DAC-Based 4-20 mA Current Loop Reference Design

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ISBN: 978-1-6683-3674-8

DAC-BASED 4-20 mA CURRENT LOOP REFERENCE DESIGN

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DAC-BASED 4-20 mA CURRENT LOOP REFERENCE DESIGN

Preface

NOTICE TO CUSTOMERS

All documentation becomes dated, and this manual is no exception. Microchip tools and documentation are constantly evolving to meet customer needs, so some actual dialogs and/or tool descriptions may differ from those in this document. Please refer to our website (www.microchip.com) to obtain the latest documentation available.

Documents are identified with a "DS" number. This number is located on the bottom of each page, in front of the page number. The numbering convention for the DS number is "DSXXXXXXXXA", where "XXXXXXXX" is the document number and "A" is the revision level of the document.

For the most up-to-date information on development tools, see the MPLAB® IDE online help. Select the Help menu, and then Topics to open a list of available online help files.

INTRODUCTION

This chapter contains general information that will be useful to know before using the DAC-Based 4-20 mA Current Loop. Items discussed in this chapter include:

- Document Layout
- Conventions Used in this Guide
- Recommended Reading
- The Microchip Website
- Customer Support
- Document Revision History

DOCUMENT LAYOUT

This document describes how to design the DAC-Based 4-20 mA Current Loop transmitter with MCP48CMD2X DAC family. The manual layout is as follows:

- **Chapter 1. "Reference Design Overview"** – Provides the insight on 4-20mA current loop industry standard.
- **Chapter 2. "Circuit Operation"** – Provides the DAC-Based 4-20 mA transmitter circuit operation.
- **Chapter 3. "Tests and Results"** – Shows the result of performed tests on EV34C35A DAC-Based 4-20 mA Current Loop transmitter board.
- **Appendix A. "Schematic and Layouts"** – Shows the schematic and layout diagrams for the EV34C45A DAC-Based 4-20 mA Current Loop.
- **Appendix B. "Bill of Materials (BOM)"** – Lists the parts used to build the EV34C45A DAC-Based 4-20 mA Current Loop transmitter board.

CONVENTIONS USED IN THIS GUIDE

This manual uses the following documentation conventions:

DOCUMENTATION CONVENTIONS

Description	Represents	Examples
Arial font:		
Italic characters	Referenced books	*MPLAB® IDE User's Guide*
	Emphasized text	...is the *only* compiler...
Initial caps	A window	the Output window
	A dialog	the Settings dialog
	A menu selection	select Enable Programmer
Quotes	A field name in a window or dialog	"Save project before build"
Underlined, Italic text with right angle bracket	A menu path	<u>*File>Save*</u>
Bold characters	A dialog button	Click **OK**
	A tab	Click the **Power** tab
N'Rnnnn	A number in verilog format, where N is the total number of digits, R is the radix and n is a digit.	4'b0010, 2'hF1
Text in angle brackets < >	A key on the keyboard	Press <Enter>, <F1>
Courier New font:		
Plain Courier New	Sample source code	`#define START`
	Filenames	`autoexec.bat`
	File paths	`c:\mcc18\h`
	Keywords	`_asm, _endasm, static`
	Command-line options	`-Opa+, -Opa-`
	Bit values	`0, 1`
	Constants	`0xFF, 'A'`
Italic Courier New	A variable argument	*`file`*`.o`, where *`file`* can be any valid filename
Square brackets [ ]	Optional arguments	`mcc18 [options]` *`file`* `[options]`
Curly brackets and pipe character: { | }	Choice of mutually exclusive arguments; an OR selection	`errorlevel {0|1}`
Ellipses...	Replaces repeated text	`var_name [, var_name...]`
	Represents code supplied by user	`void main (void)` `{ ...` `}`

RECOMMENDED READING

This reference design provides the design overview, theory of operation and test results of the DAC-Based 4-20 mA Current Loop transmitter. Another useful document is listed below. The following Microchip documents are available and recommended as a supplemental reference resource.

- **EV34C35A DAC Based 4-20 mA Current Loop Evaluation Board User's Guide (DS50003613)**

THE MICROCHIP WEBSITE

Microchip provides online support via our website at www.microchip.com. This website is used as a means to make files and information easily available to customers. Accessible by using your favorite Internet browser, the website contains the following information:

- **Product Support** – Data sheets and errata, application notes and sample programs, design resources, user's guides and hardware support documents, latest software releases and archived software
- **General Technical Support** – Frequently Asked Questions (FAQs), technical support requests, online discussion groups, Microchip consultant program member listing
- **Business of Microchip** – Product selector and ordering guides, latest Microchip press releases, listing of seminars and events, listings of Microchip sales offices, distributors and factory representatives

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- Distributor or Representative
- Local Sales Office
- Embedded System Engineer (ESE)
- Technical Support

Customers should contact their distributor, representative or field application engineer (FAE) for support. Local sales offices are also available to help customers. A listing of sales offices and locations is included in the back of this document.

Technical support is available through the website at: http://www.microchip.com/support.

DOCUMENT REVISION HISTORY

Revision A (December 2023)

- Initial release of this document.

Chapter 1. Reference Design Overview

1.1 INTRODUCTION

This chapter provides an overview of the DAC-Based 4-20 mA Current Loop Reference Design and covers the following topics:

- 4-20 mA Current Loop Overview
- Feature Summary
- Design Specifications

1.1.1 4-20 mA Current Loop Overview

In the 1950-1960 era, mechanical dominant process control industry transitioned from pneumatic control to electrical signal control. Analog signals became the medium where the information about the different process variables is transmitted via voltage or current. In the world of wireless and wired transmission systems, 4-20 mA current loop is a dominant industry standard. High accuracy, low complexity with cost effectiveness of the 4-20 mA current loop stands out against the other transmission methods. MCP48CMD21 DAC-Based 4-20 mA Current Loop transmitter offers a reliable solution with high accuracy.

There are different systems in place to use 4-20 mA current loop for processing variables and transmit control signals. Figure 1-1, Figure 1-2 and Figure 1-3 show a 2-wire, 3-wire and 4-wire system block diagram.

