HEATEC TEC-NOTE

UNDERSTANDING 4–20 mA CIRCUITS

The most common way to transfer an instrumentation signal from one device to another is by use of a four to twenty milliamp (4–20 mA) circuit. Most controls on Heatec products incorporate such a circuit. These are *series* circuits, which means the components are wired in series with each other. While there are variations in the circuits they all work on the same principle.

BASIC TERMS

Three basic electrical terms are used to describe key properties of a 4–20 mA circuit:

> volts or voltage
> milliamps or milli-amperes (mA)
> ohms

The number of volts indicates how much *electromotive force* is applied to the circuit. It's the *force* that produces electric current or amps. (Note: amps and amperes mean the same thing.) Electromotive force is often compared to pressure applied to a water hose. In that case it's the *force* that makes the water flow.

The number of milliamps is a measure of electric current or *rate of flow*. (One milliamp is one-thousandth of one amp.) Electric current is defined as ***flow of charge.**** Current in a circuit is often compared to how fast water flows from a water hose. Or how much water flows from the water hose over a given period of time.

The number of ohms indicates how much *resistance* there is to the electrical current in a circuit. Electrical resistance is often compared to a kink in a water hose. The kink restricts or slows the flow of water through the hose.

INTERACTIONS

The interaction of volts, amps and resistance with each other is defined by Ohms law or the equation: amps = volts divided by resistance. But instead of using equations you can still get a basic understanding of how these three properties interact with each other from some simple rules. You need to understand the following rules to understand 4–20 mA circuits:

1. Applying one volt to a circuit that has a resistance of one ohm causes a current of one amp.

2. Increasing the voltage increases the amps in proportion to the voltage increase. Decreasing the voltage decreases the amps in proportion to the voltage decrease. Thus, doubling the voltage causes twice as much electrical current or double the number of amps. And halving the voltage causes half the amps.

3. Increasing the resistance or number or ohms has the opposite effect. It reduces the current or number of amps. Decreasing the resistance increases the amps. The change in amps is in proportion to the change in resistance.

4. The total resistance in a series circuit is the sum of the resistances of the individual components, including the wiring.

5. The amps or current in a *series* circuit is the same in all parts of the circuit. Thus, the current through one device wired in series with another device is exactly the same.

An ammeter is used to measure the current in a series circuit. It too must be connected in series with the other devices. That means you must disconnect one of the circuit wires from a terminal and connect one lead of the ammeter to that wire. Connect the other lead to the terminal where the wire was connected.

Since the current is the same in all parts of a series circuit you might think that the voltage is also the same in all parts of a series circuit. **But it is not.** Voltage in a series circuit has some interesting aspects that we need to consider.

VOLTAGE IN A SERIES CIRCUIT

Voltage can be present in a circuit, even when there is no current. It's like a water hose with the faucet shut off. There is pressure on one side of the faucet, but

---

***Flow of charge** is used in this document instead of the traditional term "flow of current." Critics argue that "flow of current" is a misnomer and that "flow of charge" should be used instead. Despite evidence that "flow of current" is bad terminology, it may be more familar to you because it has been used extensively in text books and in courses on electricity. You can find an interesting discussion of this topic on the internet at http://amasci.com/miscon/eleca.html#poynt

there is no water flowing with it shut off. Likewise, voltage may be present at certain points in a circuit, but there will be no current if the circuit is open.

As mentioned earlier, voltage is a force similar to pressure in a water hose. Pressure exists when there is a difference in force at two points. Thus, measurements of voltage are always taken across two points in a circuit, without the need to disconnect any circuit wires.

For example, to measure voltage across a resistor in a series circuit, connect the two leads of the voltmeter to the same two terminals where the resistor is connected. The voltage shown on the meter (while the circuit is in operation) is actually the *difference* in voltage between the two points. It is the same as the amount of voltage *applied* to that resistor. And it is the same as the voltage *dropped* across that resistor.

