Application of High-Voltage, Precision, Low-Power Max9943/Max9944 Operational Amplifier in Industrial Process Control Using ±20ma OR 4-20ma Current-Loop Systems

Ezeilo Chibuike J, Okolo Chidiebere C, Okeke Obinna, Okoye Ngozi B, Nebechi Shadrach I

Electronics Development Institute, Awka, Anambra State, Nigeria

Abstract— *This article explains how to apply a high-voltage, high-current-drive operational amplifier to convert a voltage signal into a ±20mA or 4–20mA current signal for use in process-control industrial applications. The MAX9943 op amp a family of high-voltage amplifiers that offers precision, low drift, and low power consumption device was used as case study]. Experiments are described and test results presented.*

Current loops are known for their high immune to noise compare to voltage-modulated signals, a feature that makes it ideal for use in a noisy industrial environment. This signal can travel over a long distance, sending or receiving information from remote locations. A current loop typically includes a sensor, transmitter, receiver, and an ADC or a micro-controller (figure 1). The sensor measures a physical parameters such as pressure or temperature and provides a corresponding output voltage. The transmitter converts the sensor's output into a proportional 4mA-to-20mA current signal, while the receiver then converts the 4mA-to-20mA current into a voltage signal output. This receiver's output is then received, interpreted and converts into a digital signal output by an ADC or a micro-controller.

Experiment performed using the relationship the relationship stated in equation 5, shows that if the input voltage level rise above or fall below ±2.5v, the op amp device attains its saturation point and its output voltage can no longer increase. As shown in figure 3, where the curve flatten and no longer follow the ideal linearity characteristics that was supposed.

Keywords— ***4-20mA current loop, micro-controller, Transmitter, Receiver, Sensors.***

I. INTRODUCTION

An operational amplifier is a high-gain direct-coupled amplifier that is normally used in feedback connections [4]. The term operational amplifier evolved from original applications in analog computation where these circuits were used to perform various mathematical operations such as summation and integration [4].

The 4-20mA current loop is predominate process control signal in many industries today. It is the most efficient method of transferring process information because current does not change as it travels a long distance (i.e. from transmitter to receiver). It is also much simpler and cost effective. However, voltage drops and the number of process variables that need to be monitored can impact its cost and complexity [3].

The MAX9943/MAX9944 are single/dual operational amplifiers designed for industrial applications. They operate from 6V to 38V supply range while maintaining excellent performance. These devices utilize a three stage architecture optimized for low offset voltage and low input noise with only 550μA supply current. The devices are unity gain stable with a 1nF capacitive load. These well-matched devices guarantee the high open-loop gain, CMRR, PSRR, and low voltage offset.

The MAX9943/MAX9944 provide a wide input/output voltage range. The input terminals of the MAX9943/MAX9944 are protected from excessive differential voltage with back-to-back diodes. The input signal current is also limited by an internal series resistor. With a 40V differential voltage, the input current is limited to 20mA. The output can swing to the negative rail while delivering 20mA of current, which is ideal for loop-powered system applications. The specifications and operation of the MAX9943/MAX9944 family is guaranteed over the -40°C to +125°C temperature range [2].

II. METHODOLOGY

Basics of a current loop

A current loop typically includes a sensor, transmitter, receiver, and an ADC or microcontroller, as describe by the (**Figure 1**) below.

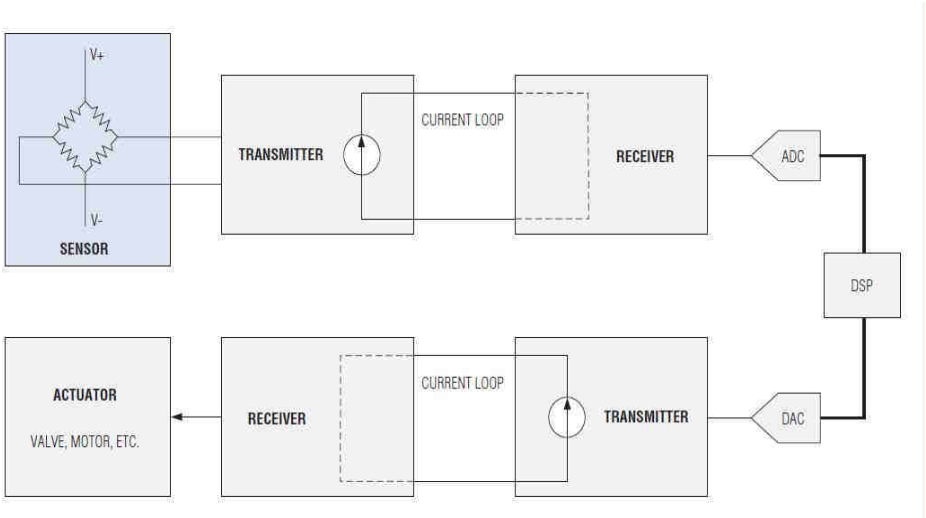

Fig.1: Complete process diagram of a 4-20mA current loop system [1]