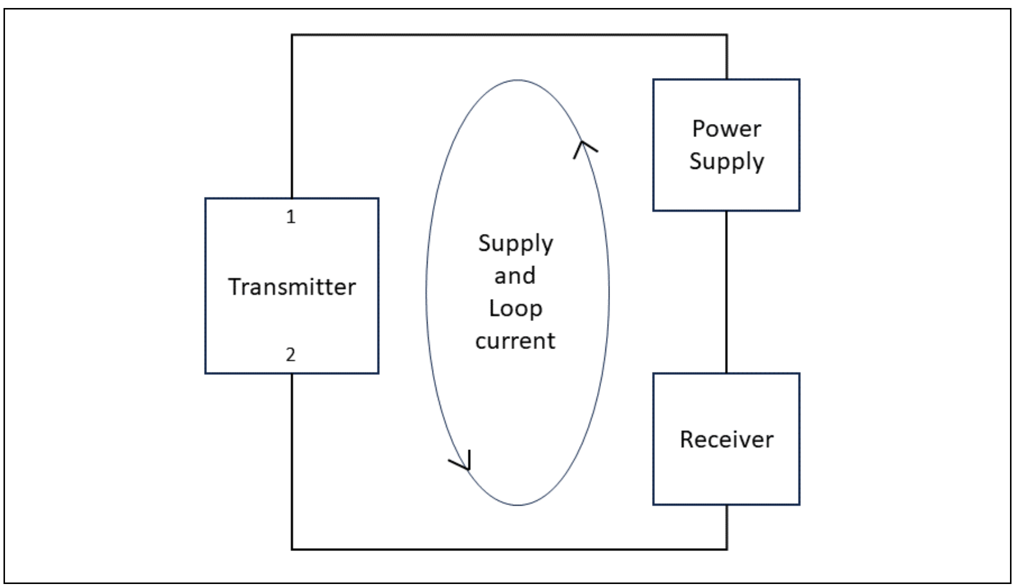


FIGURE 1-1: *2-Wire Connection.*

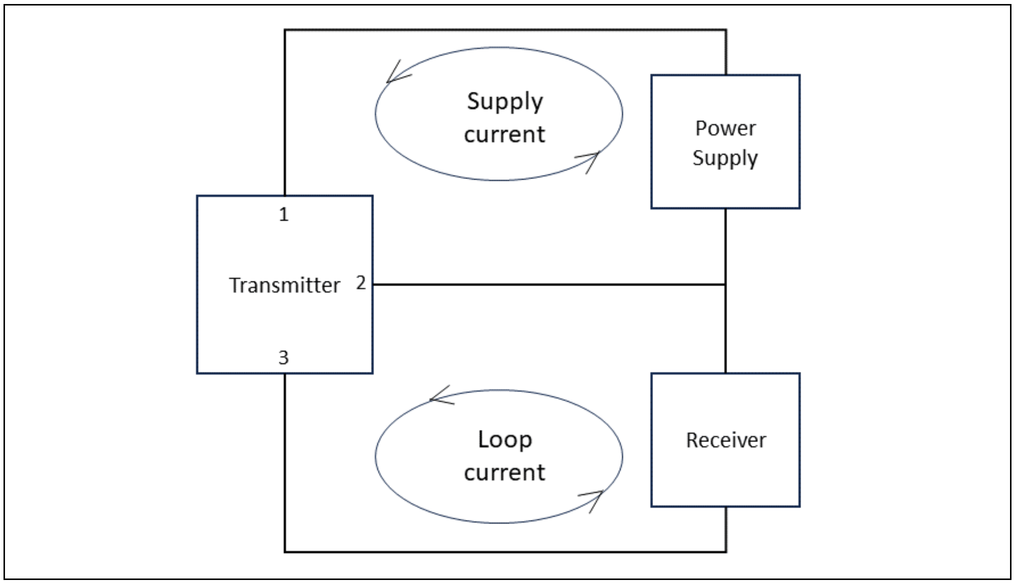


FIGURE 1-2: *3-Wire Connections.*

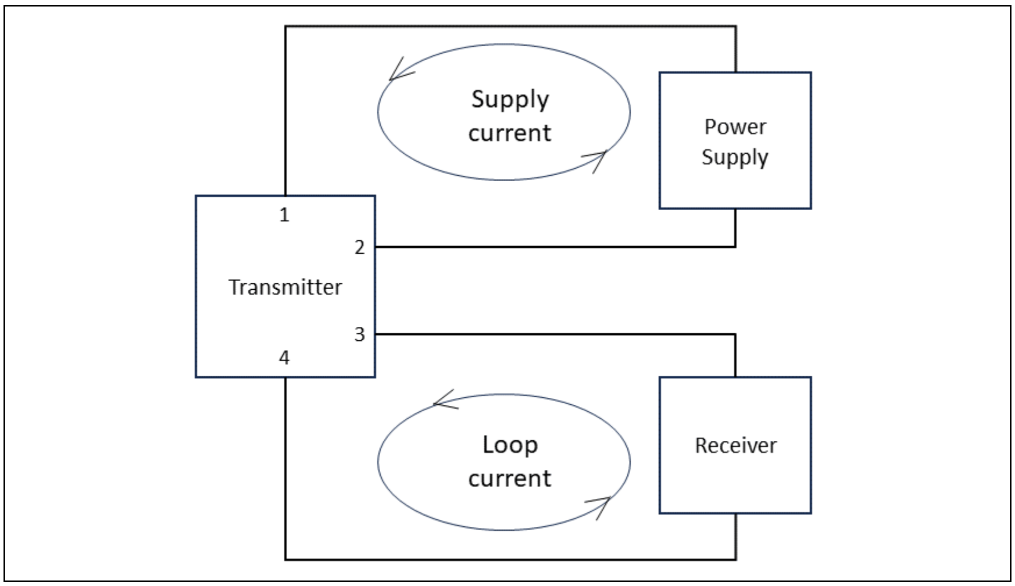


FIGURE 1-3: *4-Wire Connections.*

Microchip's DAC-Based 4-20 mA Current Loop reference design is based on the 2-wire connection systems. Following are the main components in the 2-wire current loop system:

- Sensor
- Transmitter
- Receiver
- System Power Supply
- Loop wire

Microchip's DAC-Based 4-20 mA Current Loop reference design is about the transmitter which converts process signal into 4-20 mA current and transmits it over a long distance.

1.1.2 Feature Summary

- High Accuracy
- Current budgeting with room to allocate different system level alarms
- Offset adjustment at 4 mA
- Small size printed circuit board (PCB)
- Low-cost design

1.1.3 Design Specifications

	Parameter		Specifications
Input	DAC Voltage	V_{DAC_min}	0V
		V_{DAC_max}	2.5V
Output	Loop current	I_{loop_min}	4 mA
		I_{loop_max}	20 mA
Supply	Loop Power Supply	$V_{\_Loop}$	24V
Load	Resistive load	$R_{\_Load}$	250 Ω

NOTES:

Chapter 2. Circuit Operation

2.1 CIRCUIT DESCRIPTION

DAC Based 4-20 mA Current Loop reference design of transmitter is designed to regulate the loop current according to the changes in the process variable value. Sensor output computed by the host controller (MCU) is provided through MCP48CMD21, a 12-bit 1LSb DAC as an input to current loop transmitter. MCP4152 is an 8-bit digipot that provides an offset trimming option at the lower end of current. MCP1501 is an external voltage reference that provides the precise output to DAC reference and helps to improve accuracy. Loop current flows through the return wire in 2- wire systems, thus it is necessary that the quiescent current of the transmitter and other devices in the loop is less than the minimum loop current. Appropriate current budgeting allows users to allocate alarms for system failures.

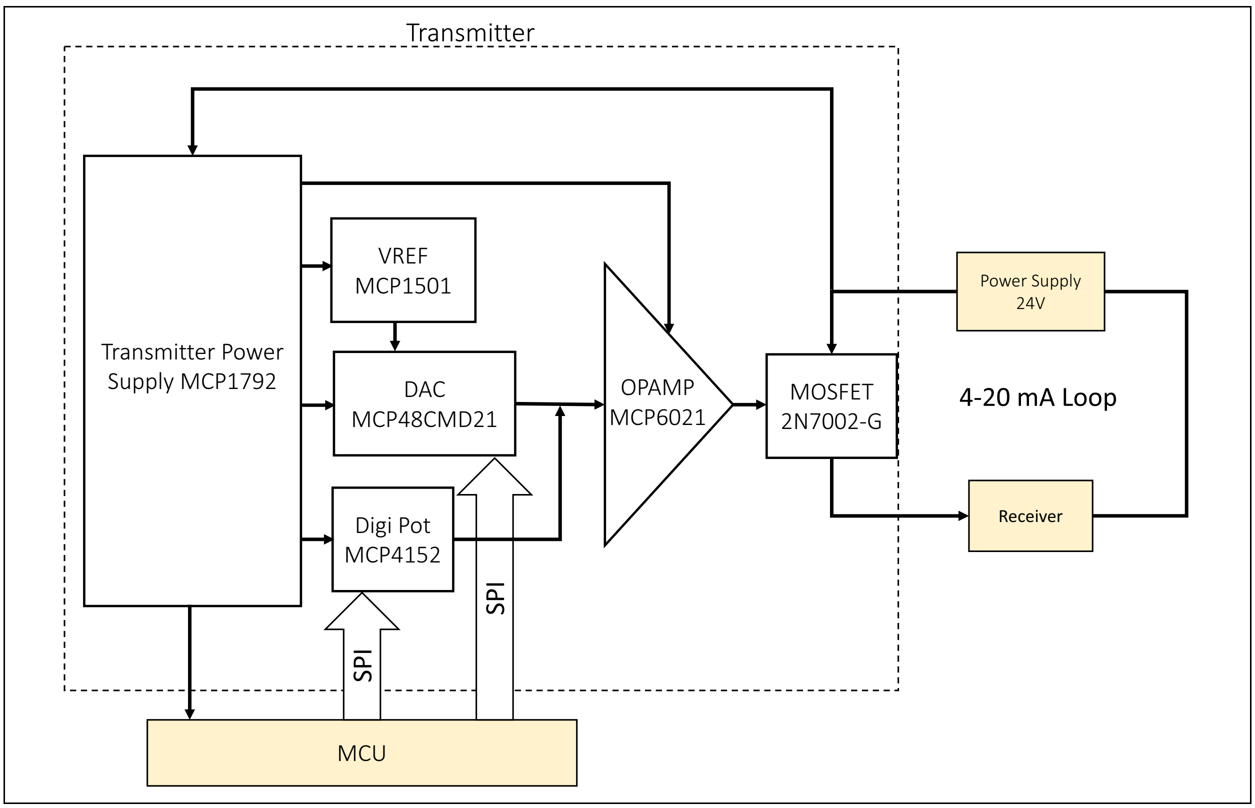


FIGURE 2-1: *Block Diagram of 4-20 mA Current Reference Design.*

2.2 DESIGN NOTES

1. For high accuracy, resistors with low tolerance (1%, 0.5% or 0.1%) are recommended.
2. Transmitter design has a floating ground for the current's return path, and it is different than the power supply ground.
3. Current budgeting with quiescent current from all the devices including MCU in the loop must be below 3.6 mA.
4. The current flowing through the MOSFET needs to be limited for proper operation.
5. Digipot selection depends on application requirement.