When *current* is present in a series circuit, the *voltage* from the output device is divided or apportioned among the components of the circuit. As you would expect, the sum of *voltages* across all components is equal to the total voltage from the output device.

When a series circuit has two or more components, the voltage across each component depends on two things:

1. The resistance of that component.
2. Its percentage of the total circuit resistance.

Consider a series circuit with two components, one with a resistance of 250 ohms and another with a resistance of 750 ohms. The total resistance is 1,000 ohms. The resistance of 250 ohms is 25% of the total resistance. The resistance of 750 ohms is 75% of the total. Thus, 25% of the total voltage is applied across the 250 ohm resistor. And 75% of the total voltage is applied across the 750 ohm resistor.

HOW THE 4–20 mA CIRCUIT WORKS

Most 4–20 mA control circuits have a device that *outputs* a control signal and another that receives the signal.

Figure 1 shows a very basic 4–20 mA circuit. It shows an output device and shows a 4–20 mA display as the receiving device. Notice that the circuit also includes a precision 250 ohm resistor, which we will discuss later.

The circuit also shows wire resistance, which is a concern when long runs of wire are used. A voltmeter is shown connected across the precision resistor for reference purposes in our discussion. (It is not actually included in 4–20 mA circuits.) All devices in the circuit (except the voltmeter) are connected in series.

The key to understanding how the 4–20 mA circuit works is knowing how the *output* device works. Remember, it is wired in series with the other devices in the circuit. That means that the number of mA through it is the same as in all other parts of the circuit. So the output device *"reads" the number of **mA** to see if it is the predetermined value needed. If not, it changes its output **voltage** to achieve the predetermined value.*

For example if 20 mA is required for 100 percent output, the output device generates the amount of voltage needed to cause a 20 mA current through the circuit. If 4 mA is required for zero percent output, the output device generates the amount of voltage that causes 4 mA. And so on.

See **Figure 1** for a comparison of mA and voltage values and how to calculate them.

AN ANALOGY

You can compare the way the output device works with driving your car. You press on its accelerator to change its speed. You "read" the speedometer to see if the speed is what you want. If not, you change pressure on the accelerator to achieve the speed you want.

Similarly, the output device can put out various amounts of *voltage*, similar to the way the accelerator changes the speed of your car. The device then "reads" the current to see if the needed number of *milliamps* was achieved, similar to the way you read your speedometer. If the number of *milliamps* is not the amount needed, the device readjusts the *voltage* to attain the milliamps needed, similar to the way you change pressure on the accelerator until the speedometer shows the speed you want.

WHY A PRECISION RESISTOR IS USED

A precision 250 ohm resistor in the 4–20 mA circuit (**Figure 1**) enables the output device to work with *virtually no error*. The resistor is connected in series with all devices in the circuit, which ensures that the amount of current through the resistor is exactly the same as the current through all other devices in the circuit.

Accordingly, when the voltage across the 250 ohm resistor is 1 volt, the current through the resistor is always exactly 4 mA. Note: **Figure 1** shows how a voltmeter has to be connected to read the voltage across the resistor. When the voltage across the resistor is 5 volts, the current through the resistor is always exactly 20 mA. And when the voltage across the resistor is somewhere *between* 1 and 5 volts the current through the resistor is exactly in direct proportion to that voltage.
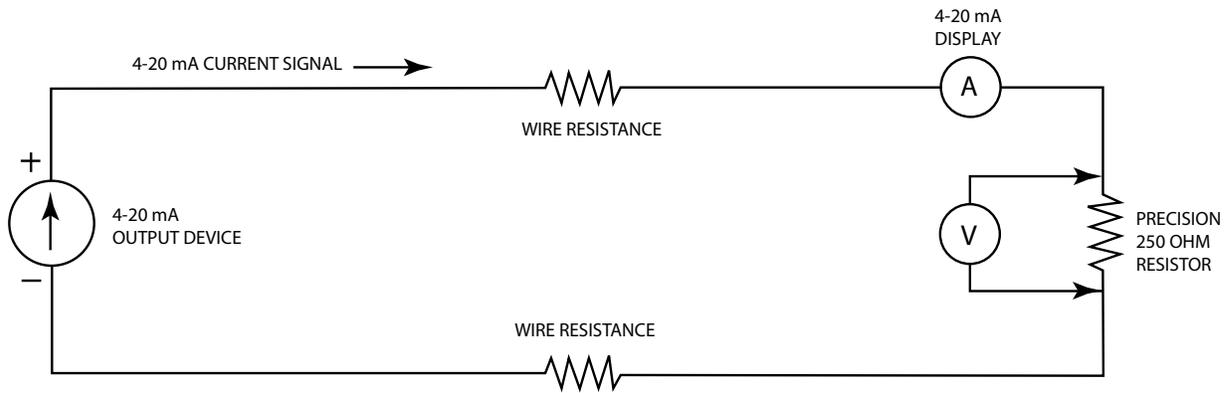
The output device "reads" mA in the circuit and varies its output voltage to achieve a predetermined mA.

