Isolated Current Sensor

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Introduction

In power electronics research, we often need to equip microcontrollers with the ability to accurately sense a high current signal. Accurately sensing the current through a circuit allows the user to gain knowledge about the circuit and be more informed with regards to the safety precautions that may need to be in place. For example, if we are looking at situations with high current, we need to be careful with which materials we use and how we use them, as we could fry the parts and/or cause injuries to ourselves. Secondly, situations such as motor-control feedback, power-supply, or even high-side sensing require accurate measurements. The result of not having such a current sensing circuit is an inefficient use of time and effort, as this would require creating a new circuit that will manually test the current for every use case. The ability to maximize the time of the user is the main attractive feature of this product.

There are three main options in terms of how to approach creating a fully isolated current sensor: (1) the current transformer, (2) the Rogowski coil, and (3) some sort of Hall-effect device. We have decided to go with a Hall-effect current sensor over the other options for a few main reasons. The Hall-effect sensors are accurate and are able to be used on a wide range of currents. The other options offer more complications as well as restrictions in terms of how we can design our circuit.

As shown below, there are a few subsystems we have to take into consideration. First, there will have to be power supplied to all the parts. We are planning on using a battery to power each component, as the power requirements are not too high. Second, we need to feed the current we want to calculate into the hall effect current sensor. This will then output a voltage that will be fed into the analog to digital convertor. From here, we will feed the digital outputs to the microcontroller, which will then calculate a current value to be displayed using the seven segment display on the outside of our casing.

Visual Aid

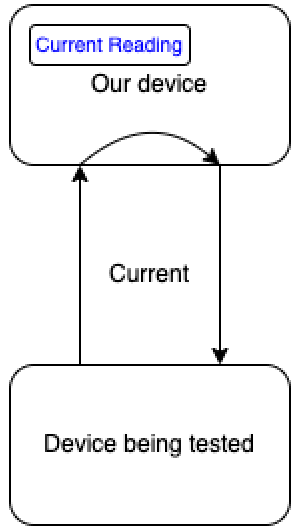

Figure 1: Simple Visual Aid

High-Level Requirements:

