



Patrick Simmons

ABSTRACT

The following document provides details on how to properly design a power monitor into a system. This document shows how to pull in various data sheet specifications to help a user design within the device's capability. In addition to those specifications, this document strives to help a user understand the scaling limitations and the purpose of the various calculations and registers. Simultaneously, a basic routine will be defined for how to set up these registers.

Table of Contents

1 Introduction	2
2 Defining Constraints	3
3 Find The Maximum Shunt Value	3
4 Find The Minimum Shunt Value	4
5 Maximum Resolution or Minimum Shunt Loss	5
6 What to Do if the Measurement Range Is Insufficient	6
7 Determine the Current LSB and Calibration Coefficient	6
8 Programming Your Device Registers	7
9 Summary	7

List of Figures

Figure 1-1. Digital Power Monitor Design Flow Diagram.....	2
Figure 4-1. INA226 Noise vs. Conversion Time.....	5
Figure 6-1. Low-side Multiple Shunt Example.....	6

List of Tables

Table 3-1. INA226 Shunt Voltage Input Range.....	3
Table 3-2. INA219 Shunt Voltage Input Range.....	3
Table 3-3. INA229 Shunt Voltage Input Range.....	3
Table 3-4. LM5056A Shunt Voltage Input Range.....	3
Table 4-1. VSHUNT Register Field Descriptions.....	4
Table 4-2. INA219 ADC Conversion Time table.....	5
Table 7-1. Calibration Register (05h) (Read/Write) Description.....	7

Trademarks

All trademarks are the property of their respective owners.

1 Introduction

There are several details that can easily be overlooked when designing with digital power monitors and overlooking these details can lead to errors and possibly late design changes. This document provides a structured design method that incorporates the key design specifications to be observed. In conjunction with this paper is a [design tool](#) that is built upon the method discussed in this paper. The method described in this paper follows the progression illustrated in the [Figure 1-1](#).