<u>Component Description of a 4-20ma Current Loop</u>

i) Sensor:

ii) This is an electronic device that measures the process variable. A typical sensor is used in measurement of physical quantities, converting it to electrical voltages. Example of these physical quantities includes pressure, temperature, flow-rate, humidity etc.

iii) Transmitter:

iv) This is where whatever the sensor is measuring is converted into a current signal between the range of 4-20mA. For example when a sensor is measuring height of a hundred feet gas tank, the transmitter would need to translate a zero feet as the gas tank being empty by transmitting a four milliamp signal. On the contrary, it would translate hundred feet as the gas tank being full, thereby transmits a twenty milliamp current signal [3].

v) Power supply:

vi) In order for the circuit to function, there must be a power source being delivered to the circuit, which must be in form of DC current i.e. flowing in one direction. There are range of voltages used with 4-20mA current loop based on the circuit setup. Though it is advised that the supply voltage must be at least 10% greater than the total voltage drop of the attached components (i.e. transmitter, receiver, connecting wires etc.)[3]. Inadequate supply voltage can lead to circuit mal-functioning or failure [3].

vii) Current Loop:

viii) Wires is used in the connection of the whole component in the circuit starting from the sensor to the receiver. If adequate supply voltage can be achieved, there is a need to take into consideration the proper material, thickness and distance that will be covered by the connecting wires. In that there is voltage drop along the wire though not significant in short distances, but very importance to be considered in long distances.

ix) An analog current signal converted by the first transmitter is converted to a digital information through an ADC interfaced on its output. This ADC can be a microcontroller or a comparator. Another conversion also occurs, this time using DAC, to converts the digital information into an analog voltage signal. A current-loop transmitter converts the DAC's output voltage into a 4–20mA or ±20mA current signal that drives the actuator [3]. An example of such a system can be found in power-grid monitoring systems where sophisticated algorithms determine the current state of the system, predict the direction of changes in the system, and implement a control loop to dynamically adjust the system [3].

x) Receiver:

xi) Finally to this end there will be a device to receive, interpret and convert the current signal into voltage signal which can be easily manipulated by the operator using devices such as controllers, valves, actuators and digital displays in order to perform a particular task automatically with the information or display the received information.

xii) These are components and step by step process it takes to achieve a 4-20mA current loop.

Advantages of 4-20mA loops

i) It makes use of less wire, connections compare to other signals and cost of initial setup greatly reduced.

ii) It offers little or no sensitivity to background electrical noise.

iii) It is suitable for travelling a long distance, owning to non-degradation of current over a long connection compared to voltage or other signal.

iv) Its simplicity makes it a better option to be considered for connection and configuration.

v) Faulty detection in the system is incredibly simple, since 4mA is equal to 0% output level.

Disadvantages of 4-20mA loops

i) Current loops transmission is limited to only one particular process signal.

ii) Several loops must be created in situations where there are many process variables that require transmission.

iii) Running plenty of wires could lead to problems with ground loops, if independent loops are not properly isolated.

iv) As the number of current loops increases, so as the isolation requirements become exponentially more complicated.

III. EXPERIMENT AND RESULT ANALYSIS

Using the op amp as a VI converter with a high-current drive

Figure 2 shows how a simple VI (voltage-to-current) converter can be designed with two op amps and a few external resistors. When powered with ±15V, the op amp (here, the MAX9943) delivers more than ±20mA output current to small impedance loads.

The MAX9943 is a 36V op amp with a high-output current drive. It is stable with up to 1nF load capacitance. The device is good for industrial applications where a voltage signal coming from a DAC needs to be converted into a proportional 4–20mA or ±20mA current signal.