1. This product should have a reading accuracy of +/- 1% with 3 concurrent current inputs.

2. This product should have the ability to handle up to 50 KHz in bandwidth.

3. This product should have the ability to handle up to 10 Amps of current.

Design

Block Diagrams

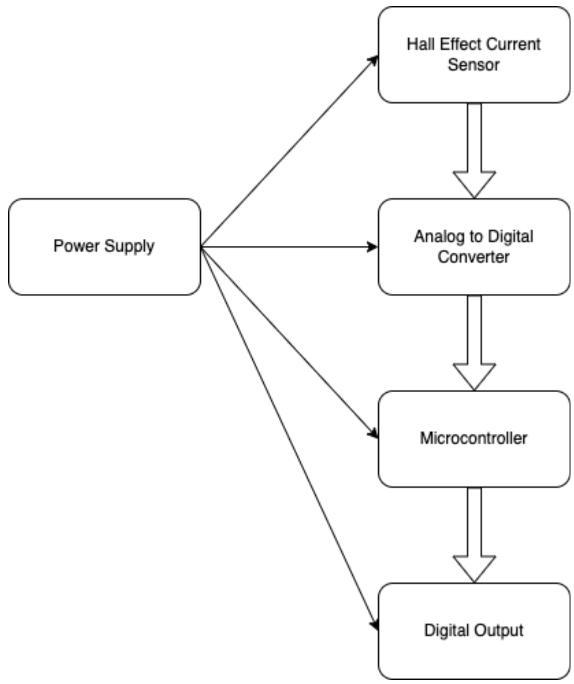

Figure 2: Simple Block Diagram

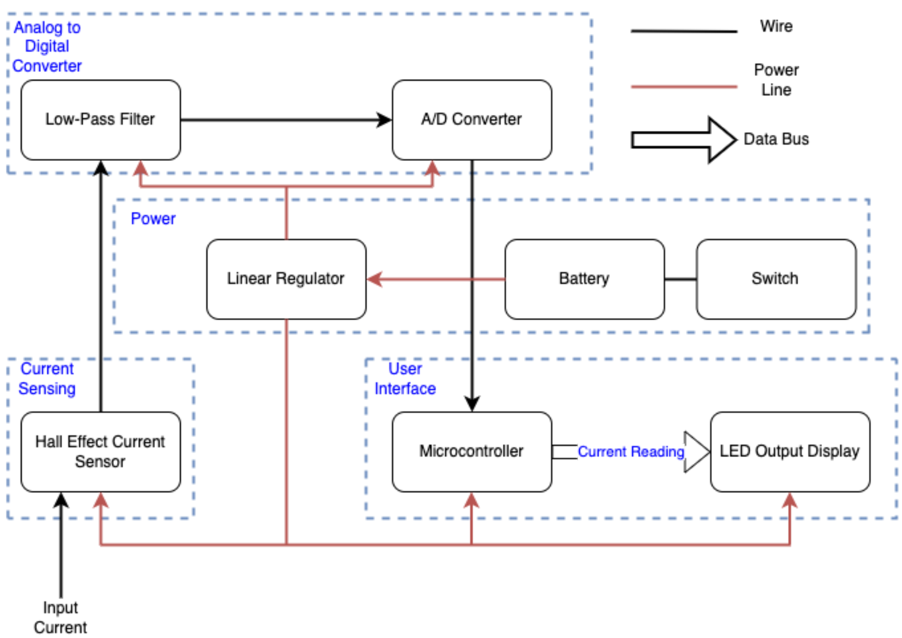

Figure 3: Detailed Block Diagram

Subsystem Components

Hall-Effect Current Sensor:

We will utilize the Texas Instruments TMCS1100, a galvanically isolated Hall-effect current sensing IC, to accurately measure current through a system. This chip will receive the current that we want to read and output voltage to the analog to digital converter subsystem. The specific chip that will be used has a sensitivity of 200 mV/A [1], meaning the max voltage output will be 2 Volts . The sensor will require between 3 and 5 Volts for the power supply and 2.5 volts for the reference voltage[1]. The Vref input pin provides a variable zero-current output voltage, enabling bidirectional or unidirectional current sensing[1]. This current detector should function between +/- 10A, however this sensor will be able to handle up to +/- 11.3 A to provide a buffer.

Requirements	**Verification**
- Power supply is 3-5 Volts - Reference Voltage 2.25 - 2.5 Volts	- A linear regulator will be used to provide the appropriate voltage - A voltmeter will be used to test to make sure the battery is supplying the appropriate amount of voltage - The black pin of the voltmeter will be touching ground, while the red pin will be touching the power supply/Vref to measure the voltage given to that pin
- Handle up to 10 Amps in current	- Current in measurements up to 10 Amps will be provided to the sensor with a DC power supply - We will set up a circuit with resistance and pass that to our sensor to ensure that it can handle up to 10 A
- Sensor has a sensitivity of 200 mV/A	- When current is provided to the sensor, the output voltage will also be measured using a voltmeter on the Vout pin - The voltmeter will ensure the pin truly has a sensitivity of 200 mV/A
- Ability to [1]handle bidirectional current	- The sensor itself is able to handle

[1] Using the Data Sheet for TMCS1100 Hall-Effect Current Sensing Chip

	bidirectional current according to the data sheet, but this will be tested by inputting reversed current - The output should be the same absolute value, but negative

Figure 4: Requirements and Verification Table for Hall-Effect Current Sensor

Analog to Digital Converter:

The next subsystem is the analog to digital converter. This takes the resulting analog voltage signal from the previous system, the Hall-Effect sensor, and converts it into a digital signal. First, the output voltage from the Hall-Effect sensor will be passed through a low pass filter to ensure there is not aliasing. Next, the resulting signal will be sent to the ADC. The ADC will be sampling at a rate of over 100 kHz to ensure no aliasing, as we want to be able to handle a bandwidth of 50 kHz. Additionally, this ADC will be a twelve bit ADC using a reference voltage of 2.5 Volts. This means that the step voltage will be 2.5/4096 = 6.103e-4 V. This is low enough to achieve an error rate of no greater than 1%. The new digital signal will be connected to the microcontroller for further calculations.

