PDHonline Course E271 (5 PDH)

Understanding 4 to 20 mA Loops

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Understanding 4 to 20 mA Loops

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Introduction:

Most industrial processes have at least one analog measurement or control loop. An analog loop has a signal that can vary anywhere in the range between and including two fixed values, such as 1 to 5 VDC. Other names for analog loops include modulating, throttling, and continuously variable loops. By contrast, a discrete or on/off loop has only two valid values. These two valid values are typically a) the available supply voltage, and b) zero volts. In a discrete loop, a signal that is not at one extreme or the other of the range is not a valid signal. For example, a typical discrete loop would have a value of 120VAC (on) or 0 VAC (off) – but a value of 50 VAC would be invalid. In an analog loop, however, the signal is acceptable when it is anywhere within the stated range. For example, in a 1 to 5 VDC loop, a value of 3.3 VDC, or any other value between and including 1 to 5 VDC, would be a valid signal.

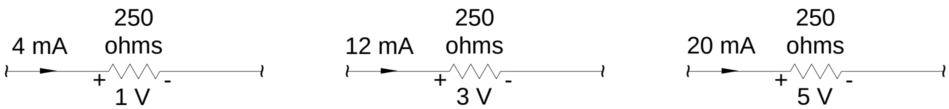
Analog Signals and Loops:

There are many types of analog signals and loops in the industrial process world, some of which are:

- 4 to 20 mA
- 1 to 5 VDC
- 3 to 15 PSIG (pneumatic)
- 10 to 50 mA
- -10 to 10 VDC
- 0 to 20 mA
- 0 to 5 VDC

What is the difference between Span and Range?
The range of a signal consists of two values, such as 4 mA to 20 mA, or 1 VDC to 5 VDC. The span of a signal is the difference between the two ends of the range, such as 16 mA and 4 VDC, respectively.

The first value given in the ranges above is the minimum or lower range value and the second value in each range is the maximum or upper range value. All of the mA signals listed above are actually mADC, but the DC suffix is often not included in documentation. The analog signal type that will be discussed in this document is 4 to 20 mA (sometimes denoted as 4 … 20 mA), which is easily converted to a 1 to 5 VDC analog signal by using a precision 250-ohm resistor. See Figure 1, which shows the derived voltage signal at three different current readings.



Converting a 4 to 20 mA Signal
to a 1 to 5 VDC Signal
Figure 1

A few of the ranges listed above have a low-end value of 0 mA or 0 VDC. These loops will not work with 2-wire (also known as loop-powered) instruments because loop-powered instruments get their power from the loop, as the name would imply. If there is no current flowing in the loop (0 mA), then there is no power for the instrument to keep its circuitry active. In order to use an instrument on a loop that has 0 mA or 0 VDC as the low end, the power for the instrument would have to come from a separate source, which would require a 3-wire or 4-wire instrument. See Figures 21, 22, 23, and 24 for examples of 2-wire, 3-wire, and 4-wire instruments.

An analog signal range that has a non-zero low-end, such as 3 to 15 PSIG or 4 to 20 mA, is known as a “live-zero”range because the low end is not dead, but has some pressure, voltage, or current present at all times.

Before the 1970s, most analog loops were 3 to 15 PSIG pneumatic loops. Gradually, 4 to 20 mA and 10 to 50 mA loops were introduced on new projects and on retrofit projects to replace most of the existing 3 to 15 PSIG loops. There are, however, still many modern applications of 3 to 15 PSIG signals. One commonplace example is the pneumatic signal from a modulating valve’s I/P (current to pressure converter) to that same valve’s positioner (see Figure 80). Another advantage to consider with regard to 3 to 15 PSIG analog loops is the intrinsic safety of using all-pneumatic loops in electrically classified hazardous (explosive) areas. One disadvantage of pneumatic loops is the degradation in the speed of response as the pneumatic transmission distances become longer for instruments located further out in the field. Electronic 4 to 20 mA signals are not affected as much by increased transmission distances.

