![Texas Instruments logo]

Monitoring Voltage, Current, and Temperature Using the UCD90xxx Devices

Michael Vega　　　　　　　　　　　　　　　　　　　　*PMP-LP Supervisors and Sequencers*

ABSTRACT

This application report discusses how to set up the UCD90xxx (excluding the UCD908x) Sequencer integrated circuits so that they can measure voltages which can represent voltage, current, and temperature measurements of power supplies. Note that although monitoring is essential for sequencing, this document does not cover setting up for sequencing.

The example discussed in this document strongly focuses on using the UCD9012x evaluation module (EVM), but the concepts discussed apply to any particular system in which a UCD90xxx device is embedded. From a setup point of view, all configurations are made using the Fusion Digital Power™ designer software. The commands that system designers need to implement in their system to interact with the UCD9012x using PMBus in the application circuit are discussed in the last section of this report.

Note that in the example used, it is recommended that jumpers J22, J25, J30, and J33 are removed. These connections are specific for power supply margining which is discussed in another document (SLVA375).

Contents

List of Figures

Fusion Digital Power is a trademark of Texas Instruments.

1 Setting Up a Rail for Voltage Monitoring

The UCD90xxx devices have multiple MON pins that give access to the ADC. The ADC has an internal 2.5V reference which requires that the MON pins do not exceed 2.5 V for proper results across all measurement range. Any of the MON pins can be selected for monitoring voltage. Based on expected voltage range (max 2.5 V input) decide if a resistor voltage divider is needed. The typical circuit for voltage monitoring looks like Figure 1. When creating a layout, ensure that connection is as close as possible to monitored voltage source (Kelvin Connection). Due to the fact that the ADC input is single ended with reference to device VSS, ensure that the UCD90xxx ground connections are separated from high current ground return paths of the application system.
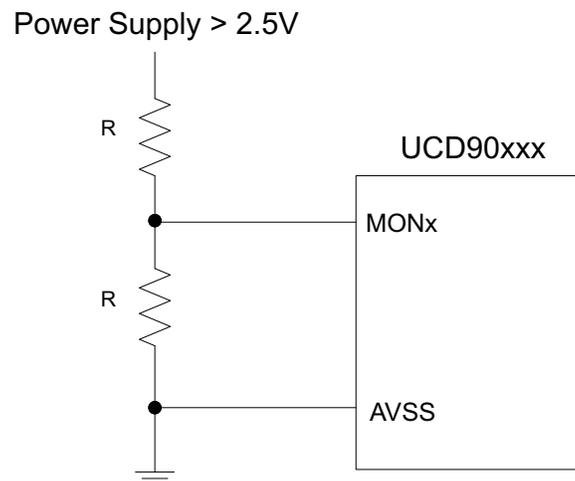
Power Supply > 2.5V

Figure 1. Voltage Monitoring Circuit (Power Supply > 2.5V)

Each UCD90xxx device supports up to a given number of rails. Every rail must contain at least one of the following: voltage measurement, current measurement, temperature measurement, a power-supply enable and a margining output. For this discussion the first rail that is set up is Rail #1 which corresponds to a 3.5-V power supply that is included in the UCD9012xEVM (HPA459). Before configuring, first ensure that the EVM is connected so that the UCD9012x can monitor voltage from the 3.5-V power supply. Using the HPA459 Rev. A board schematic and layout as reference, locate the J38 connection and place a shunt jumper to it. This gives access to the power supply enable pin. On the EVM, locate J20 connection, and place a shunt jumper across pins 1 and 2 of J20. This makes an internal connection to the MON1 pin of the UCD9012x and the 3.5-V power supply. On the EVM, locate J34 connection, and place a shunt jumper connecting pins 1 and 2 to connect to the pullup to 3.3 V forcing the power-supplyenable to always be asserted.

Once the circuit connections have been made, Rail #1 is ready to be configured. Using the Fusion Digital Power™ software select Pin Assignment from the tab menu within the Configure function. All rails that are configured are listed in the Rails section. Confirm that Rail #1 is set to monitor voltage using MON1. This must be true if this exercise was started using an UCD9012x that was not configured. Notice that in the Rails section, Rail #1 is listed with *Pin 1 MON1* under the Voltage column and *Pin 11 GPIO1* under the Enable column. To demonstrate that having an enable setup is not required for measuring voltage; the GPIO1 is reconfigured as a GPO. The instructions to change the function of GPIO1 are just for demonstration purposes, and GPO configurations are discussed in more detail in a GPO dedicated section. Configuring a rail that does not show in the Rails section is discussed later in this document
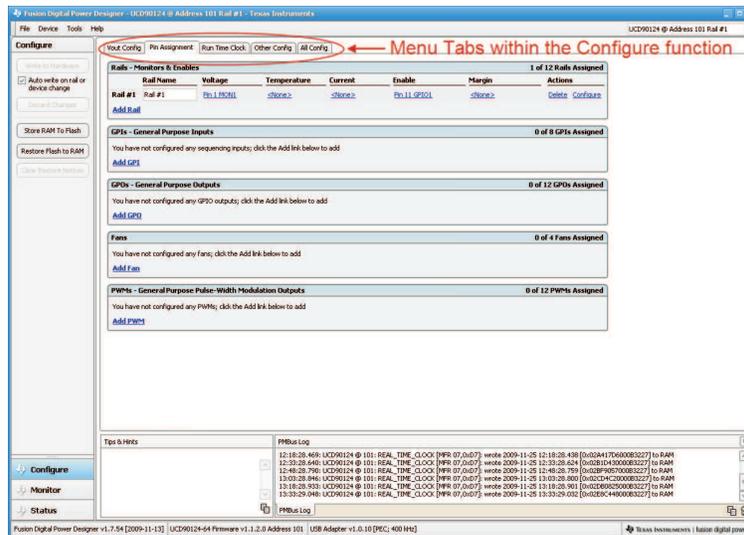
Figure 2. Pin Assignment Screen Within the Configure Function