Percent of Measurement	4–20 mA signal	1–5 V signal
0	4.0 mA	1.0 V
10	5.6 mA	1.4 V
20	7.2 mA	1.8 V
25	8.0 mA	2.0 V
30	8.8 mA	2.2 V
40	10.4 mA	2.6 V
50	12.0 mA	3.0 V
60	13.6 mA	3.4 V
70	15.2 mA	3.8 V
75	16.0 mA	4.0 V
80	16.8 mA	4.2 V
90	18.4 mA	4.6 V
100	20.0 mA	5.0 V

If you know the number of mA, multiply it by 250 ohms to find how many volts are across the resistor. For example, 4.0 mA (0.004 amps) times 250 equals 1.0 volt. And 20.0 mA (0.020 amps) times 250 equals 5.0 volts.

If you know the number of volts across the resistor, divide it by 250 ohms to find the current or mA. For example, 1.0 volt divided by 250 ohms equals 4.0 mA (0.004 amps). And 5.0 volts divided by 250 ohms equals 20.0 mA (0.020 amps).

Figure 1. A basic 4-20 mA circuit with a constant current output device.

So the precision 250 ohm resistor ensures that a predetermined current in the circuit will always have a predetermined voltage across the 250 ohm resistor. Accordingly, a 4 mA current will always have 1 volt across the resistor *even though the voltage in other parts of the circuit may be different due to wiring resistance or other variables.* Likewise a 20 mA current will always have 5 volts across the resistor even though the voltage may be different in other parts of the circuit.

ADVANTAGES OF A 4–20 mA CIRCUIT

A question that often arises is, "why not just use predetermined *voltages* instead of predetermined currents to provide the control signals?" The answer is that current is always exactly the same in *all* parts of a series circuit. But voltage may vary throughout a circuit according to resistance in the circuit. Thus, actual voltage at the receiving device would depend on resistance in another part of the circuit and would be less reliable.

For example, consider how resistance of wiring in the circuit could affect voltage at the receiving device. The resistance of wiring depends on wire size and length. Thus variances in wiring would produce variances in the voltage values for control. And this would produce control errors.

Using a precision resistor and an output device that varies its output voltage to produce predetermined currents eliminates error due to resistance. The output device simply outputs enough voltage to overcome wiring resistance and produce predetermined mA currents. Consequently, *voltage measured at the output device and voltage measured across the resistor may be significantly different*. But the voltage across the precision resistor depends entirely on the predetermined current. It will always match the mA values shown in Figure 1.

USE OF 4 mA FOR ZERO PERCENT

Another question that is sometimes asked is, "why is 4 mA used instead of 0 mA to produce zero percent or to shut off a device?" The answer is that a loss of power would result in 0 mA and the device being controlled could not sense the difference.