Note:	Please refer to **Appendix A. "Schematic and Layouts"** for the schematic and Table 2-1 for current budgeting, which lists out the quiescent current of the components used in the transmitter board. This total current includes the current for the MCU controlling the DAC and digipot.

2.3 THEORY OF OPERATION

DAC Based 4-20 mA Current Loop reference design accepts DAC voltage and converts it to a current in such a way that the relation between input process variable and the output loop current is linear. The design specification table provides the relationship between DAC voltage and the loop current. DAC Based 4-20 mA Current Loop reference design circuit diagram is shown in Figure 2-2.

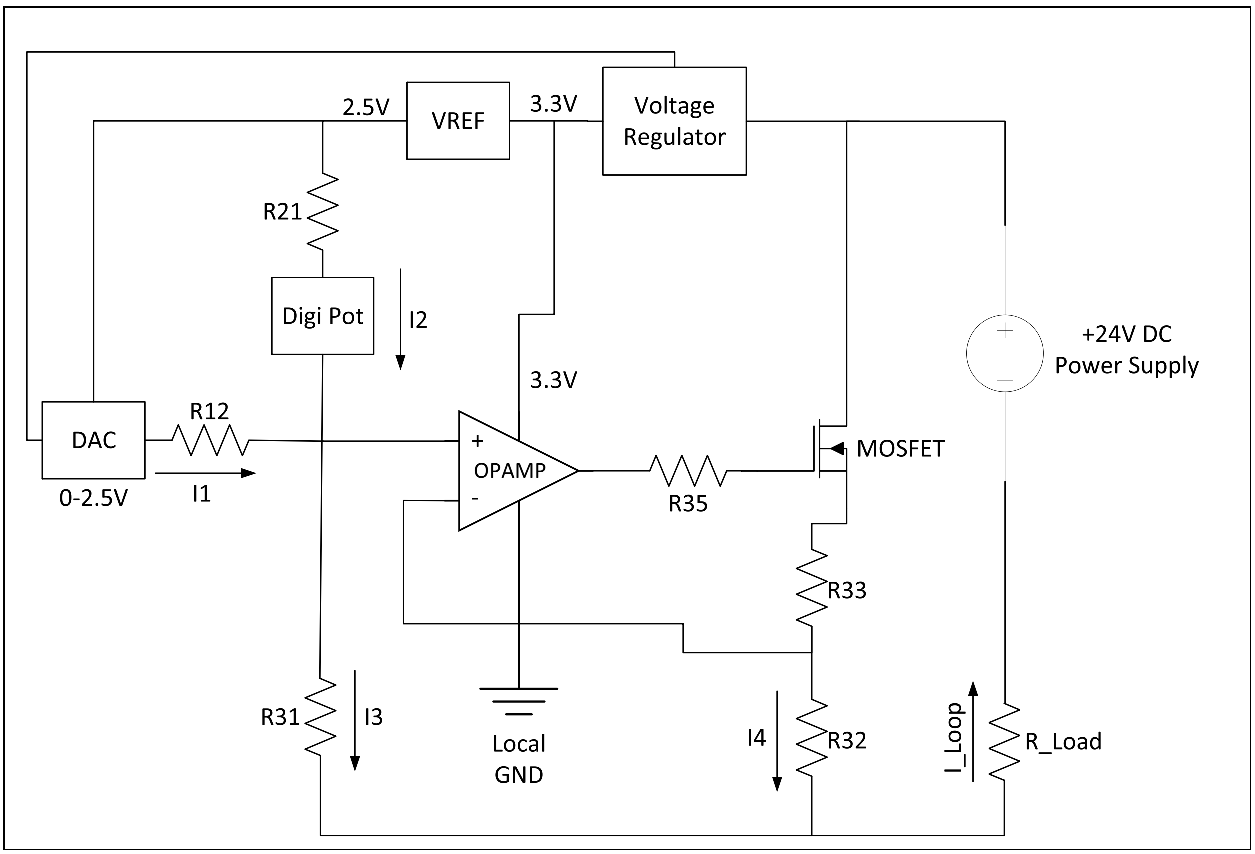


FIGURE 2-2: *Circuit Diagram of 4-20 mA Current Loop Transmitter.*

The loop current I_Loop is the sum of the currents flowing through R31 and R32, which are denoted by I3 and I4.

EQUATION 2-1:

$$I\_Loop = I3 + I4$$

I3 is a combination of the current flowing from R12 and R21, assigned as I1 and I2.

EQUATION 2-2:

$$I3 = I1 + I2$$

In this design, op amp inverting terminal is connected to return path which can be called local ground for the future reference in this design. All the devices including voltage regulator, voltage reference, DAC, digipot and op amp return paths are connected to this local ground. An external MCU who computes the sensor output shares this local ground as well.

I3 can be calculated from Equation 2-3.

EQUATION 2-3:

$$I3 = \frac{V\_DAC}{R12} + \frac{V\_REF}{R21}$$

Summation of all the local return currents and the current through MOSFET compensate the remaining loop current other than I3. The potential at the non-inverting input terminal will be driven to local ground due to negative feedback. The voltages across R31 and R32 must be equal for proper operation of the op amp. Assuming voltage across R31 is V3 and voltage across R32 is V4, where (V3 = V4) gives:

EQUATION 2-4:

$$I3 \times R31 = R32 \times I4$$

By rearranging Equation 2-4:

EQUATION 2-5:

$$I4 = I3 \times \frac{R31}{R32}$$

Equation 2-1 can be rewritten as shown in Equation 2-6:

EQUATION 2-6:

$$I\_Loop = I3\left(1 + \frac{R31}{R32}\right)$$

This equation indicates the loop current dependency on I3 and provides the relationship between loop current and input.

Linear operation of circuit depends on Equation 2-7:

EQUATION 2-7:

$$\frac{I3\_min}{I3\_max} = \frac{I\_Loop\_min}{I\_Loop\_max}$$

Design requirements are set with I_Loop_min = 4 mA and I_Loop_max = 20 mA. Substitute these values in Equation 2-7:

EQUATION 2-8:

$$\frac{I3\_min}{I3\_max} = \frac{4}{20} = \frac{1}{5}$$

As per circuit diagram and Equation 2-2:

EQUATION 2-9:

$$I3 = \frac{V\_DAC}{R12} + \frac{V\_REF}{R21}$$

- I1 is the current flowing through R12 and depends on the VDAC. It is a driving force for the loop current.
- I2 is the current from digipot which can be used for calibration. Ideally, I2 = I3 when V_DAC is not present. As per Equation 2-6, I3 is directly proportional to I_Loop. So, for this design, I2 is assumed at 40 µA.

From Equation 2-2, it can be concluded that I3_min = 40 µA when I1 = 0. Then, I3_max = 40 µA x 5 = 200 µA as per Equation 2-8.

$$I3\_min = \frac{V\_DAC\_min}{R12} + \frac{V\_REF}{R21}$$

$$40\ \mu A = \frac{0}{R12} + \frac{2.5V}{R21}$$

$$R21 = \frac{2.5V}{40\ \mu A} = 62.5K$$

For offset trimming, R21 = 47K in series with digipot is selected. Digipot will provide an option to trim the lower value exactly at 4 mA.