To reconfigure GPO1 so that it does not act as an enable, click on Pin11 GPIO1 under the Enable column, and select the link message that is on top of the screen (Figure 3). Within the GPO section, click on Add GPO. A GPO is assigned automatically. If this GPO is not GPIO1, then click on the GPIO name so that the GPO can be reassigned (Figure 4). Select GPIO1 from the GPOs available list (Figure 5).
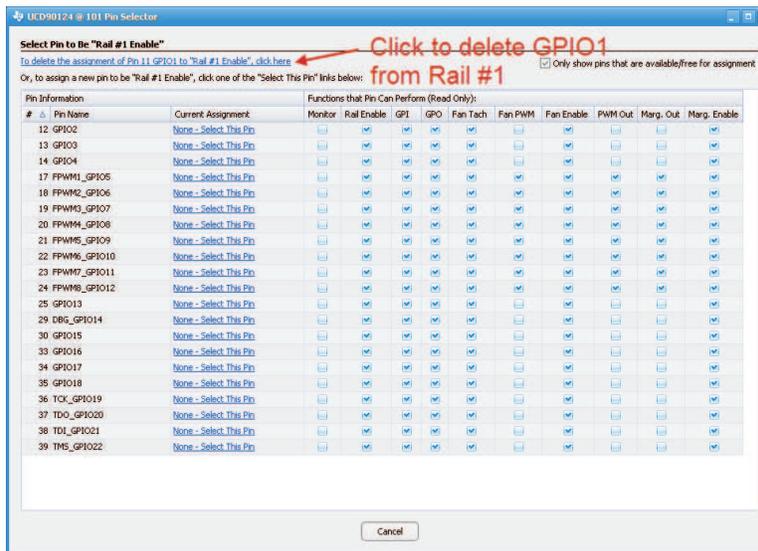
Figure 3. Delete GPIO1 from Rail #1
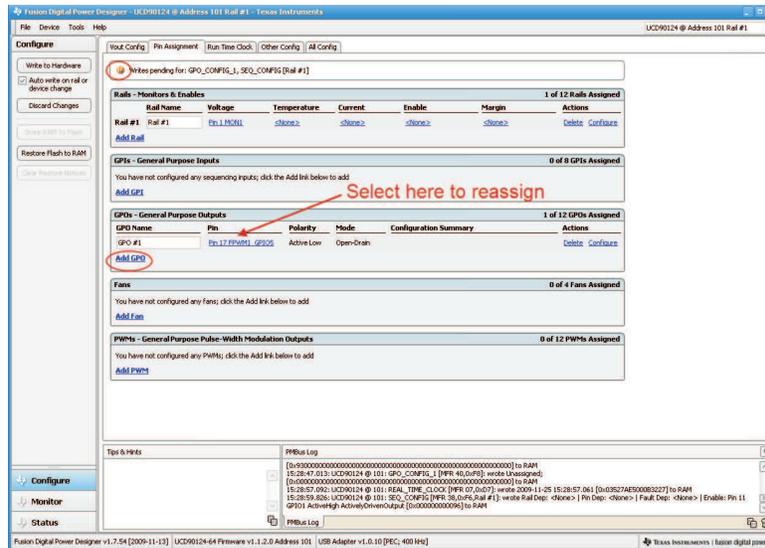
Figure 4. Create GPO #1
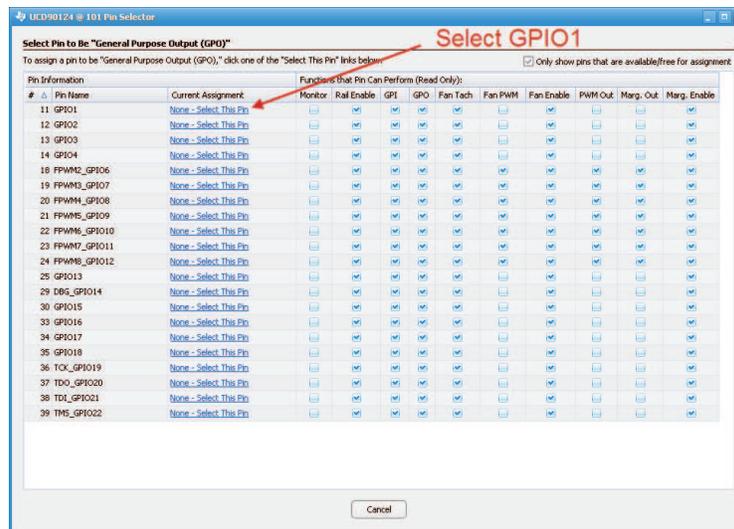
Figure 5. Select GPIO1