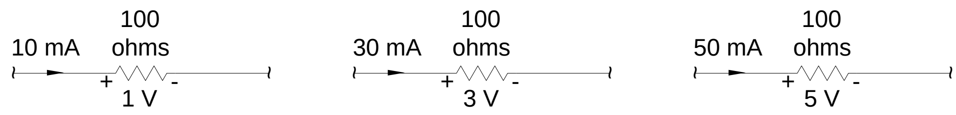
Why was the range of 4 to 20 mA chosen, rather than some other range, like 3 to 15 mA? Actually, in the early days of electronic analog loops, in addition to instruments intended for 4 to 20 mA loops, there were also instruments that were manufactured for 10 to 50 mA loops. This was because some manufacturers required the extra current of the 10 to 50 mA loops to power some models of their equipment. Eventually, 4 to 20 mA loops became the industry standard.

There are many opinions as to why 4 to 20 mA became the standard, such as lower energy being available in 4 to 20 mA loops, compared to 10 to 50 mA loops, with regard to intrinsically safe applications and the fact that digital 20 mA communications have been around since the first half of the 20th century in the form of teletype machines (such as the ASR33, by Teletype Corporation, and the 32-ASR by Telex). Technical people were accustomed to dealing with 20 mA components in the digital applications of teletype machines, so it may have had some bearing on choosing 20 mA as the high limit of the 4 to 20 mA loop, rather than some other value like 30 mA.

With 20 mA as the top end of the 4 to 20 mA loop, why was 4 mA chosen for the bottom end, rather than 10 mA or some other value? On this topic as well, opinions vary, but consider the loops that were being replaced, namely 3 to 15 PSIG. The low-end value ("live-zero") is 20% of the high-end value, meaning that the high end value is 5 times the low-end value. To phrase this differently, the span from low end to high end is 4 times the low-end value. This is true for :

- 3 to 15 PSIG (low end = 15 / 5 = 3, span = 4 * 3 = 12),
- 4 to 20 mA (low end = 20 / 5 = 4, span = 4 * 4 = 16),
- 10 to 50 mA (low end = 50 / 5 = 10, span 4 * 10 = 40), and
- 1 to 5 VDC (low end = 5 / 5 = 1, span = 4 * 1 = 4).

As mentioned previously, 4 to 20 mA signals are easily converted to 1 to 5 VDC signals by using a precision 250-ohm resistor (see Figure 1). Similarly, this is true for a 10 to 50 mA signal using a precision 100-ohm resistor (see Figure 2). Precision resistors are used because the accuracy of the mA signal is usually very important and it could easily be degraded by using a general-purpose resistor. A lot of money has already been spent on getting an accurate transmitter, so there is no reason to skimp on the resistor. From this point forward, let's have the understanding that all such resistors discussed in this document are precision (0.01% or better) resistors.



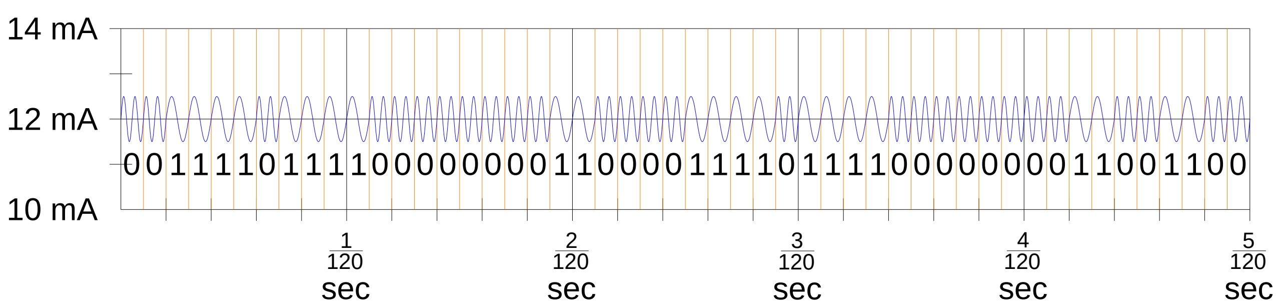
Converting a 10 to 50 mA Signal
to a 1 to 5 VDC Signal
Figure 2

