

Isolated Current Sensor

Team Number 73

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1. Introduction

1.1 Problem

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.

1.2 Solution

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.

1.3 Visual Aid

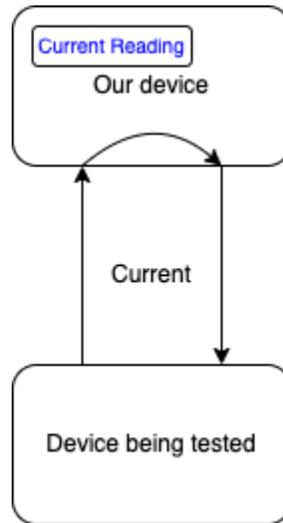


Figure 1: Simple Visual Aid

1.4 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.

2. Design

2.1 Block Diagrams

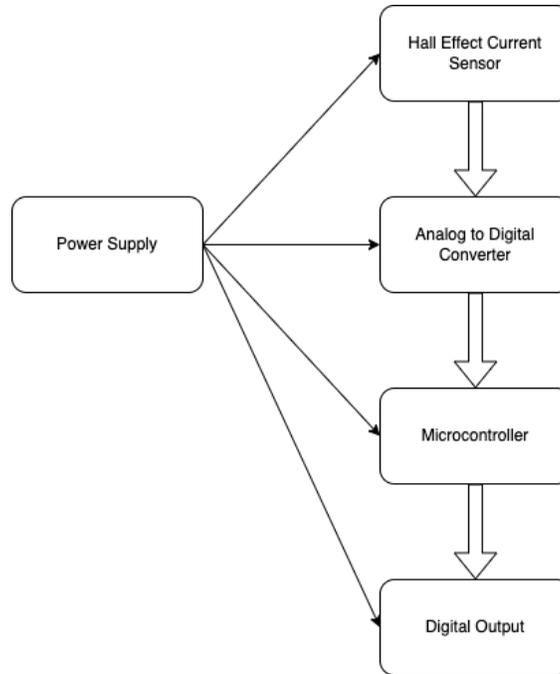


Figure 2: Simple Block Diagram

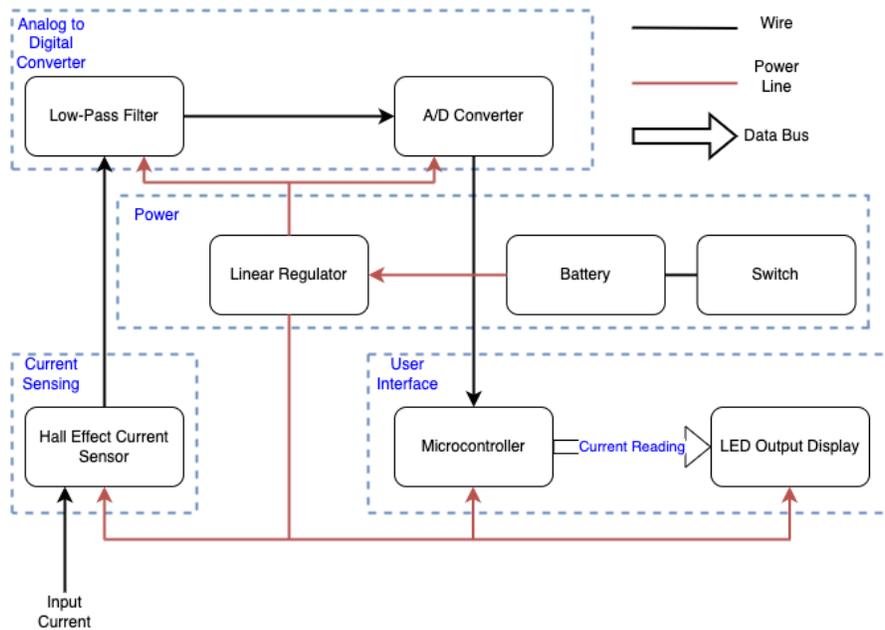


Figure 3: Detailed Block Diagram

2.2 Subsystem Components

2.2.1 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 V_{REF} 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
<ul style="list-style-type: none"> - Power supply is 3-5 Volts - Reference Voltage 2.25 - 2.5 Volts 	<ul style="list-style-type: none"> - 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/V_{REF} to measure the voltage given to that pin
<ul style="list-style-type: none"> - Handle up to 10 Amps in current 	<ul style="list-style-type: none"> - 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
<ul style="list-style-type: none"> - Sensor has a sensitivity of 200 mV/A 	<ul style="list-style-type: none"> - When current is provided to the sensor, the output voltage will also be measured using a voltmeter on the V_{OUT} pin - The voltmeter will ensure the pin truly has a sensitivity of 200 mV/A
<ul style="list-style-type: none"> - Ability to ¹handle bidirectional current 	<ul style="list-style-type: none"> - 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
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Figure 4: Requirements and Verification Table for Hall-Effect Current Sensor

2.2.2 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
<ul style="list-style-type: none"> - Low pass filter passes Frequencies < 50 kHz 	<ul style="list-style-type: none"> - A Network Analyzer will be used to see whether the Low Pass Frequency is working as intended. - Given an input signal source, the analyzer will show a dB vs Frequency graph, and if the filter is working as intended it should be steady at 0 dB initially, then slowly fall to -3dB at the cutoff frequency (50 kHz), and then finally fall more steeply beyond the cutoff point. This is a transfer function.
<ul style="list-style-type: none"> - Supply voltage is 2.35-5 V - Reference Voltage is 2.25-2.5 V 	<ul style="list-style-type: none"> - 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/ V_{REF} 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

2.2.3 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 $1.25 \text{ Volts} / 0.2 \text{ V/A} = 6.25 \text{ A}$. 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

	<ul style="list-style-type: none"> - 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/V_{REF} to measure the voltage given to that pin