For V_DAC = 2.5V, Equation 2-10 will be as follows:

EQUATION 2-10:

$$I3\_max = \frac{V\_DAC\_max}{R12} + \frac{V\_REF}{R21}$$

$$200\ \mu A = \frac{2.5V}{R12} + \frac{2.5V}{62.5V}$$

$$R1 = \frac{2.5V}{160\ \mu A} = 15.6K$$

In design, 15K is selected for the R12 and the digipot is given headroom to trim the 4 mA current.

As per Equation 2-6, gain of the current loop is set by R31 and R32.

EQUATION 2-11:

$$I\_Loop\_min = I3\_min\left(1 + \frac{R31}{R32}\right)$$

$$4\ mA = 40\ \mu A\left(1 + \frac{R31}{R32}\right)$$

EQUATION 2-12:

$$\frac{R31}{R32} = 99$$

R31 = 2.2K and R32 = 22Ω are selected respectively in this design. Selecting R32 in this design is important as the higher value of R32 may exhibit headroom issues for regulator input voltage. The load voltage at maximum load current is:

- V_Load = I_Loop_max x R_Load
- V_Load = 20 mA x 250Ω
- V_Load = 5V

Most of the loop current comes through MOSFET and flows through R32 and R33. Assume 20 mA flows through R32. Voltage at local ground node is calculated by the following relation:

- V_local_gnd = V_Load + R32 x 20 mA

To provide the enough headroom, R32 = 22Ω is selected.

- V_local_ gnd = 5V + 0.4V = 5.4V

Headroom voltage = 24 - 5.4V = 18.6V

This will provide more than enough head room for LDO input and prevent it from entering dropout and affecting the linear performance of current loop.

Current budgeting for the board is essential for 4-20 mA current loop system performance.

Table 2-1 shows the current budgeting for DAC Based 4-20 mA Current Loop board design.

TABLE 2-1:

Device	Part Number	Supply Current
Regulator	MCP1792 (3.3V)	45 µA
DAC	MCP48CMD21	140 µA
VREF	MCP1501 (2.5V)	350 µA
Digipot	MCP4152	5 µA
Op Amp	MCP6021	1.3 mA
MOSFET	2N7002	1 µA
	Total Transmitter Current =	1.8 mA approximately

The microcontroller (MCU) can be selected as per permitted loop current. For example, if 4-20 mA current loop system is set for 3.6 mA fault alarm, total current consumption for the transmitter board and MCU have to be less than 3.6 mA.

Therefore, MCU current has to be limited around 1.8 mA as per total current required at transmitter (see Table 2-1).

NOTES:

Chapter 3. Tests and Results

3.1 SIMULATION

DAC Based 4-20 mA Current Loop circuit is simulated with dummy DAC supply in MPLAB MINDI software. DAC voltage is swept from 0V to 2.5V and output current is observed from 4 mA to 20 mA.

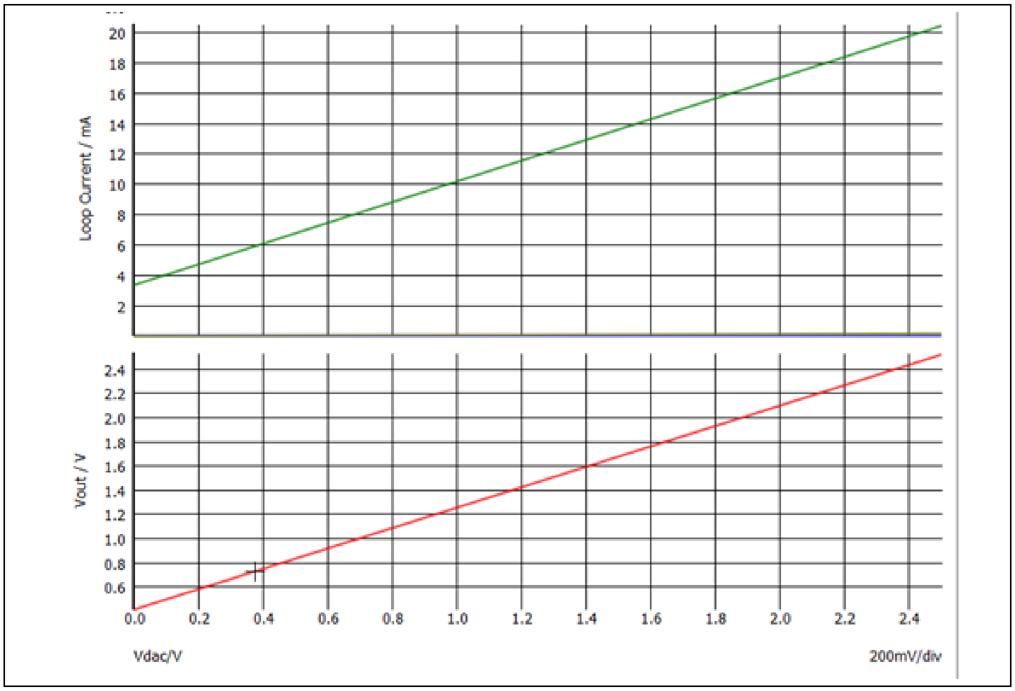


FIGURE 3-1: *Simulation Result.*

3.2 LINEARITY TEST

As shown in **Section 2.3 "Theory of Operation"**, the output current depends on the DAC voltage. Accuracy and linearity mainly depend on the DAC performance.

Figure 3-2 shows the block diagram of the DAC system and Figure 3-3 shows the 12-bit DAC performance when code swept from 0 to 4095.

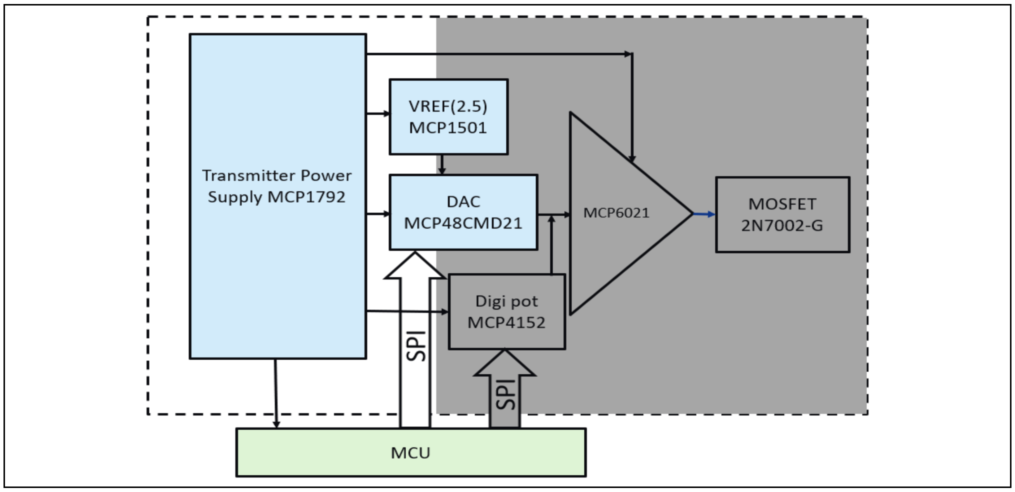


FIGURE 3-2: *DAC Subsystem Block Diagram.*

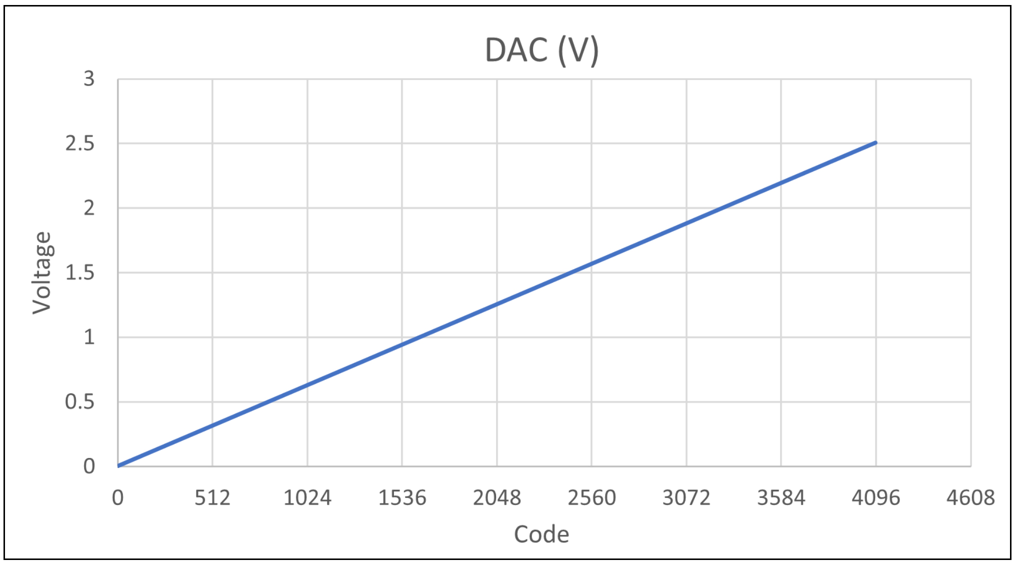


FIGURE 3-3: *DAC Subsystem Output Voltage.*

DAC subsystem DNL and INL performance are shown in Figure 3-4 and Figure 3-5.