PLCs, DCSs, and other loop controllers with 4 to 20 mA analog input cards or modules don't really measure the 4 to 20 mA current signal directly. It is easier to measure voltage than it is to measure current (an analogy to this is that it is easier to measure pressure than it is to measure flow), so analog input cards or modules typically use a 250-ohm resistor to convert the 4 to 20 mA signal to a 1 to 5 VDC signal (see Figures 21 & 28). Some signal conditioners or isolation modules use a 100-ohm (or smaller) resistor to convert the 4 to 20 mA signal to a 0.4 to 2 V (or smaller) signal (see Figure 30). Such devices use a smaller input resistor so that they won't put as much resistance load on the current loop (more on this later).

For more information on analog DC signals, refer to ISA publication *ANSI/ISA-50.00.01-1975 (R2002) Compatibility of Analog Signals for Electronic Industrial Process Instruments*.

<u>HART Overview:</u>

HART is the acronym for Highway Addressable Remote Transducer and is a two-way Frequency-Shift Keying (FSK) digital communications protocol (see Bell 202 Standard sidebar on next page) that is superimposed on the 4 to 20 mA DC signal. Figure 3 shows HART communications on a current signal that happens to be 12 mA at this point in time. Notice in Figure 3 that when the frequency is 2,200 Hz, the digital value is zero (0) and when the frequency is 1,200 Hz, the digital value is one (1). The average value of the superimposed signal is zero, so it does not affect the DC reading of the 4 to 20 mA signal.



HART Communications on 12 mA Current Signal
Figure 3

The HART communication protocol allows HART-enabled controllers and other HART-enabled devices to communicate with each other over the same pair of conductors that carries the 4 to 20 mA signal. This 1,200 bits-per-second communication allows two updates per second (three to four updates per second in burst mode) and can carry far more information than the one parameter that is present in the 'regular' 4 to 20 mA signal. For example, the HART signal can carry information such as device identification, device diagnostics, health, status, device configuration, additional measured or calculated values, and many more possibilities (typically 35 to 40 data items are accessible in most HART devices).

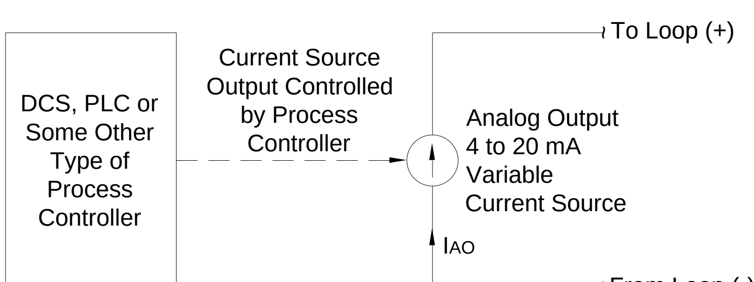
A HART Communicator handheld device is often used to monitor and change the settings in the instruments and devices wired in to the HART loops. The HART specification calls for a minimum loop resistance of 230 ohms, but 250 ohms is often cited as the requirement. The HART specification also calls for a maximum loop resistance of 1,100 ohms, but some HART-enabled devices have lower maximum loop resistance ratings. In all cases, confirm the minimum and maximum total loop resistance requirements with the instruments that have been installed on that loop.

The HART signal will not pass through some types of intrinsic safety barriers, so care must be taken in the specification of barriers when HART protocol is intended to be used on a loop now or in the foreseeable future.

Bell 202 Standard:
This is, more specifically, a binary frequency shift keying (BFSK) method, since it alternates the frequency between two distinct values, 1,200 Hz for Mark or One and 2,200 Hz for Space or Zero. The magnitude of this FSK signal is 1 mA peak-to-peak, which is 0.5 mA peak above and below the 4 to 20 mA signal that is carrying the main parameter signal. Bell 202 is a full-duplex modem standard, but HART uses this standard as a half-duplex system, which means information can flow in both directions, but only one direction at a time. Half-duplex requires only two conductors, whereas full-duplex would require four conductors.