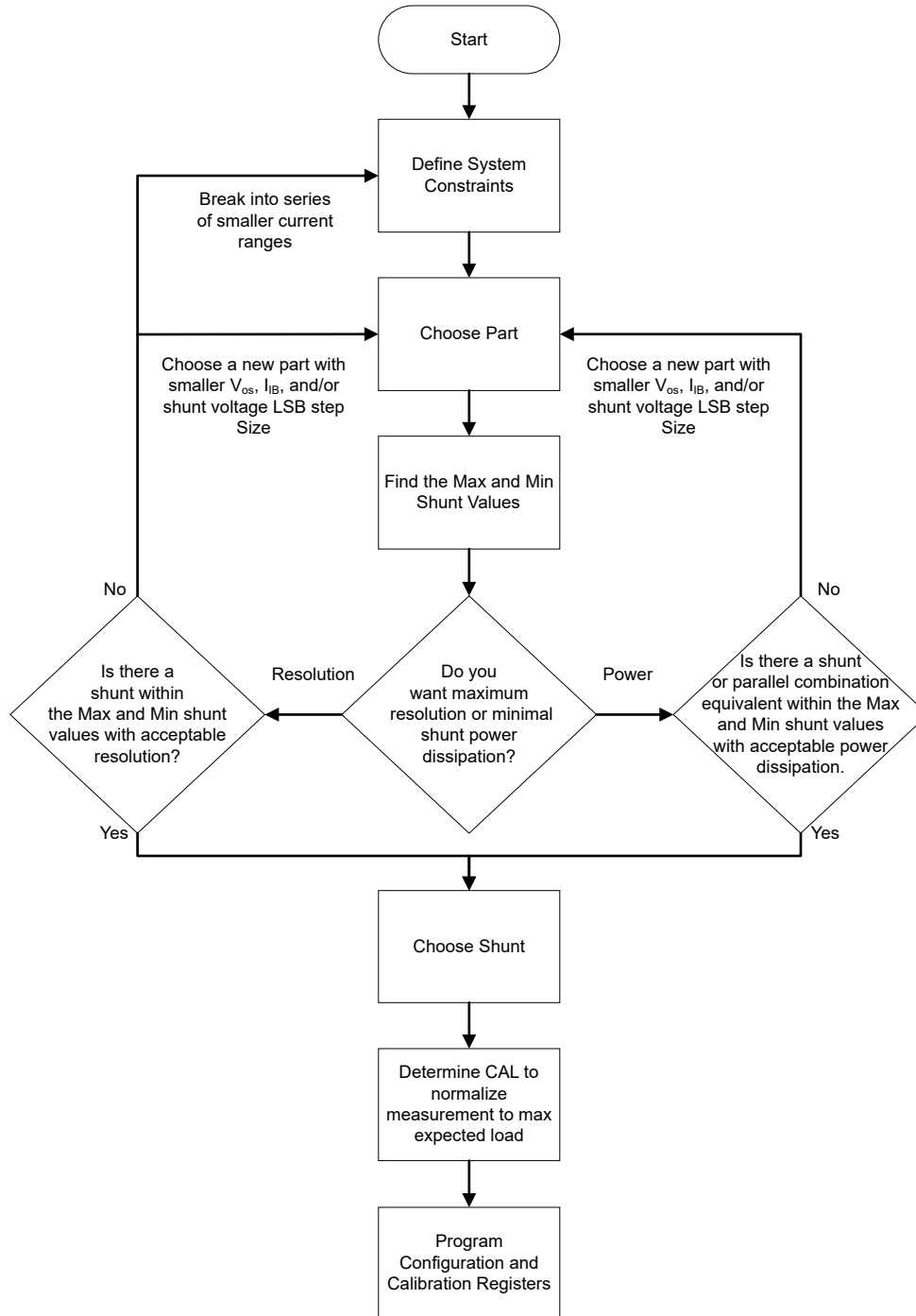


Figure 1-1. Digital Power Monitor Design Flow Diagram

2 Defining Constraints

The first and most crucial step for designing with a digital power monitor is to define your system constraints for the device. These include the common mode voltage expected at the sense pins, the supply voltage you would like to use, the maximum current you want to measure, and the minimum current you want to measure. Common mode voltage and supply voltage are two specifications that can easily be extracted from the data sheet and used to narrow down your options. These specifications must be adhered to insure the device operates correctly and is not damaged. As for the current range the device can measure, the data sheet does not provide any bounds that can be simply looked up. The bounds are not only dependent on device specifications, but on design goals that include shunt power dissipation and resolution. The ensuing steps will provide details on how to assess a given device's current measurement bounds and determine if it will be adequate for your needs.

3 Find The Maximum Shunt Value

The shunt value ultimately determines the current measurement bounds. For a given current range, there may be a range of shunt resistance values that can be used allowing flexibility in your design. The maximum and minimum shunt values need to be calculated, to ensure you choose a shunt that will work for your application. To calculate the max shunt value, you need to look up the shunt voltage input range max listed in the electrical characteristics section of the data sheet. Some devices may have a fixed shunt voltage range as found in the [Table 3-1](#), while others may have ranges that change according to certain register settings such as can be seen in the [Table 3-2](#). One thing to note, is that some devices may have a different name for the shunt voltage input specification. The [Table 3-3](#) lists this specification as V_{DIFF} while the [Table 3-4](#) lists this specification as IIN_{FSR} .

Table 3-1. INA226 Shunt Voltage Input Range

Parameter	Test Conditions	MIN	TYP	MAX	UNIT
INPUT					
Shunt voltage input range		-81.9175		81.92	mV

Table 3-2. INA219 Shunt Voltage Input Range

Parameter	Test Conditions	INA219A			INA219B			UNIT
		MIN	TYP	MAX	MIN	TYP	MAX	
INPUT								
V_{SHUNT} Full-scale current sense (input) voltage range	PGA = /1	0		±40	0		±40	mV
	PGA = /2	0		±80	0		±80	mV
	PGA = /4	0		±160	0		±160	mV
	PGA = /8	0		±320	0		±320	mV