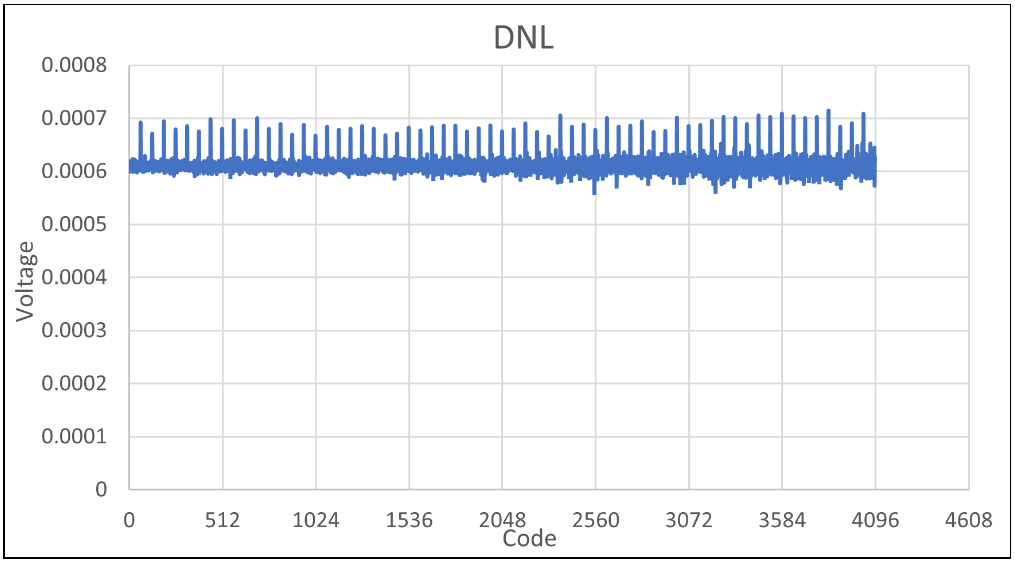


FIGURE 3-4: *DAC Subsystem DNL.*

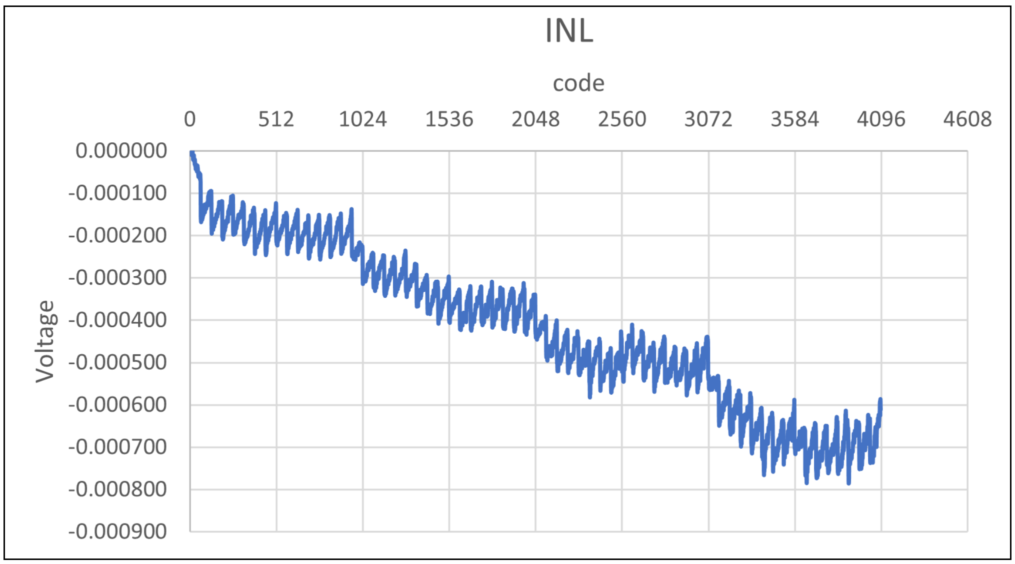


FIGURE 3-5: *DAC Subsystem INL.*

Looking at the differential nonlinearity, each code is 1 LSb apart from each other for the entire DAC code range and the INL graph also shows around 1 LSb error over entire code range.

Figure 2-1 shows the complete 4-20 mA current loop transmitter block diagram.

Performance of the 4-20 mA current loop system over the 0 to 4095 DAC code range is shown in Figure 3-6, Figure 3-7 and Figure 3-8.