Analog Outputs to Control Devices (Control):

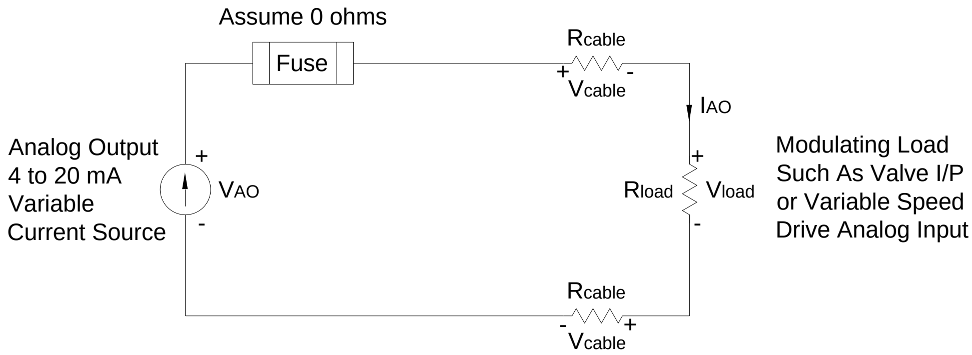
Analog output loops use 4 to 20 mA signals to control the position of modulating (throttling) valves, to control the speed of variable speed drives, or to control other types of modulating loads. A simplified example of an analog output loop is shown in Figure 4.



Analog Output
Figure 4

A constant current source produces a certain current through it, no matter what, within its operational limits. It is similar to a constant voltage source, which produces a certain voltage across it, no matter what, within its operational limits. A variable current source such as that shown in Figure 4 is a constant current source with an adjustable output, just as a variable voltage source, such as a benchtop power supply, can be dialed in to a desired constant voltage output setting.

A typical 4 to 20 mA analog output loop is shown in Figure 5. In this scenario, the analog output is powered by the internal backplane of the control system, which is the most common scenario. The other scenario is shown in Figure 6, in which the analog output is powered by an external power supply.



Analog Output Loop
Loop Power Supply Internal to Control System
Figure 5

The voltage across the variable current source (V_{AO}) of the analog output is whatever it needs to be to provide 4 to 20 mA into the loop resistance, but is typically limited to 24 V maximum. If the voltage across the analog output is limited to 24 V, then the maximum loop resistance will be 24 V / 20 mA = 1,200 ohms. See the Appendix for more information on voltage drops around a current loop. The voltage drops in the loop in Figure 5 are V_{cable}, V_{load}, and V_{cable}, all of which must add up to be equal toV_{AO}.

EXAMPLE 1

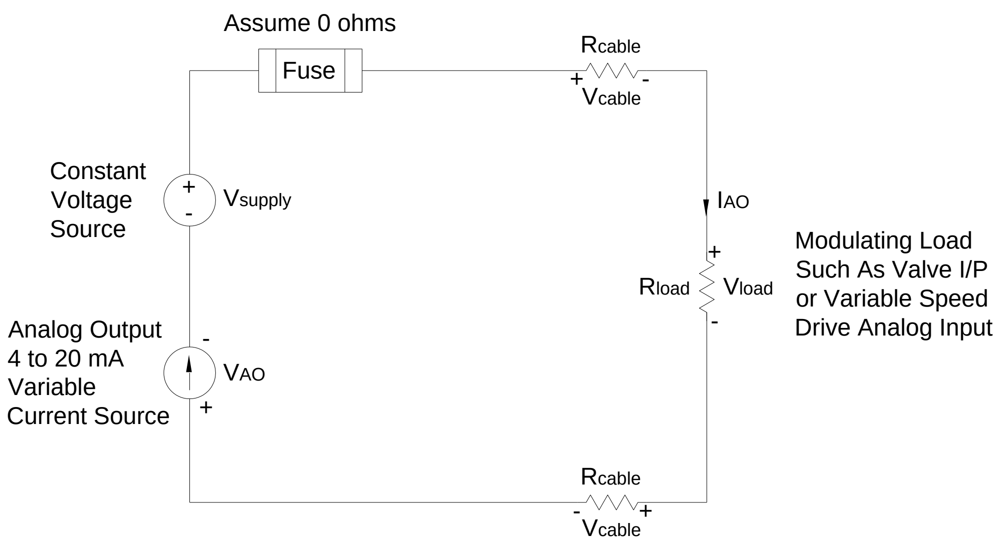
Let's work an example using Figure 5 with a total loop resistance (R_{cable} + R_{load} + R_{cable}) of 1,000 ohms. The asterisk symbol (*) will be used in formulas and calculations in this document to denote multiplication. At 4 mA, the voltage across the analog output (V_{AO}) would be:

4 mA * 1,000 ohms = 4 V at 4 mA

At 20 mA, the voltage across the analog output (V_{AO}) would be:

20 mA * 1,000 ohms = 20 V at 20 mA END OF EXAMPLE

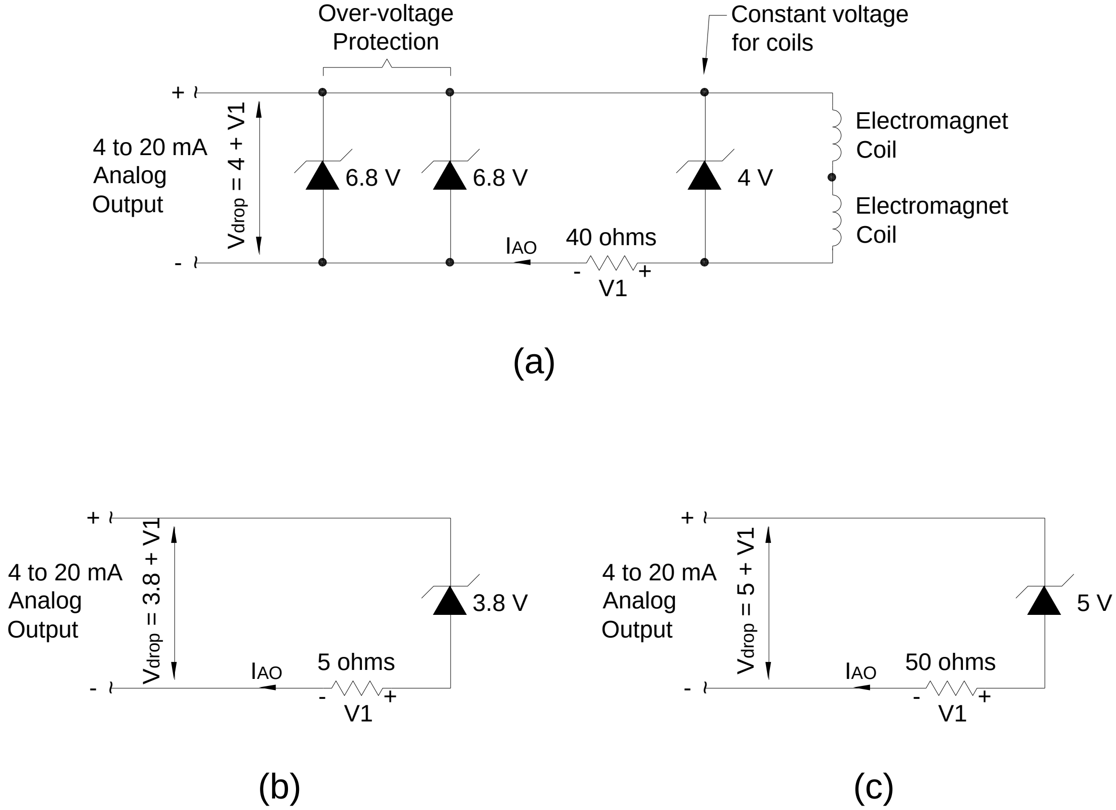
As previously stated, most analog output cards and modules are powered by the controller's internal backplane. There are, however, some brands and models of equipment that require an external loop power supply for their analog outputs, an example of which is shown in Figure 6.