USE WITH HEATEC PRODUCTS

Typical uses of 4–20 mA circuits for Heatec products are as follows:

- Vega radar units on asphalt tanks
- Triac valves on fuel preheaters
- Siemens pressure transmitters on fuel tanks
- Honeywell burner controls on heaters

The device that *outputs* the signal usually does so in response to one or more inputs it receives from other devices outside of the 4-20 mA circuit. These include devices such as sensors, transmitters and thermocouples.

The device that *receives* the signal may be a readout or display. Or it may be a valve that opens or closes in proportion to a 4–20 mA signal. Or it may be a Honeywell modulation motor on the burner of a heater.

A detailed explanation of how the radar works is given below as an example of how a typical 4–20 mA circuit actually works. Brief explanations of the other uses follow the radar discussion.

HOW RADAR CONTROLS WORK

Figures 2, 3 and 4 show a Heatec asphalt tank, a Vega radar sensor, and a Honeywell controller.

The radar sensor uses electromagnetic waves to determine the fluid level in the tank. It converts level information into a 4–20 mA signal and transmits it to the Honeywell controller. The controller converts the 4–20 mA signals into feet (and tenths of a foot) and shows this on its built-in display.

These numbers represent the height or level of asphalt above the bottom of the tank. Operators can use a printed table that converts levels to volume to learn how many gallons of asphalt are in the tank.

The 20 mA signal represents 100 percent of the so-called "full" level of the asphalt tank. The "full" level is an arbitrary level that reserves some empty space to allow for expansion of the asphalt.

A 4 mA signal represents zero percent or the empty level of the tank. Thus, when the sensor outputs a 4 mA signal the display shows 0.0 feet, which means that the tank is empty.

Since 4 mA represents empty and 20 mA represents "full" there is a total of 16 mA (between 4 mA and 20 mA) available to represent intermediate levels from "full" to empty. And each mA is subdivided into smaller values. Consequently, there are many discrete or separate values from 4 mA to 20 mA. These mA values are converted into height values in feet and tenths of a foot and shown on the display as levels of asphalt in the tank.

The height values are in *direct proportion* to the mA values. Thus, 5.6 mA is 10% of the "full" height. 7.2 mA is 20% of the "full" height. 8 mA is 25% of the "full" height. 12.0 mA is 50% of the "full" height. And so on. See **Figure 1**.

Figure 3. The Vega radar sensor outputs a 4–20 mA signal in response to feedback from the radar beam it emits to determine asphalt level.

Figure 4. Honeywell controller displays asphalt levels in feet and tenths of a foot.

Figure 2. Heatec vertical asphalt tanks equipped with radar sensors for level indications.

The operator needs to be aware of the level (in feet) that represents "full". This is because the display will not show any feet higher than what is shown for a 20 mA signal. Remember, the 20 mA is the maximum signal and represents 100 percent.

Consequently, if the asphalt expands so as to cause the actual level to rise above the number of feet displayed at 20 mA, *the display will not change.*

Incidentally, the controller cuts off the unloading pump before the asphalt reaches overflow level. And it shuts off heat to the coils when the tank nears empty to prevent coking the coils.

HOW OTHER CONTROLS WORK

Heatec fuel preheaters use a 4–20 mA circuit to transfer signals from a Yokogawa temperature controller to a

Triac valve that modulates the flow of hot oil that heats the fuel.

Heatec fuel tanks equipped with Siemens pressure transmitters use a 4–20 mA circuit to transfer signals from the transmitter to a Honeywell controller. The controller has a display that indicates the fuel levels and initiates signals to shutoff certain devices at predetermined levels.

Heatec heaters use a 4–20 mA circuit to transfer signals from a Honeywell modulation controller to the modulation motor that controls the burner. However, please note that the resistor used is not fixed at 250 ohms as in conventional circuits. Consequently the voltage needed to produce the 4–20 mA current is not the same as in circuits with a fixed 250 ohm resistor. Otherwise, the burner control circuit works the same as other 4–20 mA circuits.

Heatec, Inc. 5200 Wilson Road Chattanooga, Tennessee 37410 www.heatec.com (423) 821-5200 (800) 235-5200 Fax (423) 821-7673

Page 5