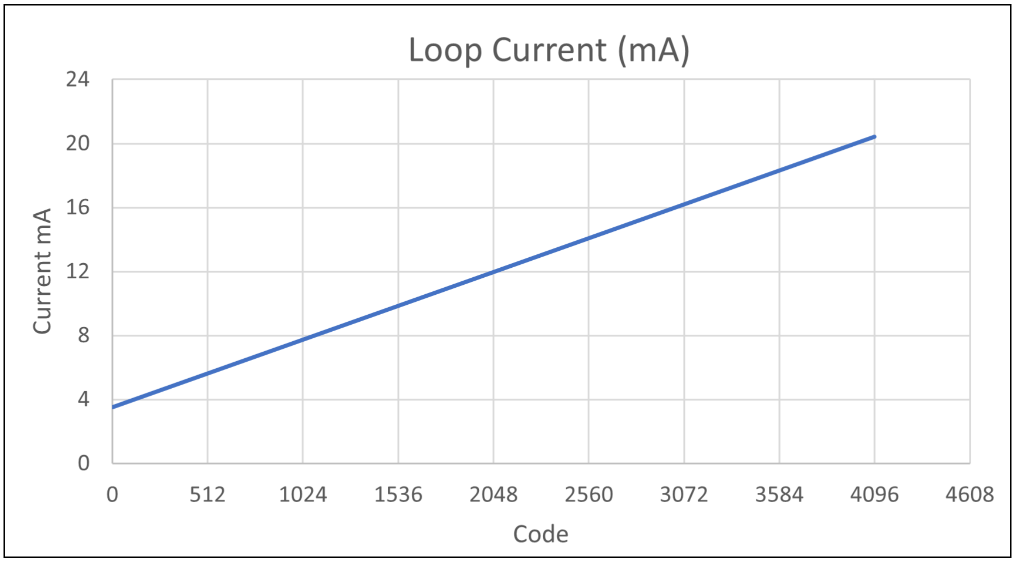


FIGURE 3-6: *Transmitter Loop Current.*

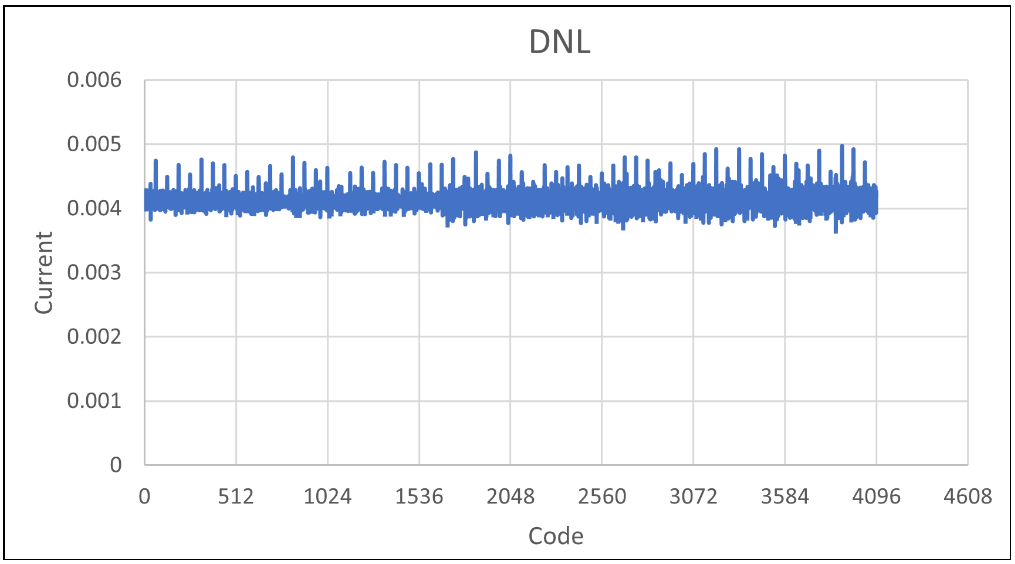


FIGURE 3-7: *Transmitter Loop Current DNL.*

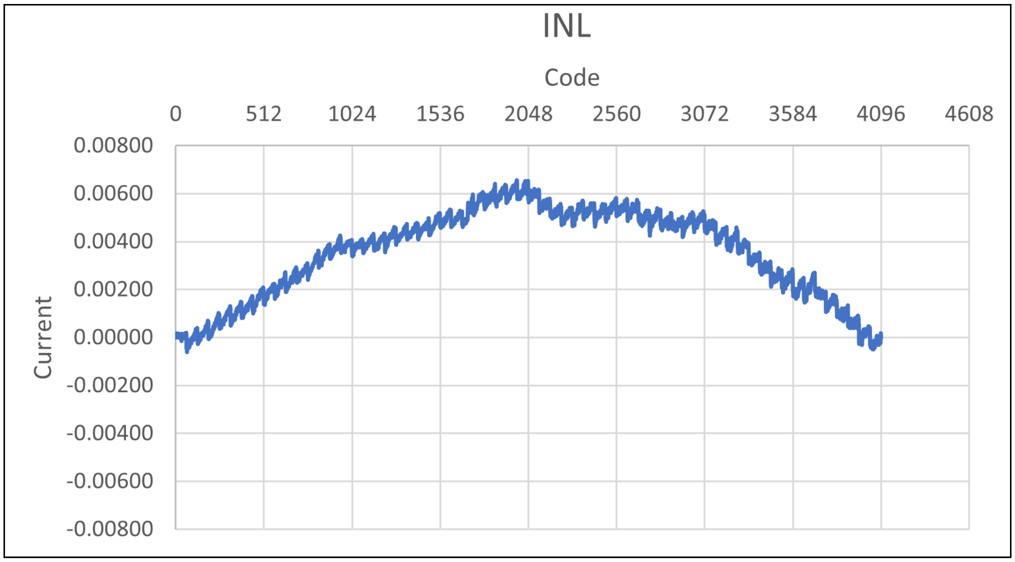


FIGURE 3-8: *Transmitter Loop Current INL.*

From the graphs, it is visible that the relation between DAC voltage and loop current is linear over the entire 0 to 4095 code range. INL and DNL graphs show the complete system error is within 1 LSb.

3.3 CURRENT OUTPUT DRIFT

This test was conducted under a room temperature (not in a controlled temperature environment or heat chamber) on a work bench set up. The test run time was 48 hours. Result shows the amount of change of a measured current reading at ambient conditions over a given period.

The following tables show the test results for output drift at 4 mA and 20 mA.

Output Drift	
Minimum	4.000554 mA
Maximum	4.001863 mA
Average	4.001125 mA
Total Count (Readings)	734381

Output Drift	
Minimum	19.99856 mA
Maximum	20.00164 mA
Average	19.99985 mA
Total Count (Readings)	738152

- % Drift Error over 4-20 mA span is calculated by the following formula:
  - % Drift = (Maximum current reading - minimum current reading)/16 mA x 100

The drift error at ambient temperature is around 0.01% - 0.02% of the span.

3.4 TEMPERATURE DRIFT

Output drift test over the temperature range from (-25°C to +60°C) is performed using temperature oven. Output drift of 5 boards is observed at -25°C, 0°C, +25°C and +60°C temperature points. The temperature of the oven is set at each set point for 2 hours and collects the output data. The graph in Figure 3-9 shows the average of the temp drift at each temperature set point. It is observed the % temperature drift error is below 0.02%.