Notice that when changing configurations of the GPIOs, an orange ball with a U shows. This indicates that a change has been requested with the software but, that it has not been written to the IC yet. To complete writing the value to the IC, click on the Write to Hardware button on the top left of the screen (Figure 6).
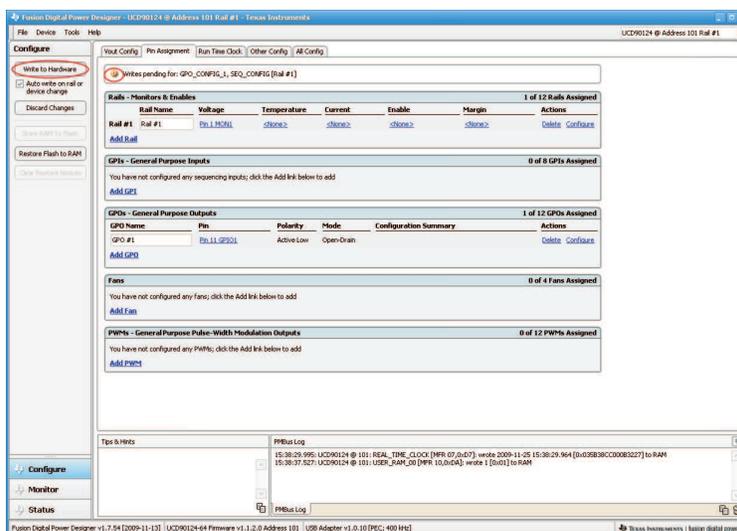
Figure 6. Write to Hardware

Going forward in the document, it is expected that all writes are completed accordingly whenever writing a value is instructed. It is unnecessary to click Write to Hardware after every immediate change of values. When making several changes, the user can wait until completing all changes before clicking on Write to Hardware. The orange U balls remains on the screen until actually writing to the IC. The write to hardware is simply writing to RAM. Any IC resets causes a loss of changes that are not committed to data flash.

The reason for selecting MON1 as the monitor pin is due to the hardwired connections that are in the HPA459 EVM. Although in this example it is Rail #1 that is being configured, this does not mean that MON1 has to be used for Rail #1 on every customer application.

Now that Rail #1 is confirmed to be linked to MON1, select Other Config from the Menu Tabs. Given that when a voltage measurement is the measurement of interest, the focus is on setting the Vout Scale Monitor. The Vout Scale Monitor is within the Scaling section. The maximum voltage that can be measured by the UCD9012x ADC is 2.5 V. Any voltage expected to be higher than this must be scaled externally before reaching any of the MON pins. For demonstration purposes, the EVM already has voltage dividers at each MON pin. The voltage dividers reduce the input voltage to half. The Vout Scale Monitor must be set so that the UCD9012x reports measured voltage based on the actual power supply voltage and not the direct input voltage to the MON pin. In this case, the Vout Scale Monitor is set to 0.500 (Figure 7).
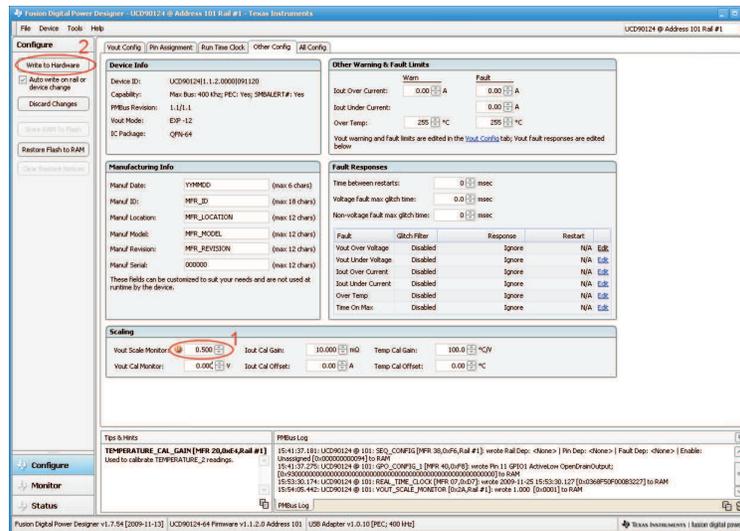
Figure 7. Set Vout Scale Monitor