Table 3-3. INA229 Shunt Voltage Input Range

Parameter	Test Conditions	MIN	TYP	MAX	UNIT
INPUT					
V_{DIFF} Shunt voltage input range	$T_A = -40^\circ\text{C}$ to $+125^\circ\text{C}$, ADCRANGE=0	-163.84		163.84	mV
	$T_A = -40^\circ\text{C}$ to $+125^\circ\text{C}$, ADCRANGE=1	-40.96		40.96	mV

Table 3-4. LM5056A Shunt Voltage Input Range

Parameter	Test Conditions	MIN	TYP	MAX	UNIT
Telemetry Accuracy					
IIN_{FSR} Current input full scale range	CL = GND		54.4		mV
	CL = VDD		27.0		

To find the $R_{SHUNT\ MAX}$ divide the max shunt input voltage value by your max expected current value.

$$R_{SHUNT\ MAX} \leq \frac{\text{Shunt Voltage Input Range}_{MAX}}{I_{Sense\ MAX}} \quad (1)$$

4 Find The Minimum Shunt Value

Upon calculating the max shunt value, the minimum shunt value should also be determined. To determine this value, you need to know the lowest meaningful shunt input voltage value. At minimum, this value corresponds to the shunt voltage register 1 LSB step size. There are some devices, like the INA209, INA219, and INA220 that for certain ADC configuration settings require a register bit higher than the LSB to be used, because the conversion time will not be sufficient to achieve the full possible resolution as alluded to in [Table 4-1](#)'s test conditions column. Be sure to check the Vsense register to gain better insight into what sense values are possible and how the data is stored. Below is the [Table 4-2](#) for the INA228. Here we can see that the lowest resolvable shunt voltage neglecting noise corresponds to 312.5nV/LSB or 78.125nV/LSB depending on a ADCRANGE setting found in another register. Also we can see the register LSB does not correspond to the lowest ADC measurement LSB, which is important to be aware of when reading from the device.

Table 4-1. VSHUNT Register Field Descriptions

Bit	Field	Type	Reset	Description
23-4	VSHUNT	R	0h	Differential voltage measured across the shunt output. Two's complement value. Conversion factor: 312.5 nV/LSB when ADCRANGE = 0 78.125 nV/LSB when ADCRANGE = 1
3-0	RESERVED	R	0h	Reserved. Always reads 0.

To find the ideal $R_{SHUNT\ MIN}$ divide the shunt voltage 1 LSB step size by your minimum expected current value.

$$R_{SHUNT\ MIN} \geq \frac{\text{Shunt voltage 1 LSB step Size}}{I_{Sense\ MIN}} \quad (2)$$

The LSB voltage corresponds the lowest measurable shunt value if error sources are neglected. The primary source of error for low current measurements is the input-referred offset voltage. This will vary with respect to common mode voltage, supply voltage, temperature, and device. As most power devices are bidirectional, you should be able to detect changes in your measured current even when the shunt voltage offset is larger than the shunt voltage LSB step size. Depending on your design, setup, and desired level of accuracy, you can calibrate this error out by taking an initial no load measurement at your common mode voltage and current conditions. If you have no intention of calibrating and are concerned about the percent error for your lower measurements, you can calculate $R_{SHUNT\ MIN}$ according to input referred offset voltage max and the percent error you can tolerate.

$$R_{SHUNT\ MIN} \geq \frac{V_{OS\ max}}{I_{Sense\ MIN} \times \frac{\text{error \% allowed}}{100\%}} \quad (3)$$

The other significant source of error particularly noticeable at your lowest measurement is noise. Your device conversion and averaging setting will determine how significantly this impacts your measurement. As can be seen from the [Figure 4-1](#), longer conversion times lead to measurements with much less noise. With typically the longest conversion time, averaging can also be used to further reduce variability from noise.