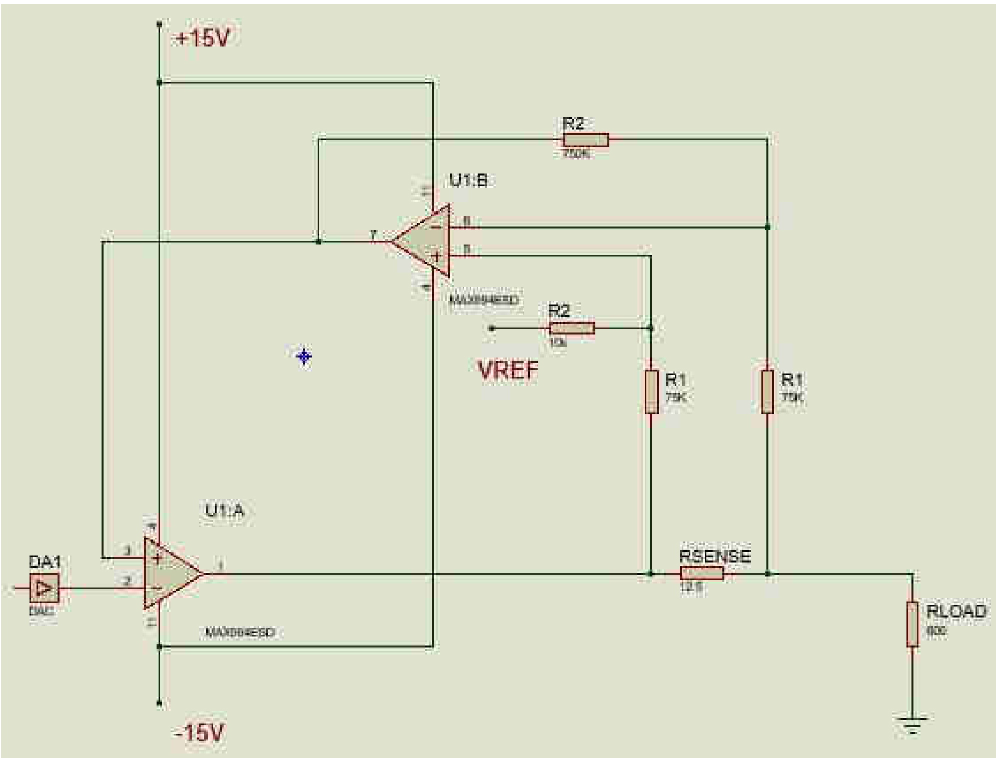

Fig.2. A VI converter transforms the DAC output to load current. This circuit uses two MAX9943 op amps

The relationship between the input voltage, V_{IN}, and the load current is given by Equation 1:

$V_{IN} = (R2/R1) \times R_{SENSE} \times I_{LOAD} + V_{REF}$ (Eq. 1)

In this circuit example the component values are:

$R1 = 75k\Omega$, $R2 = 750k\Omega$, $R_{SENSE} = 12.5\Omega$, $R_{LOAD} = 600\Omega$

A typical load value would be in the order of several hundred ohms. However, significantly smaller impedance loads can occur either from short-to-ground faults, or to allow long-distance signal transmission by reducing the voltage burden requirements at the receiver.

V_{REF} can be synchronized with the reference voltage used by the DAC. In that case all voltages (V_{IN}) are ratio metric with V_{REF}, and errors from variation in V_{REF} can be eliminated.

Creating a ±20mA current drive from a ±2.5V range

The circuit in Figure 2 can also be used to create a ±20mA current drive. With V_{REF} = 0V, the input range between -2.5V and +2.5V produces a nominal ±20mA current output, as shown in **Figure 3**.

The relationship between the input voltage (V_{IN}) and the output voltage (V1) of the "forward" op amp is given by:

$V_{IN} = (R2/R1) \times (1 - \alpha/\beta) \times V1 + V_{REF} \times (1 - (R2/R1) \times 1/(\beta \times (R2+R1)))$ (Eq. 2)

Where:

$\alpha = (1/R_{SENSE}) + R2/(R1 \times (R1 + R2))$ (Eq. 3)

$\beta = (1/R_{SENSE}) + (1/R1) + (1/R_{LOAD})$ (Eq. 4)

Using the component values specified in Equations 2, 3 and 4:

$V1 = 4.897 \times V_{IN} - 4.896 \times V_{REF}$ (Eq. 5)

The relationship in Equation 5 helps to avoid saturating the output devices. In fact, when V_{IN} = +2.5V, the output of the lower op amp (V1) reaches approximately 12.2V. If the input voltage increases beyond 2.5V, eventually the output device reaches its saturation point and the output voltage can no longer increase. The Figure 3 curves flatten and no longer follow the ideal profile. A similar process happens when the negative input is lowered below -2.5V.

The Figure 3 data show that the MAX9943 still operates in the linear range when sourcing and sinking up to approximately ±21.5mA, which corresponds to the input of ±2.68V and of ±13V at the output of the forward (lower) op amp. The negative current could actually be a much larger magnitude because the MAX9943's output voltage can operate very close to the negative supply voltage.