So far, this exercise has considered only the minimum requirement when using the UCD9012x to measure any voltage applied to a given MON pin. To verify the measurement seen by the UCD9012x, click on the Monitor function. The last numeric measurement value for Rail #1 in the Readings section labeled as Vout #1 can be seen as well as the plot of the latest measurements. If the plot is not visible, ensure that Vout is checked in the Show/Hide Plots: section (Figure 8).
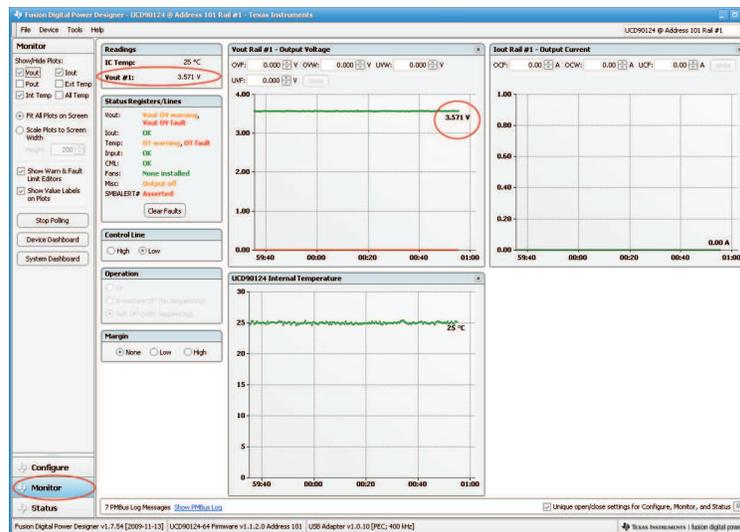
Figure 8. Voltage Measurement for Rail #1

2   Setting Up a Rail for Current Monitoring

Setting up current monitoring is very easy if you understood how to do voltage monitoring. The UCD90xxx ADC inputs truly measure voltage signals. To obtain a current measurement we need to let the UCD90xxx know what voltage to current conversion it must do so that it can report its measurements in actual units of current (mA).

The most common way to measure a current flow is to measure the voltage across a resistor that is in the series path of the current flow. The sense resistor is selected so that it does not incur a significant voltage drop when the maximum expected current flows through it. System designers would have to select them based on their current requirements. The UCD90xxx ADC only has single input and is referenced with respect to IC VSS. It is ideal that a circuit is used to convert the voltage across the sense resistor which is likely to be on the high side of a power supply current path to a voltage amplified and referenced to VSS. The INA196 is a current shunt monitor that can be used to measure the voltage across the current sense resistor and provide a voltage signal with a gain of 20 back to the UCD90xxx monitor inputs (Figure 9). When creating layout, ensure that connections to sense resistor are Kelvin Connection. The current to voltage circuit is to be expected as part of the UCD90xxx circuit for which all circuitry other than sense resistor should not be in the high current ground paths.
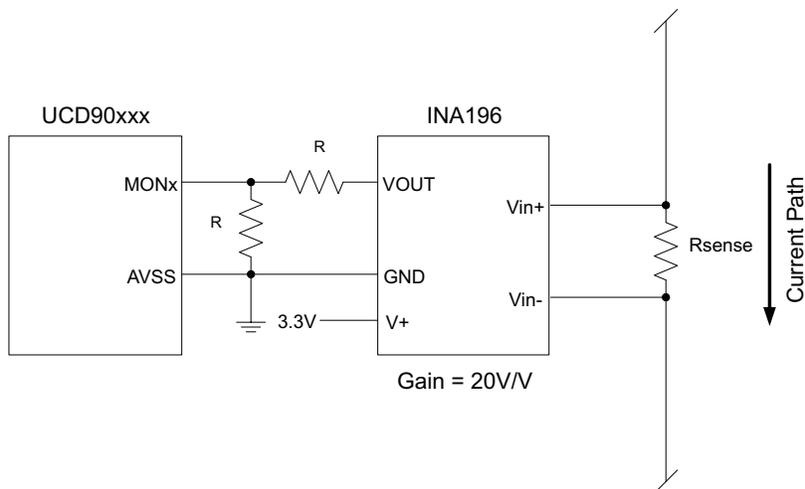
Figure 9. Current Monitoring Circuit Using the INA196

The UCD9012x EVM has an INA196 current shunt monitor IC that takes a differential voltage input and amplifies it 20 times out to a single voltage output. The voltage provided in the input is the current that flows through a 100-mΩ, ½-W sense resistor. The current to be measured is a 24-Ω resistor in series with the 100-mΩ sense resistor loading the 3.5-V Rail #1 that was set up in our voltage monitoring example.

The EVM board connections for current monitoring consist of connecting pins 5 and 6 (Current VR1) of J28 with a shunt jumper. This will connect the INA196 circuit with the MON3 input of the UCD9012x. For now, ensure that J26 connection is open on the EVM disconnecting the Rail #1 power supply from the load.