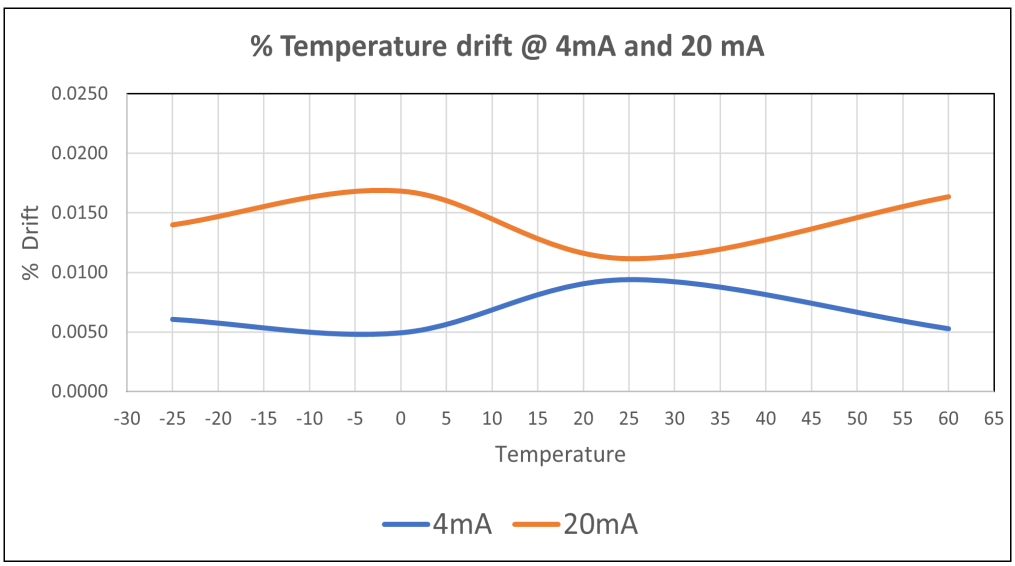


FIGURE 3-9: *Temperature Drift.*

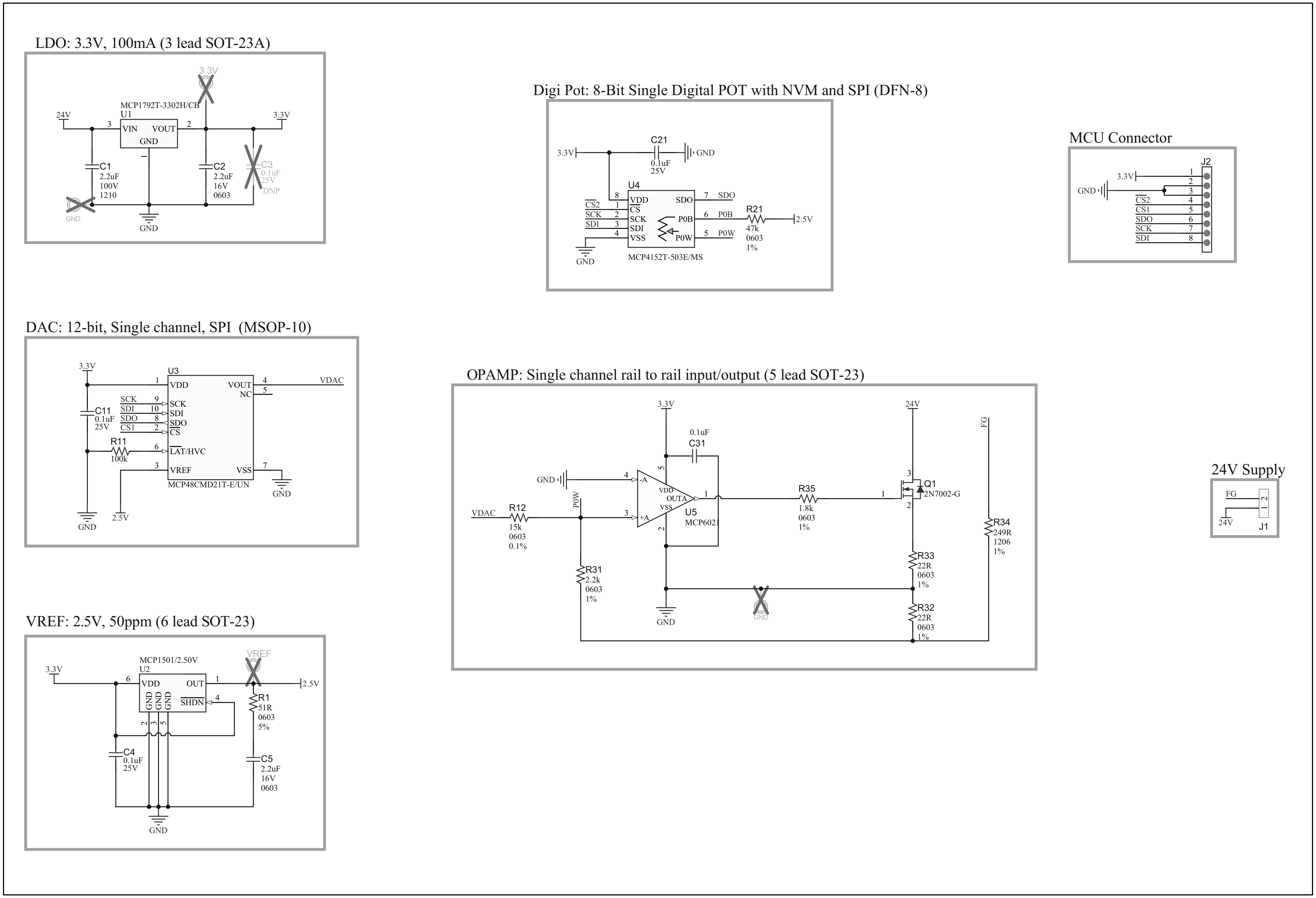
Appendix A. Schematic and Layouts

A.1 INTRODUCTION

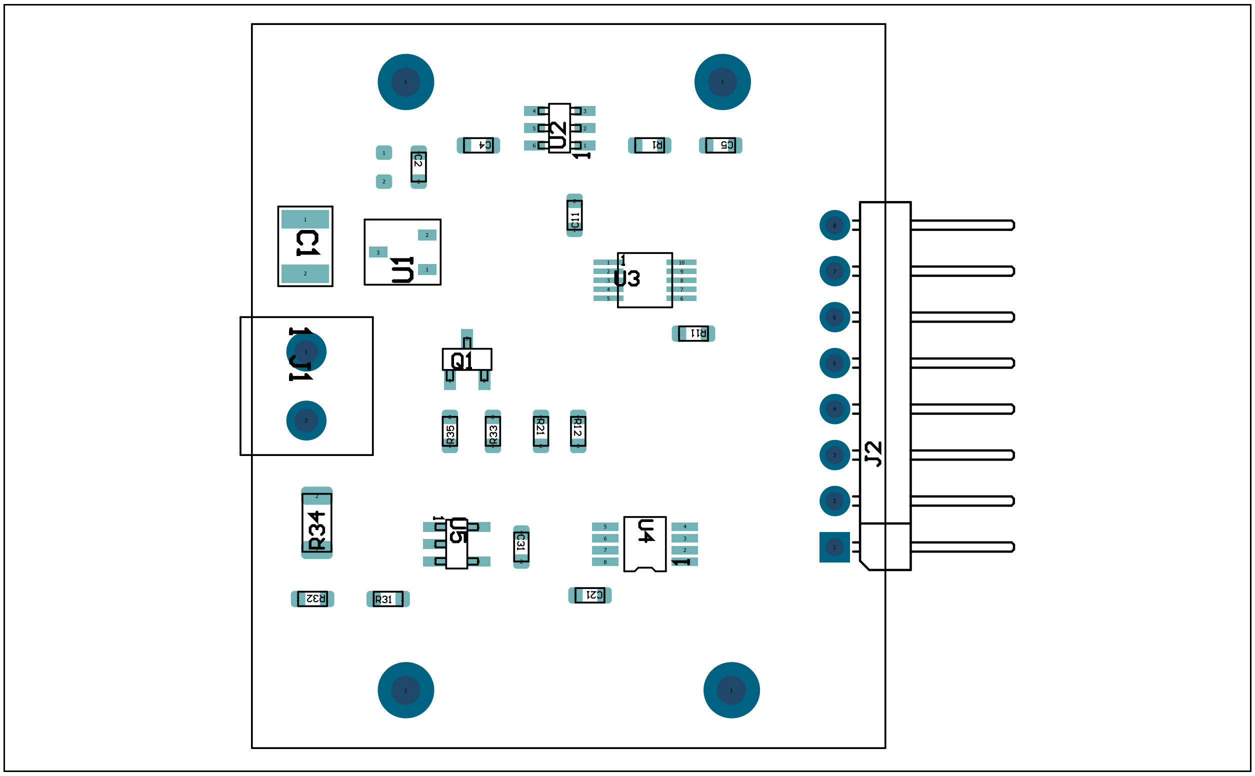
This appendix contains the following schematics and layouts for the DAC Based 4-20 mA Current Loop:

- Board – Schematic
- Board – Top Assembly
- Board – Bottom Assembly
- Board – Top View
- Board – Bottom View