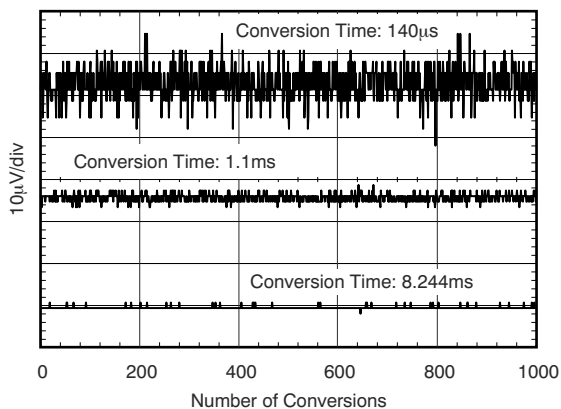


Figure 4-1. INA226 Noise vs. Conversion Time

Table 4-2. INA219 ADC Conversion Time table

Parameter	Test Conditions	INA219A			INA219B			UNIT
		MIN	TYP	MAX	MIN	TYP	MAX	
ADC TIMING								
ADC conversion time	12 bit		532	586		532	586	µs
	11 bit		276	304		276	304	µs
	10 bit		148	163		148	163	µs
	9 bit		84	93		84	93	µs

5 Maximum Resolution or Minimum Shunt Loss

Depending on how wide your current range is, you might have the option of optimizing your design for maximum resolution or for minimizing power dissipated across your shunt. The shunt resistor you choose will be the key factor for determining the resolution and shunt dissipation.

The calculated $R_{SHUNT\ MAX}$ is the value needed for maximum resolution assuming the calculated value is also larger than $R_{SHUNT\ MIN}$. The value calculated may not be a standard value and therefore unavailable from part distributors or even manufacturers. Consequently, you will need to adjust your value to match what can practically be done. To get the max desired current within your measurement range with max measurement resolution, you will need to choose a resistor value smaller than what you calculated, preferably the nearest, affordable, normally stocked option you can find.

For minimizing the power dissipation across the shunt, you simply need to use a resistor value smaller than $R_{SHUNT\ MAX}$. The exact value chosen will be dependent upon what error is allowed at the minimum sense current, where the error is dominated by the input offset voltage. If you are able to calibrate out the device input offset voltage and use one of the larger conversion settings you may be able to choose a shunt value at or close to $R_{SHUNT\ MIN}$.

6 What to Do if the Measurement Range Is Insufficient

In the event that not a single shunt can satisfy your design constraints, you may need to explore different options. The simplest option might be to use a different device. Devices with lower input offset voltage, with lower input bias current, and with more ADC bits of resolution, typically will allow you to measure a broader range of current. If these are still inadequate, you will need to get creative. One option would be to multiplex a parallel network of shunt resistors like in this [Figure 6-1](#).

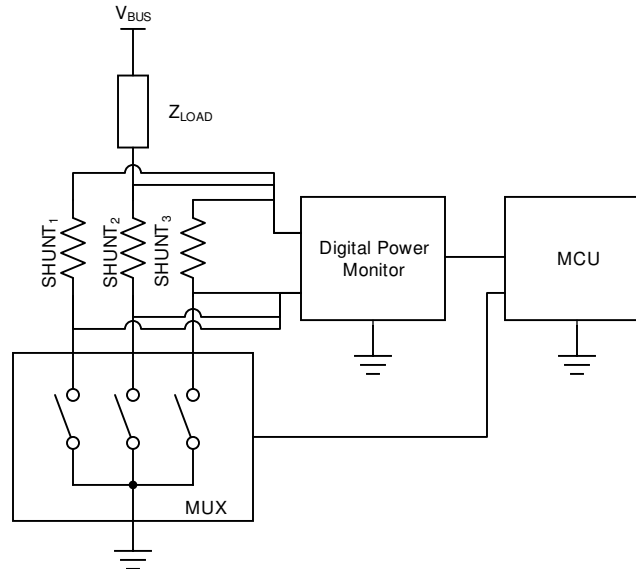


Figure 6-1. Low-side Multiple Shunt Example

7 Determine the Current LSB and Calibration Coefficient

The primary principle to understand is that all power monitors measure voltages. These voltages can then be used to calculate current and power provided the user knows the value of the shunt resistance being used. Voltage registers have fixed LSB values defined in the data sheet electrical characteristics section, whereas current and power registers have flexible LSBs based upon design criteria. The device needs the user tell it what those LSB values are. For convenience, we recommend scaling the LSB according the register bits and the max current you plan to measure. Consequently, we provide the [Equation 4](#).