On the Fusion GUI, while in the Configure function, select Pin Assignment from the Menu Tab. Associate the current monitoring to be set up with Rail #1. Click on the <None> under the Current column (Figure 10). Select MON3 from the list of MON inputs (Figure 11).
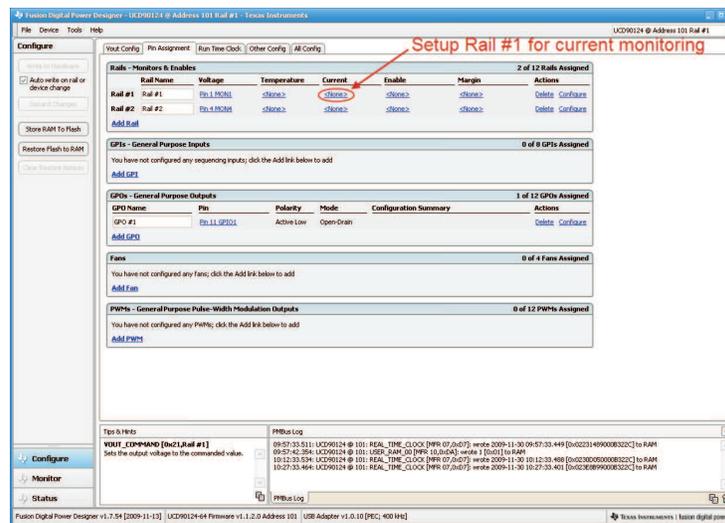
Figure 10. Rail #1 Current Setting
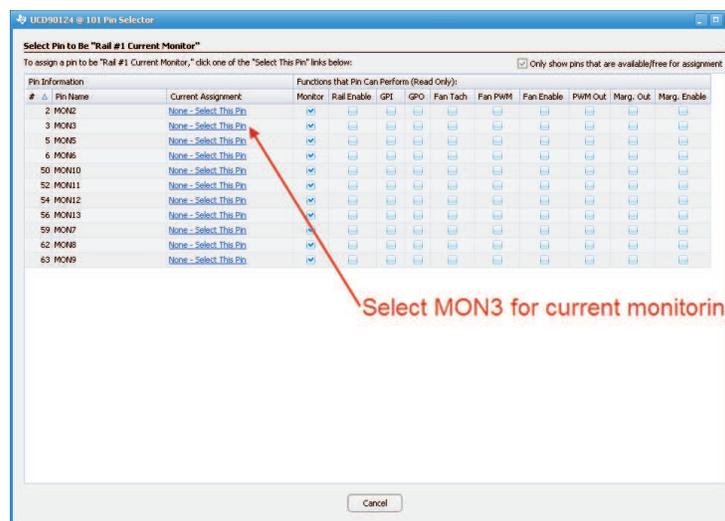
Figure 11. Select MON3 for Current Monitoring

Select Other Config from the Menu Tab. Verify that Rail #1 is selected from drop down list at the top right of the screen. The Iout Cal Gain is in terms of mΩ. In this example the gain is determined as 100 mΩ times 20 (from the INA196 gain) and then divided by 2 (due to the voltage divider at the MON3 input) giving a final Iout Cal Gain of 1000 mΩ. Write 1000.00 into the Iout Cal Gain. If necessary the Iout Cal Offset can provide some adjustments for the current measurement.

Go to the Monitor function and check for the current measurement for Rail #1. If the Measurement Plot does not show, make sure to have it checked on the top left of the Monitor screen. Notice that current is close to 0 A. Connect a shunt jumper to J26 (connecting the load). See that the current measurement rises close to 0.14 A (Figure 12).
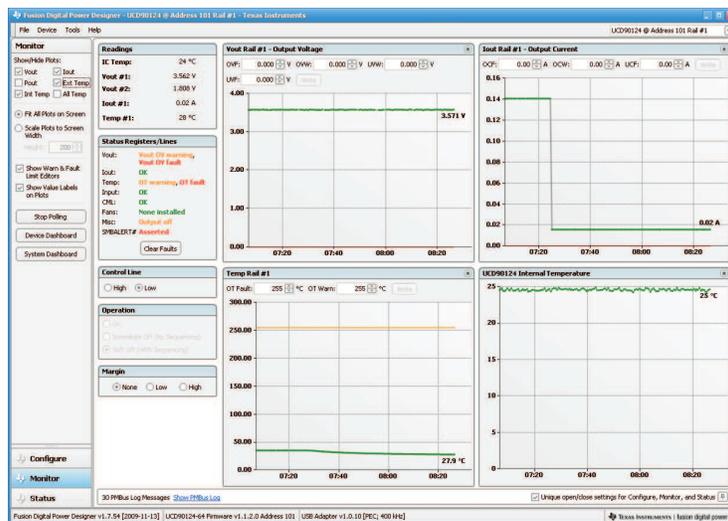
Figure 12. Rail #1 Voltage and Current Measurements