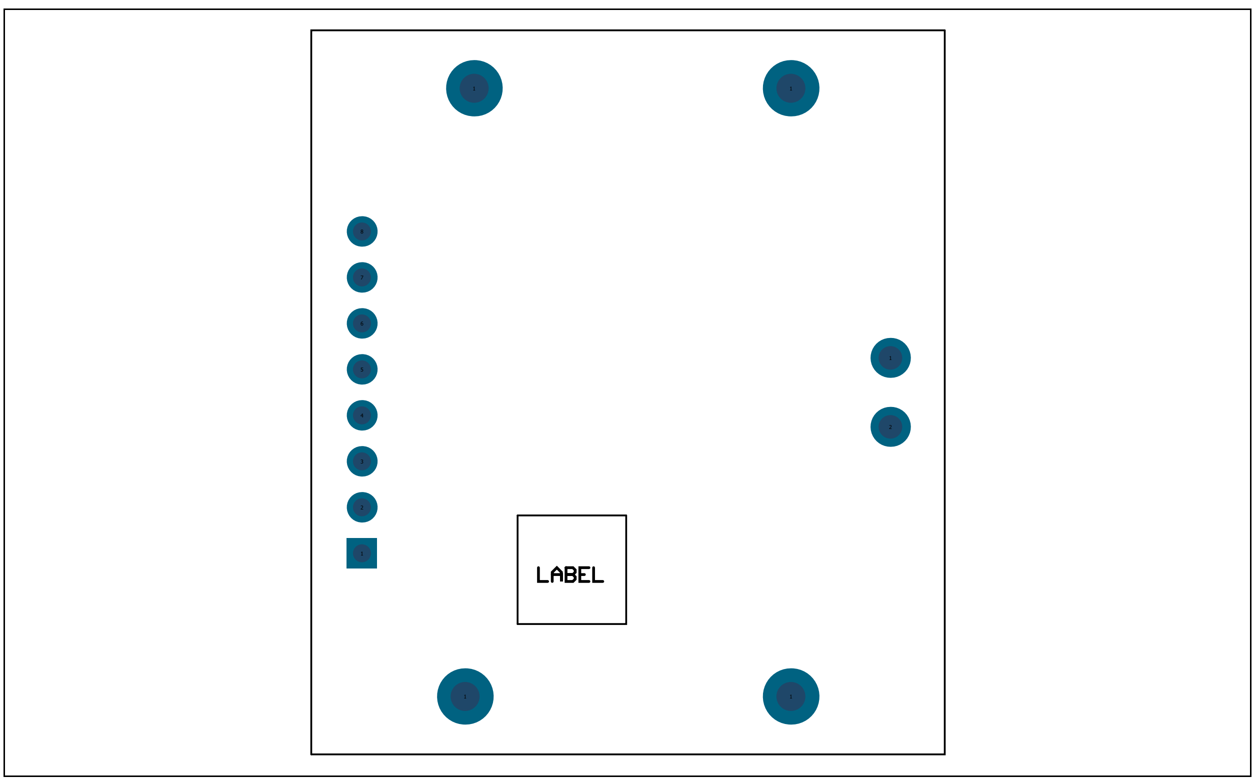
A.2 BOARD – SCHEMATIC



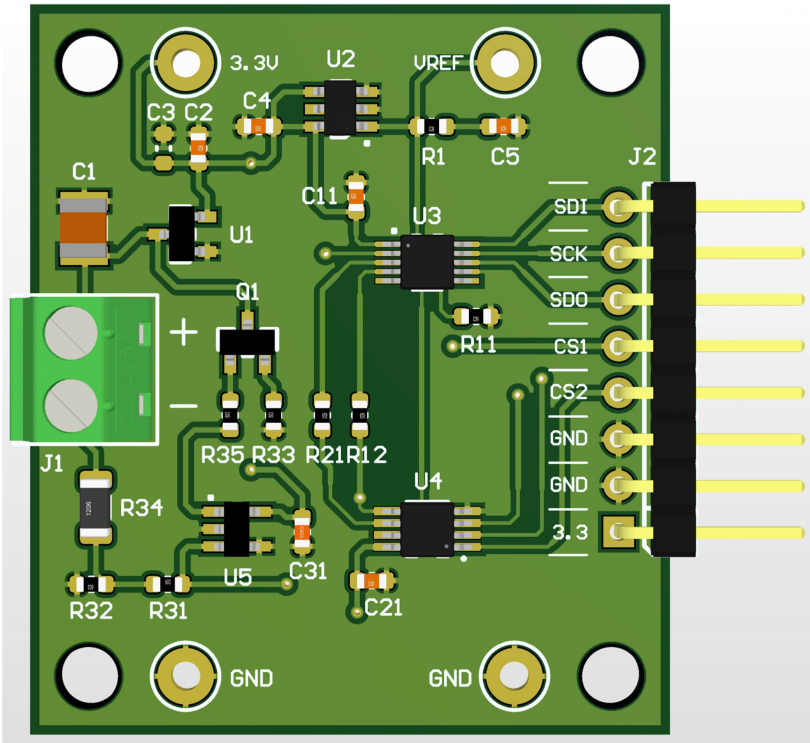
A.3 BOARD – TOP ASSEMBLY



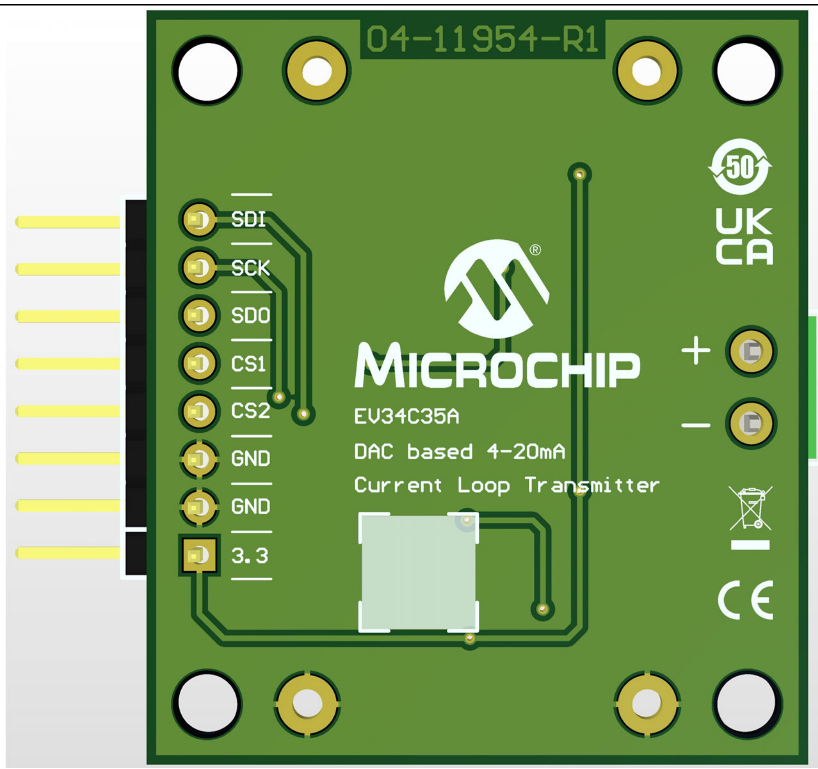
A.4 BOARD – BOTTOM ASSEMBLY



A.5 BOARD – TOP VIEW



A.6 BOARD – BOTTOM VIEW



Appendix B. Bill of Materials (BOM)

TABLE B-1: BILL OF MATERIALS (BOM)

Qty.	Reference	Description	Manufacturer	Part Number
1	C1	CAP CER 2.2 µF 100V 10% X7R SMD 1210	Samsung Electro-Mechanics America, Inc.	CL32B225KCJSNNE
2	C2, C5	CAP CER 2.2 µF 16V 10% X5R SMD 0603	TDK Corporation	C1608X5R1C225K080AB
0	C3	CAP CER 0.1 µF 25V 10% X7R SMD 0603 – **Do Not Populate**	KEMET	C0603C104K3RAC7013
4	C4, C11, C21, C31	CAP CER 0.1 µF 25V 10% X7R SMD 0603	KEMET	C0603C104K3RAC7013
1	J1	CON TERMINAL 3.81 mm 1x2 Female 16-30AWG 13.5A TH R/A	Phoenix Contact	1727010
1	J2	CON HDR-2.54 Male 1x8 Gold 5.84MH TH R/A	Sullins Connector Solutions	PBC08SBAN
1	LABEL	LABEL PCBA 6x6 mm Info Text	ACT Logimark AS	505462
1	PCB1	Printed Circuit Board – DAC Based 4-20 mA Current Loop	Microchip Technology Inc.	**04-11954-R1**
1	Q1	MCHP ANALOG MOSFET N-CH 2N7002-G 60V 115 mA SOT-23-3	Microchip Technology Inc.	**2N7002-G**
1	R1	RES TKF 51R 5% 1/10W SMD 0603	Panasonic® – ECG	ERJ-3GEYJ510V
1	R11	RES TKF 100 kΩ 5% 1/10W SMD 0603 AEC-Q200	Panasonic – ECG	ERJ-3GEYJ104V
1	R12	RES TF 15 kΩ 0.1% 1/10W SMD 0603	Panasonic – ECG	ERA-3AEB153V
1	R21	RES TKF 47 kΩ 1% 1/10W SMD 0603	Panasonic – ECG	ERJ-3EKF4702V
1	R31	RES TKF 2.2 kΩ 1% 1/10W SMD 0603	Panasonic – ECG	ERJ-3EKF2201V
2	R32, R33	RES TKF 22R 1% 1/10W SMD 0603	Panasonic – ECG	ERJ-3EKF22R0V
1	R34	RES TKF 249R 1% 1/4W SMD 1206	ROHM Semiconductor	MCR18EZHF2490
1	R35	RES TKF 1.8 kΩ 1% 1/10W SMD 0603	Panasonic – ECG	ERJ-3EKF1801V
0	3.3V, TP1, TP2, VREF	CON TP LOOP Red TH – **Do Not Populate**	Keystone® Electronics Corp.	5010
1	U1	MCHP ANALOG VOLTAGE REGULATOR 3.3V 3LD MCP1792T-3302H/CB SOT-23A-3	Microchip Technology Inc.	**MCP1792T-3302H/CB**
1	U2	MCHP ANALOG VREF 2.50V MCP1501T-25E/CHY SOT-23-6	Microchip Technology Inc.	**MCP1501T-25E/CHY**

TABLE B-1: BILL OF MATERIALS (BOM) (CONTINUED)

Qty.	Reference	Description	Manufacturer	Part Number
1	U3	MCHP ANALOG DAC 1-Ch 12-bit MCP48CMD21T-E/UN MSOP-10	Microchip Technology Inc.	**MCP48CMD21T-E/UN**
1	U4	MCHP ANALOG DIGIPOT 50KOHM 257TAP 8MSOP	Microchip Technology Inc.	**MCP4152T-503E/MS**
1	U5	MCHP ANALOG OPAMP 1-Ch 10MHz MCP6021T-E/OT SOT-23-5	Microchip Technology Inc.	**MCP6021T-E/OT**

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