Requirements	**Verification**
- Low pass filter passes Frequencies < 50 kHz	- An Oscilloscope will be used to measure the frequencies that are being passed by the filter. - The reading on the oscilloscope should be stable at 0 dB, then should show a downslope until it reaches - 3 dB (which is the point of the cutoff frequency), and then it should finally continue the downslope at a faster rate.
- Supply voltage is 2.35-5 V - Reference Voltage is 2.25-2.5 V	- A linear regulator will be used to provide the appropriate voltage - A voltmeter will be used to test to make sure the battery is supplying the appropriate amount of voltage - The black pin of the voltmeter will be touching ground, while the red pin will be touching the power supply/Vref to measure the voltage

	given to that pin
- Sampling rate is > 100 kHz	- An Oscilloscope will be used to test whether the sampling frequency being generated is greater than 100 kHz or not.
- Error rate of Output is < 1%	- An Oscilloscope will be used to test whether the digital signal that is generated by the ADC results in the error rate being less than 1% - The Oscilloscope will give us the digital value that is being generated. This value will then be multiplied by the step voltage determined above (2.5/4096) and the value of that will be the error rate.

Figure 5: Requirements and Verification Table for Analog to Digital Converter

User Interface:

The final subsystem is the human interface, which will display the current reading from our device. Our system will have an ATtiny85-20SU microcontroller that takes the digital signal from the ADC and should be able to calculate the current passing through. The microcontroller will be programmed to understand the readings of the ADC. For example, if the ADC outputs a value of 2048, the microcontroller will convert that to Amps in the following way. First, it is established that the reference voltage will be 2.5 volts. This means that a reading of 2048 from the microcontroller will evaluate to 2048/4096 *2.5 = 1.25 volts. Next, to convert voltage to Amperes, the microcontroller will divide the voltage by the sensitivity, which is 200 mV in this case. Therefore, we will have 1.25 Volts/0.2 V/A = 6.25 A. This value will be outputted to the seven segment display and will have a display value of 6.25 A. This reading should be accurate up to the hundredths decimal place, and be capable of displaying the information received from the microcontroller in real time.

Requirements	**Verification**
- Supply voltage is 1.8-5.5 V	- A linear regulator will be used to provide the appropriate voltage - A voltmeter will be used to test to make sure the battery is supplying the appropriate amount of voltage - The black pin of the voltmeter will be

	touching ground, while the red pin will be touching the power supply/Vref to measure the voltage given to that pin
- LED displays provide the correct output	- The microprocessor will feed test values into the LED and will observe whether those values are showing up or not.
- Ability to compute appropriate values using simple mathematical operations	- Once the LED connection is tested , it will display the output reading of the current being read by the sensor. - Based on the value found at the ADC, the theoretical value of the current will be found and compared to the value being displayed.

Figure 6: Requirements and Verification Table for the User Interface

Power

Our device will use a 9V battery to power each of the components. The battery will be connected to two linear regulators that will output two different voltages. As for power supply, there are only two values we need: 2.5 Volts and 5 Volts. All of our components need 5 volts, whereas the Hall-Effect Sensor and the ADC both need a reference voltage of 2.5 volts. This battery will be turned on and off by a switch and should be able to feed into the linear regulators at 9 +/- 0.1V continuously.