3   Setting Up a Rail for Temperature Monitoring

To measure temperature using the UCD9012x EVM it is required to configure the circuit accordingly. The UCD9012x EVM has a temperature monitor IC (Figure 13) that converts IC ambient temperature sensed to voltage defined by the linear function $Vout_{(V)} = 0.01V/°C × T(°C) + 0.5V$. This IC is in a connection path to MON2 input of the UCD9012x. To connect the MON2 input to the temperature sensing IC, connect J24 with a jumper shunt so that only pins 5 and 6 of J24 are shorted. To bypass the voltage divider at the MON2 input, short pins 2 or 4 of J24 with test point TP15 using a jumper wire.
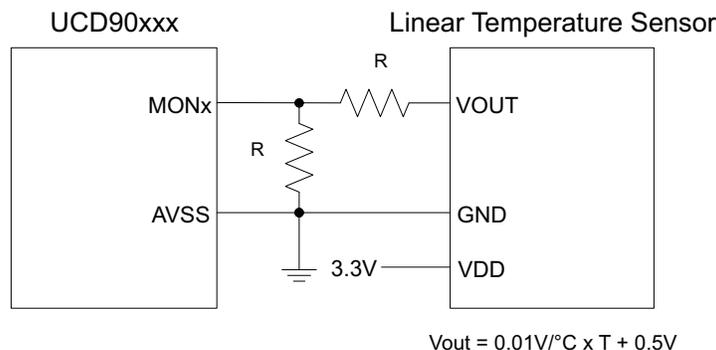
Figure 13. Temperature Monitoring Circuit in UCD9012x EVM

Assign the MON2 to Rail #1 temperature monitoring. On the Fusion GUI, while in the Configure function, select Pin Assignment from the Menu Tab. Click on the <None> under the Temperature column for Rail #1. Select MON2 from the list of MON inputs. MON2 is used in this example because of fixed connections at EVM. Any MON input could be used in any other application system.

For the UCD9012x to report the voltage input in units of °C the Temp Cal Gain must be set accordingly. The Temp Cal Gain is in units of °C/V. Take the temperature to voltage function and express to solve for °C and obtain $T(°C) = 100 × Vout(V) − 50$. Based on a linear equation of type $y = mx + b$ in which $m = Δy / Δx$ and b is the value of y when x = 0 then we determine that Temp Cal Gain = 100°C/V and Temp Cal Offset = −50°C.

Go to the Monitor function and check for the temperature measurement for Rail #1. If the Measurement Plot does not show, make sure to have Ext Temp checked on the top left of the Monitor screen. The temperature sensor IC is in the proximity of the 100 mΩ sense resistor used for current monitoring. Most of the temperature change for Rail #1 monitor will be due to power dissipation in sense resistor. Remove J26 to stop current flow in sense resistor to see how the temperature for Rail #1 drops (Figure 14). Replace the jumper and see how the temperature rises.
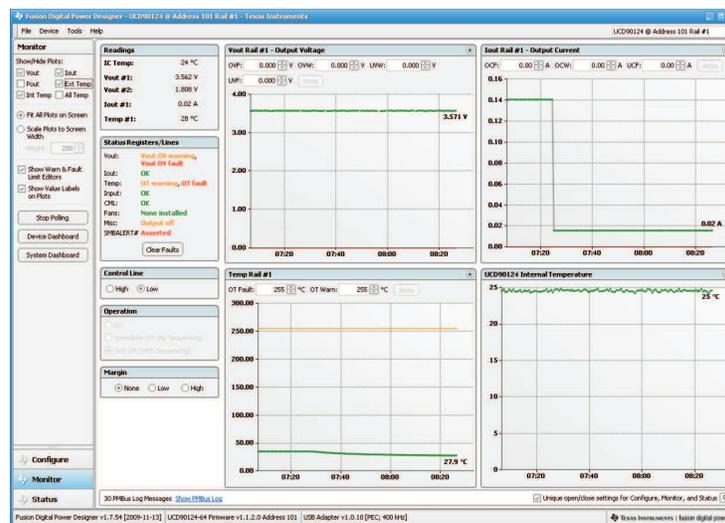
Figure 14. Rail #1 – Voltage, Current and Temperature Measurements

4 Using PMBus to Read Measurements

The information discussed in this section references to *UCD90xxx Sequencer and System Health Controller PMBus Command Reference* (SLVU352) and the *PMBus Power System Management Protocol Specification Part II - Command Language, Revision 1.1, dated 5 February 2007* available from www.pmbus.org. Refer to these documents for more detailed understanding of the PMBus commands available to use with the UCD90xxx devices.

We will list in this section I²C commands needed to implement different PMBus commands. All byte values are represented in hexadecimal format. This is the code to understand all I²C communication that occurs:

- [St] - This is the I²C Start bit.
- [Sr] - This is the I²C Restart bit. It is identical to the Start bit.
- [Sp] - This is the I²C Stop bit.
- [A] - This is the I²C Acknowledge bit.
- [N] - This is I²C No Acknowledge bit or NACK.
- [AddrW] - This is the I²C device address with the Write bit.
- [AddrR] - This is the I²C device address with the Read bit.
- [W:x55] - This is an example of a write byte for value 55 hexadecimal.
- [R:Data_n] - This is to indicate that a byte is being read by the I²C master. The n subscript is an ordered integer use to distinguish multiple bytes read back. Data_1 would be the MSB and Data_2 the LSB for two bytes read.