$$\text{CURRENT_LSB} = \frac{\text{Max Expected Current}}{2^{(\text{Valid Current Register Bits} - \text{Sign Bit})}} \quad (4)$$

Upon determining the current LSB, you can then determine the appropriate calibration coefficient. Depending on the device you will use an [Equation 5](#) or an [Equation 6](#). Refer to the device data sheet implementation section to determine which is appropriate.

$$\text{CAL} = \frac{\text{Datasheet Coefficient}}{\text{CURRENT_LSB} \times R_{\text{SHUNT}}} \quad (5)$$

$$\text{SHUNT_CAL} = \text{Datasheet Coefficient} \times \text{CURRENT_LSB} \times R_{\text{SHUNT}} \quad (6)$$

After calculating the coefficient, you need to verify that the value does not exceed the register size. The following [Equation 7](#) will help you determine if the value satisfies that criteria. If you find your calibration coefficient to be too large, you have three options that include choosing a larger shunt, scaling the register to a higher max current than what is expected, or choosing a different device or ensemble of devices with greater measurement range.

$$\text{CAL or SHUNT_CAL} \leq 2^{(\text{Writeable Calibration Register Bits})} \quad (7)$$

Several calibration registers have 16 bits, yet not all of the bits may be writable for the user as can be seen from the [Table 7-1](#).

Table 7-1. Calibration Register (05h) (Read/Write) Description

BIT #	D15	D14	D13	D12	D11	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1	D0
BIT NAME	—	FS14	FS13	FS12	FS11	FS10	FS9	FS8	FS7	FS6	FS5	FS4	FS3	FS2	FS1	FS0
POR VALU E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

One subtle nuance to recognize is that your CURRENT_LSB as well as several other values may be impossible to read from the device. The only values you can possibly read correspond to values that directly relate to the shunt voltage register. This issue can become quite noticeable if the difference between $R_{\text{SHUNT MAX}}$ and $R_{\text{SHUNT MIN}}$ is quite large and you proceed with a shunt value close to $R_{\text{SHUNT MIN}}$ to minimize power dissipation. In these cases, your current LSB will be significantly smaller than what can actually be resolved. To realize this, consider a simple high level example where the max shunt voltage is 80mV and the chosen shunt results in 40mV for the highest expected current, which you decide to program the calibration register to scale to. If the shunt voltage register has the same number of numerical bits as the current register, the CURRENT_LSB will be directly equivalent to half a shunt voltage LSB. As the current is actually calculated from the shunt voltage register, reading a single bit from the current register will not be attainable even if in reality the measurable current matches the CURRENT_LSB.

8 Programming Your Device Registers

Once the calibration value is determined, you can write that value to the calibration register. To ensure you read meaningful results, you will also likely need to program the configuration register(s) as the default settings might not be adequate for your design. As the configuration register(s) have ADC conversion settings, averaging settings, programmable gain settings, or some setting for selecting an ADC range, neglecting to program it can lead to significant deviations from expectation.

9 Summary

This application note shows a basic method for designing with a digital power monitor. Key specifications were discussed for determining shunt resistor range. Subsequently some insight was provided on how a shunt value can be tailored for resolution or power dissipation. After stressing the importance of the shunt, current range scaling was discussed along with programming registers.

IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATASHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES "AS IS" AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, or other requirements. These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you will fully indemnify TI and its representatives against, any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI's products are provided subject to TI's Terms of Sale (<https://www.ti.com/legal/termsofsale.html>) or other applicable terms available either on [ti.com](https://www.ti.com) or provided in conjunction with such TI products. TI's provision of these resources does not expand or otherwise alter TI's applicable warranties or warranty disclaimers for TI products.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2021, Texas Instruments Incorporated