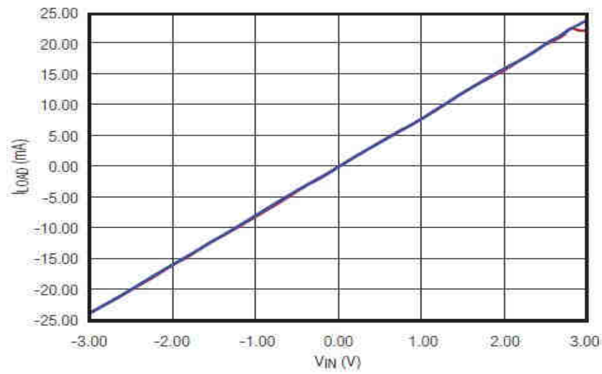

Fig.3: A ±20mA output current range is produced by a ±2.5V input voltage range. The blue line is the ideal gain curve; the red line is the measured data. VCC = +15V; VEE = -15V [1].

The device is limited to approximately 2V from the positive supply. (The 2V value depends on the load, and is given as a worst-case specification vs. process and temperature.)

Some applications require higher output current, either to satisfy margin concerns or to provide room for calibration. For those applications the Figure 2 circuit can be operated with dual ±18V supply voltages (instead of ±15V). Now the op amp can drive up to ±24mA (corresponding to ±3V inputs) and remain in the linear zone. This performance is illustrated in **Figure 4** below.

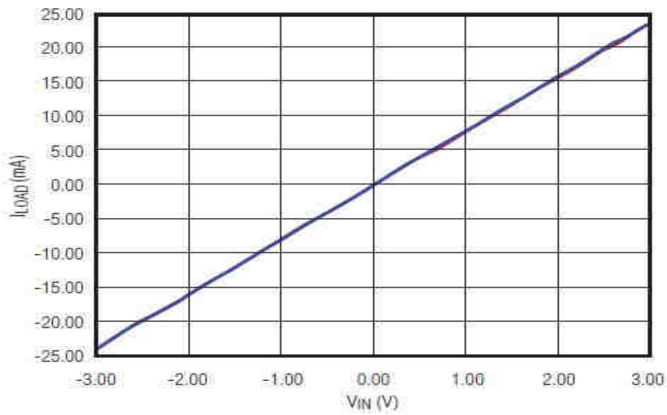

Fig.4: A ±24mA output current range is produced by a ±3V input voltage range. The blue line is the ideal gain curve; the red line is the measured data. VCC = +18V; VEE = -18V [1].

Creating a 4–20mA current drive from a 0 to +2.5V range

Referring back to Equation 5, when V_{REF} = -0.25V the input range between 0 and +2.5V produces a 2mA-to-22mA current output (**Figure 5**). Normally in 4–20mA current loops, designers want extra "room" in the dynamic range (e.g., from 2mA to 22mA) to allow for software calibration. If more current is required, then the MAX9943 circuit can be powered with a dual ±18V supply voltage, as explained earlier.

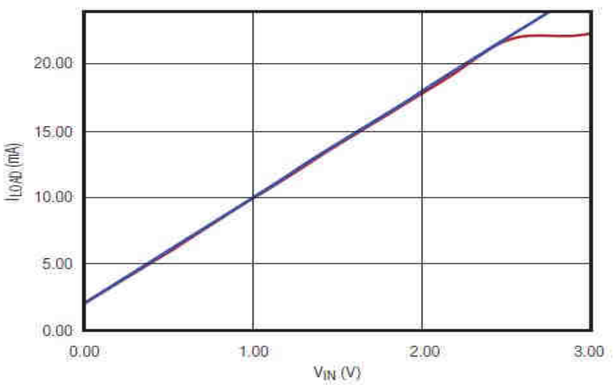

Fig.5: A 4–20mA output current range is produced by a 0 to 2.5V input voltage range. The blue line is the ideal gain curve; the red line is the measured data. VCC = +15V; VEE = -15V [1].

IV. CONCLUSION

Current loops are very necessary for industrial applications where information are been transferred from remote sensors to central processing units or from those central units to remote actuators.

The key advantages of the current loop are that the accuracy of the signal is not affected by voltage drop in the interconnecting wiring, and that the loop can supply operating power to the device [3].

The MAX9943 op amp has been shown to be ideal for control-loop applications where a voltage from a sensor or a DAC needs to be converted into either a 4–20mA or ±20mA current range. The MAX9943 offers a precision, low drift, low power consumption and high-current drive over its specified automotive temperature range of -40°C to +125°C. It has a unity gain stable with capacitive loads up to 1nF, as obtainable in long transmission lines.

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