4.1 Reading Voltage

Here's an example on how to read the voltage from a measurement in Rail #1. To read a voltage measurement, you read two PMBus commands and make a calculation. The voltage is calculated as Voltage = V x 2^X; in which V is the 16-bit unsigned integer obtained from the READ_VOUT command and X is the 5-bit signed two's complement integer obtained from the VOUT_MODE command.

- **Select the Rail:** Given that there's only one READ_VOUT command and multiple rails to which the

READ_VOUT command may be associated with, then the first thing that must be done before attempting to read voltage is to specify what rail it is associated with. The PAGE command (0x00) is used to designate which rail is associated with any PMBus command that has a PAGE scope. Table 1 shows the relationship between the desired rail and the value for the PAGE command. Our example is based on Rail #1 which gives us the value 0 for PAGE. The highest rail value possible will be limited to the UCD90xxx device that is being used. For example the UCD90120 supports a maximum of 12 rails. See the device data sheet to determine the maximum number of rails that the device supports.

Write 0x00 to PAGE command (0x00).

[St] [AddrW] [A] [W:x00] [A] [W:x00] [A] [Sp]

Table 1. Relationship Between Page and Rail

Page	Output Rail
0	1
1	2
2	3
3	4
...	...
−1	n

- **Establish Range and Revolution:**PMBus allows to manage wide ranges of voltage measurements. The VOUT_MODE command is used for setting up the range and the resolution of all values related to output voltage. As defined in the PMBus specification, The VOUT_MODE is a one byte command in which bits [4:0] represent the 5-bit two's complement integer for the N exponent in the equation Voltage = V x 2^N. Table 2 represents the exponent value for the different ranges that are supported. Bits [7:5] represent the mode for which will always be LINEAR MODE [0x000] in the UCD90xxx devices. VOUT_MODE is a command that is expected to be written once during customer manufacturing. From a host perspective the I²C master should only need to read VOUT_MODE once for each defined rail.

  Read the exponent value from the VOUT_MODE command (0x20).

  [St] [AddrW] [A] [W:x20] [A] [Sr] [AddrR] [A] [R:Data_1] [N] [Sp]

  Let's assume that the data read back was 0x14 which when converting to two's complement for a 5-bit value gives -12 decimal. By looking at Table 2 observe that the maximum range for the rail voltage is 7.99988V, which is reasonable for a 3.5V rail.

Table 2. Exponent Influence on Voltage Range and Resolution

Exponent	Range (V)		Resolution (mV)
-9	0	63.99805	1.95313
-10	0	31.99902	0.97656
-11	0	15.99951	0.48828
-12	0	7.99976	0.24414
-13	0	3.99988	0.12207
-14	0	1.99994	0.06104
-15	0	0.99997	0.03052

- **Read the Voltage:** To read the V value for the equation Voltage = V x 2^N use command READ_VOUT (0x8B). The READ_VOUT is a two-byte command.

  Read the V value from the READ_VOUT command (0x8B)

  [St] [AddrW] [A] [W:x8B] [A] [Sr] [AddrR] [A] [R:Data_1] [A] [R:Data_2] [N] [Sp]

  Let's assume that the data read back was Data_1 = 0x39 and Data_2 = 0x2C. The full value of V = 0x39 x 256 + 0x2C = 14636 decimal.

- **Calculate the Voltage Measurement:** Now we have all the data necessary to calculate the measured voltage. Solving the equation Voltage = V x 2^N

  Voltage = 14636 x 2^{-12} = 3.573 V

4.2 Reading Current

The current measurement must be associated with a rail. This example is based on a current that is assigned to Rail #1. Reading current can be seen as an extension of the process to read voltage measurement described above or as a measurement for a different rail. Reading one command is all that is needed to calculate the current measurement in units of Amperes. The current is calculated as Current $= I \times 2^X$; in which I is the 11-bit signed two's complement integer obtained from the 11 least significant bits of READ_IOUT and X is the 5-bit signed two's complement integer obtained from the 5 most significant bits of READ_IOUT.

- **Select the Rail:** If this process was done right after the previous voltage measurement reading example then there would be no need to set the PAGE command. When the current measurement reading is done after random system activity from which we can't guarantee that the PAGE is set appropriately it would be required to write the PAGE command as described in the previous example.

  Read the I value and the exponent: The READ_IOUT (0x8C) is a two-byte command that contains the exponent (X) and the I value for the equation Current $= I \times 2^X$.

  Read READ_IOUT command (0x8C)

  [St] [AddrW] [A] [W:x8C] [A] [Sr] [AddrR] [A] [R:Data_1] [A] [R:Data_2] [N] [Sp]

  Let's assume that the data read back was Data_1 = 0xA2 and Data_2 = 0x40. Breaking down to the 11 least significant bits you get that I = 576 decimal. The 5 most significant bits give you 20 decimal which its two's complement leads to an exponent of -12.

