day for any adjustments or revisions.

Team Members

This is a brief introduction of the members of ECE 480 Design Team Five and their technical and non-technical roles. The roles shown below are considered as the minimum expected from that team member. It is expected that all team members will participate in the completion of all aspects of the project, whether it be technical or non-technical.

Team Member	Non-Technical Role
Stephen England	Team Management
Joshua Myers	Webmaster
Kenji Aono	Document Preparation
Ryan Laderach	Presentation Preparation/Lab Coordinator

Team Member	Technical Role
Stephen England	Lead Hardware Design
Joshua Myers	Lead PCB Design
Kenji Aono	Lead Software Design & Support
Ryan Laderach	Lead Simulation & Testing

Budget

Item	Projected Cost (per unit)	Current Cost
Current Shunt Monitor: INA128	$3.77 [4]	Sampled
Instrumentation Amplifier: INA333	$5.40 [4]	Sampled
MSP430 microprocessor: F2013	$3.60 [4]	Sampled
Analog to Digital Converter: ADS1113	$6.30 [4]	Sampled
PCB Fabrication:	$250.00 **(total)**	TBD
Comparator: TLV3491	$0.56 [4]	Sampled
Current Shunt Resistors:	$1.27 [4]	$3.81
Switch: TPS2033	$1.61 [4]	Sampled
MSP430 Target Board/Development Tool	$149.00	Sampled
Total cost	**$417.75**	**TBD**
Budget Left	**$82.25**	**TBD**

Cost Justification

PCB fabrication

The cost of PCB fabrication varies with every vendor. For most of the testing we have the ability to fabricate our own PCBs which will help with studies of PCB design without affecting our budget. The projected cost has a $250 ceiling, so there is a substantial limit set for fabrication from vendors and for final fabrication. The current cost is unknown due to the possibility of testing different vendors and programs.

Current Shunt Resistors

The resistors need to have an uncommonly low resistance to allow the maximum power transfer between the supply and load.

MSP430 Target Board

The development boards will allow for rapid deployment or development of code and improve debugging capabilities.

References

[1] Gabriel A. Rincón-Mora and H. Pooya Forghani-zadeh, “Accurate and Lossless Current-Sensing Techniques: A Practical Myth?” Power Management Design Line, Mar. 17, 2005.

[2] Paul Emerald, “Non-Intrusive Hall-Effect Current-Sensing Techniques Provide Safe, Reliable Detection and Protection for Power Electronics,” in International Appliance Technical Conference, Ohio State University, May 6, 1998, pp 1-2.

[3] Texas Instruments, “What is a Current Sensor and How is it Used?”, Last Accessed on Feb. 10, 2011. Available at: http://focus.ti.com/analog/docs/microsite.tsp?familyId=57&micrositeId=7&sectionId=560&tabId=2180

[4] Digikey Catalogue, Last Accessed on Feb 27, 2011. Available at http://www.digikey.com/

[5] TI Website (Part Datasheets), Last Accessed on Feb 10, 2011. Available at http://www.ti.com/