<ul style="list-style-type: none"> - LED displays provide the correct output 	<ul style="list-style-type: none"> - The microprocessor will feed test values into the LED and will observe whether those values are showing up or not.
<ul style="list-style-type: none"> - Ability to compute appropriate values using simple mathematical operations 	<ul style="list-style-type: none"> - 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

2.2.4 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, and the Hall-Effect Sensor and the ADC also 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 $9 \pm 0.1V$ continuously.

Requirements	Verification
<ul style="list-style-type: none"> - Supply voltage at $9 V \pm 1V$ 	<ul style="list-style-type: none"> - 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
<ul style="list-style-type: none"> - Linear regulator appropriately 	<ul style="list-style-type: none"> - A voltmeter will be used to test to

regulates the supply voltage for the necessary values	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 turn on the circuit when it is at the on position	- If the circuit has power through it when the on switch is in the on state 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

2.3 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 filters and digitizes our input data to be fed 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 V_{OUT} can go up to 2 Volts +/- .9%. Since, the max voltage of V_{OUT} 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
$2.5/4096 = 6.103e-4 \text{ V}$	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.
$ \text{Input Voltage} - \text{Digital Output} / 0.2 = .00152$ = Current Reading	Converts the voltage to Amps
$(\text{Input Current} - \text{Current Reading} / \text{Input Current}) < 0.01$	Percent Error Formula
Input Current = $.00152 / 0.01 = .152 \text{ Amps}$	Using Substitution from Above

Figure 8: Proof of Concept Math and Reasoning

Hall-Effect Current Sensor:

$$V_{\text{OUT}} = (\text{Input Current}) * (0.2\text{V}) \pm 0.9 \%$$

ADC:

$$\text{Digital Output} = (2^{N(\text{bits})} * V_{\text{OUT}}) / V_{\text{REF}}$$

$$\text{Voltage reading} = (\text{Digital Output} / 2^{N(\text{bits})}) * V_{\text{REF}}$$

Final Answer Percent Error:

$$| (\text{Input current} - (\text{Digital Output} / 0.2)) / \text{Input Current} | < .01$$

3. 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 $\pm 10 \text{ A}$, 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

2. We will keep insulator objects around and put other safeguards in place to prevent anyone from getting hurt, and
3. We will take the required power training tutorials to ensure that all of us understand how to work with high powers and currents and know how to take the necessary precautions.

4. References

- [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].