- **Calculate the Current Measurement:** Now we have all the data necessary to calculate the measured current.

  Solving the equation Current $= I \times 2^X$

  Current $= 576 \times 2^{-12} = 0.140$ A

4.3 Reading Temperature

If the user understand how to make a current reading, then the user should have no problem learning how to make a temperature measurement reading. The command used for reading a temperature associated with a given rail is READ_TEMPERATURE_2 (0x8E). The calculated temperature measurement is in units of °C. The temperature is calculated as Temperature $= T \times 2^X$; in which T is the 11-bit signed two's complement integer obtained from the 11 least significant bits of READ_TEMPERATURE_2 and X is the 5-bit signed two's complement integer obtained from the 5 most significant bits of READ_TEMPERATURE_2.

- **Select the Rail:** The PAGE command is set just as it was done with voltage and current measurement readings.

  Read the T value and the exponent: The READ_TEMPERATURE_2 (0x8E) is a two-byte command that contains the exponent (X) and the T value for the equation Temperature $= T \times 2^X$.

  Read READ_TEMPERATURE_2 command (0x8E)

  [St] [AddrW] [A] [W:x8E] [A] [Sr] [AddrR] [A] [R:Data_1] [A] [R:Data_2] [N] [Sp]

  Let's assume that the data read back was Data_1 = 0xDB and Data_2 = 0x21. Breaking down to the 11 least significant bits you get that T = 801 decimal. The 5 most significant bits give you 27 decimal which its two's complement leads to an exponent of -5.

- **Calculate the Temperature Measurement:** Now we have all the data necessary to calculate the measured temperature.

  Solving the equation Temperature $= T \times 2^X$

  Temperature $= 801 \times 2^{-5} = 25.03$°C

Knowing how to configure monitoring is essential for setting up power supply sequencing. Look for a separate application report within the UCD90xxx Product Web folders for how to setup sequencing at www.ti.com.

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, modifications, enhancements, improvements, and other changes to its products and services at any time and to discontinue any product or service without notice. Customers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All products are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its hardware products to the specifications applicable at the time of sale in accordance with TI's standard warranty. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by government requirements, testing of all parameters of each product is not necessarily performed.

TI assumes no liability for applications assistance or customer product design. Customers are responsible for their products and applications using TI components. To minimize the risks associated with customer products and applications, customers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any TI patent right, copyright, mask work right, or other TI intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information published by TI regarding third-party products or services does not constitute a license from TI to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. Reproduction of this information with alteration is an unfair and deceptive business practice. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI products or services with statements different from or beyond the parameters stated by TI for that product or service voids all express and any implied warranties for the associated TI product or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

TI products are not authorized for use in safety-critical applications (such as life support) where a failure of the TI product would reasonably be expected to cause severe personal injury or death, unless officers of the parties have executed an agreement specifically governing such use. Buyers represent that they have all necessary expertise in the safety and regulatory ramifications of their applications, and acknowledge and agree that they are solely responsible for all legal, regulatory and safety-related requirements concerning their products and any use of TI products in such safety-critical applications, notwithstanding any applications-related information or support that may be provided by TI. Further, Buyers must fully indemnify TI and its representatives against any damages arising out of the use of TI products in such safety-critical applications.

TI products are neither designed nor intended for use in military/aerospace applications or environments unless the TI products are specifically designated by TI as military-grade or "enhanced plastic." Only products designated by TI as military-grade meet military specifications. Buyers acknowledge and agree that any such use of TI products which TI has not designated as military-grade is solely at the Buyer's risk, and that they are solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI products are neither designed nor intended for use in automotive applications or environments unless the specific TI products are designated by TI as compliant with ISO/TS 16949 requirements. Buyers acknowledge and agree that, if they use any non-designated products in automotive applications, TI will not be responsible for any failure to meet such requirements.

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

Products		**Applications**	
Audio	www.ti.com/audio	Automotive and Transportation	www.ti.com/automotive
Amplifiers	amplifier.ti.com	Communications and Telecom	www.ti.com/communications
Data Converters	dataconverter.ti.com	Computers and Peripherals	www.ti.com/computers
DLP® Products	www.dlp.com	Consumer Electronics	www.ti.com/consumer-apps
DSP	dsp.ti.com	Energy and Lighting	www.ti.com/energy
Clocks and Timers	www.ti.com/clocks	Industrial	www.ti.com/industrial
Interface	interface.ti.com	Medical	www.ti.com/medical
Logic	logic.ti.com	Security	www.ti.com/security
Power Mgmt	power.ti.com	Space, Avionics and Defense	www.ti.com/space-avionics-defense
Microcontrollers	microcontroller.ti.com	Video and Imaging	www.ti.com/video
RFID	www.ti-rfid.com		
OMAP Mobile Processors	www.ti.com/omap		
Wireless Connectivity	www.ti.com/wirelessconnectivity		

TI E2E Community Home Page   e2e.ti.com