Requirements	**Verification**
- Supply voltage at 9 V	- A voltmeter will be used to test to make sure the battery is supplying the appropriate amount of voltage - The black pin of the voltmeter will be touching ground, while the red pin will be touching the power supply to measure the voltage being supplied
- Linear regulator appropriately regulates the supply voltage for the necessary values	- A voltmeter will be used to test to make sure the regulator is outputting the correct values
- The on/off switch should turn off the circuit when its at the off position and	- If the circuit has power through it when the on switch is in the on state

turn on the circuit when it is at the on position	and it does not have power through when it is at the off state, the switch works correctly

Figure 7: Requirements and Verification Table for Power Supply

Tolerance Analysis:

Of all of the subsystems, the analog to digital converter poses the most risk to the completion of our project. It is the most complicated of the subsystems as it involves programming the filters onto the chip and it feeds the output needed into the microcontroller. The project also deals with three simultaneous current inputs, so the choice of ADC chip is crucial to ensure that all the requirements are being met.

The most crucial part to the design is the Analog to Digital Converter and ensuring it is able to output voltages within reasonable parameters, allowing the final output reading to be within 1% of the input current. Current will be inputted into a Hall-Effect Current sensor with a typical error of .4%. However, the extreme cases are vital here, so the maximum error, which is .9%, is the important number to analyze. The output voltage from the Hall-Effect Current Sensor, will be fed into a low pass filter to be bandlimited. Then, this will flow to the ADC and finally the microcontroller. The ADC needs to have enough bits and a high enough sampling rate so that we do not lose any data and report accurate results.

Here is the analysis of the Hall-Effect Current sensor with the ADC, to ensure that the results will be within +/- 1% of the true current. Our input current can go up to 10 Amps, which means that the Vout can go up to 2 Volts +/- .9%. Since, the max voltage of Vout is 2.018 Volts, the reference voltage should be around that value or slightly higher, in this case 2.5 Volts. This means that the number of bits the ADC outputs will be very important in the accuracy of the circuit. Twelve bits seems to be the optimal number as it gives us the cheapest ADC that still has enough bits +/- 1%. This can be proven with some analysis. With a twelve bit ADC, each increment in value is given by our reference voltage divided by 2^{12}. This would be 2.5/ 4096 = 6.103e-4 Volts. Now, when the percent error is being calculated the biggest difference between the actual voltage and the expected voltage is the step voltage divided by two, which gives us 3.05e-4. Now, we want the percent error to be less than or equal to 1%, so we divide this value by 0.01 and then convert it back to Amps by dividing by 0.2. This results in .152 Amps. The only time the percent error could be greater than 1% is if the current is less than .152 Amps.

Additionally, the error from the current sensor would not affect the accuracy of the circuit as at very low amperage discussed here, it would not change the output of the ADC. Similarly, at higher amperes closer to 10 A, it still would not affect the output because the difference in the reading and the error value would be too low to push the total error to above 1%.

Proof as Written Above:

Mathematical Step	Reasoning
2.5/4096 = 6.103e-4 V	This represents the step voltage of the ADC.
Input Voltage - Digital Output < 6.103e-4/2	This is the largest value that difference can have.
|Input Voltage - Digital Output| /0.2 = .00152 = Current Reading	Converts the voltage to Amps
(|Input Current - Current Reading| /Input Current) <0.01	Percent Error Formula
Input Current = .00152/.01 = .152 Amps	Using Substitution from Above

Figure 8: Proof of Concept Math and Reasoning

Hall-Effect Current Sensor:
Vout = (Input Current) * (0.2V) +/- 0.9 %
ADC:
Digital Output = ($2^{N(bits)}$ * Vout)/Vref
Voltage reading = (Digital Output/$2^{N(bits)}$) * Vref
Final Answer Percent Error:
|(Input current - (Digital Output/0.2))/Input Current| < .01

Schedule and Cost Analysis

Cost Analysis

To calculate labor costs for our project, we took the average salaries of computer and electrical engineers from the University of Illinois for the 2020-2021 academic year[2] in order to find an hourly rate that we would earn while creating this project. This came out to an average of $92,824, and assuming 50 working weeks with five eight-hour days, this gives us an hourly rate of $46.41. Assuming that we each dedicate 8 hours per week for the next nine weeks, we come to the final figure out 3 members * 9 weeks * 8 hours * $46.41/hour = $10,024.56 for our labor.

The labor required from the machine shop will be quite minimal, including helping us to order our enclosure and then drilling several holes in the enclosure. In our first conversation they said that this would not be very difficult at all, and we estimated that it would take no more than two hours for them to assist in ordering and modifying the enclosure. Assuming a $75/hour rate for the machine shop worker, this adds $150 to our costs. As seen below in figure 9, the combined cost for the parts we plan to order adds up to $57.88. With an additional 5% for shipping and 10% sales tax, this comes out to $66.56. Thus our total cost comes out to be $10,241.12.

Component	Description	Manufacturer	Part #	Quantity	Cost
Hall Effect Sensor	Utilizes galvanic isolation to detect current and output a proportional voltage	Texas Instruments	TMCS1100	3	$13.26
Microcontroller	An MCU unit that will calculate the current, and send it to the LEDs to be displayed	Microchip Technology	ATtiny85	1	$1.50
ADC	Digitizes the voltage output from hall effect sensor	Texas Instruments	ADS7886	3	$11.04
9V Battery	Supply power and reference voltages to circuit	Toshiba	6F22KG	1	$0.74
7-Segment LED	Displays the output of the circuit	Würth Elektronik	157119	15	$11.60
Resistors	Used for the Low Pass Filter	Lighthouse LED’s	8WATTSMD30OHMRESISTORS	3	$0.30

Capacitors	Used for the Low Pass Filter	Kemet	C0603C104K5RAC3121	3	$0.39
Linear Regulator	Transform 9V from battery to proper voltage required for each device	Texas Instruments	UCC283T-ADJ	2	$18.38
Switch	Toggle the device on and off	E-Switch	RA1113112R	1	$0.67

Figure 9: Component List

Schedule

Week	Goals	Person
Week 7 (2/27)	Finalize component choices, begin designing PCB	Everyone
Week 8 (3/6)	Complete PCB design, choose device enclosure and talk with machine shop, buy components	Everyone
Week 9 (3/13 - Spring Break)	Review and improve PCB design, select new components if necessary	Everyone
Week 10 (3/20)	Implement low-pass filter	Akshat
	Develop first prototype - assemble components	Everyone
	Begin programming	Rohan, Sean
Week 11 (3/27)	Finalize updated PCB, buy new components if necessary	Everyone
	Continue programming	Rohan, Sean

Week 12 (4/3)	Assemble final prototype	Everyone
	Complete programming device	Rohan, Sean
Week 13 (4/10)	Test and refine final prototype, look for possible bugs	Everyone
Week 14 (4/17)	Work out any remaining bugs, give mock demo to TA, practice for final demo	Everyone
Week 15 (4/24)	Complete final demo, practice for and give mock presentation, begin putting together final papers, practice final presentation	Everyone
Week 16 (5/1)	Practice for and give final presentation, complete final papers	Everyone

Figure 10: Weekly Schedule

Ethics and Safety Considerations:

In accordance with point 5 of the IEEE code of Ethics, it is important that we are honest about the claims and objectives that we achieve and hold ourselves accountable for errors and mistakes that may pop up over the course of the project. It is also important that as a group, we treat each other with respect and ensure that we abide by the IEEE code of ethics as dictated by points 7-10.

The main area of caution would be around the use of high currents. Our goal is to ensure that our device is able to handle currents up to ± 10 A, and issues may arise because of this. To prevent this we will ensure that 1) at least 2 of us are working on the project at all times, and 2) we will keep insulator objects around and put other safeguards in place to ensure no one gets hurt.

Bibliography

[1] Texas Instruments, "1% High-Precision, Basic Isolation Hall-Effect Current Sensor With ±600-V Working Voltage," TMCS1100 datasheet, Sept. 2019 [Revised July 2021].

[2] Grainger Engineering Office of Marketing and Communications, "Salary averages," *Electrical & Computer Engineering | UIUC*, 2022. [Online]. Available: https://ece.illinois.edu/admissions/why-ece/salary-averages. [Accessed: 22-Feb-2023].