Analog Output Loop
Loop Power Supply External to Control System
Figure 6

Notice that the + and – voltage drop sign convention is flipped on the analog output (V_{AO}) in Figure 6 (when compared to Figure 5), since the loop power supply (V_{supply}) is now the driving force in the loop, rather than the analog output. See Appendix for further explanation with regard to + and – voltage drop sign convention.

One of the most common devices connected to an analog output is a current to pressure transducer or I/P converter. They come in a variety of equivalent circuits, as shown in Figure 7, or with simple verbal descriptions, such as “Minimum Voltage Available at Instrument Terminals must be 11 VDC for HART communication.”



Current to Pressure (I/P) Converter
Various Equivalent Circuit Representations
Figure 7

EXAMPLE 2

Let's consider Figure 5 with an I/P described by the equivalent circuit in Figure 7(c). These two Figures are combined in Figure 8. Assume that the one-way cable resistance is 10 ohms. At 20 mA, the voltage drops around the loop are described in Figure 8. What will be the voltage drop V_{AO} across the analog output?

The voltage drop across each R_{cable} will be

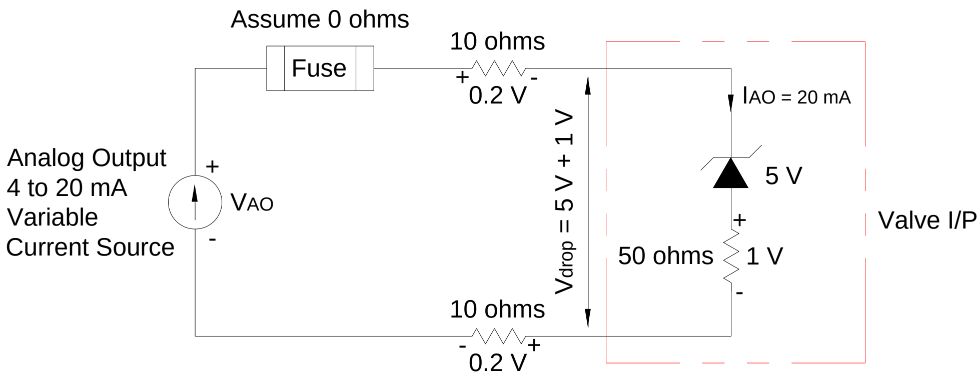
20 mA * 10 ohms = 0.2 V.

The total voltage drop across the I/P will be the sum of the 5V drop across the 5V zener diode plus the voltage drop (V1) across the 50-ohm resistor:

5V + (20 mA * 50 ohms) = 5 V + 1 V

The voltage drop (V_{AO}) across the analog output will be whatever it needs to be and will be the sum of the voltage drops around the rest of the loop:

V_{AO} = 0.2 + 5 + 1 + 0.2 = 6.4 V END OF EXAMPLE



Analog Output Loop at 20 mA
Loop Power Supply Internal to Control System
Figure 8

EXAMPLE 3

Let's consider an I/P described only by the following input resistance values:

- 1,370 ohms at 4 mA
- 470 ohms at 12 mA
- 290 ohms at 20 mA

By calculating the voltages at each current value, we can add more information to that which we were given, thusly:

- 1,370 ohms * 4 mA which is a voltage drop of 5.48 V
- 470 ohms * 12 mA which is a voltage drop of 5.64 V
- 290 ohms * 20 mA which is a voltage drop of 5.8 V

From these voltages, we can see that the value of V1 [as illustrated in Figure 7(a), (b), and (c)] will vary by 5.8 – 5.48 = 0.32 V.

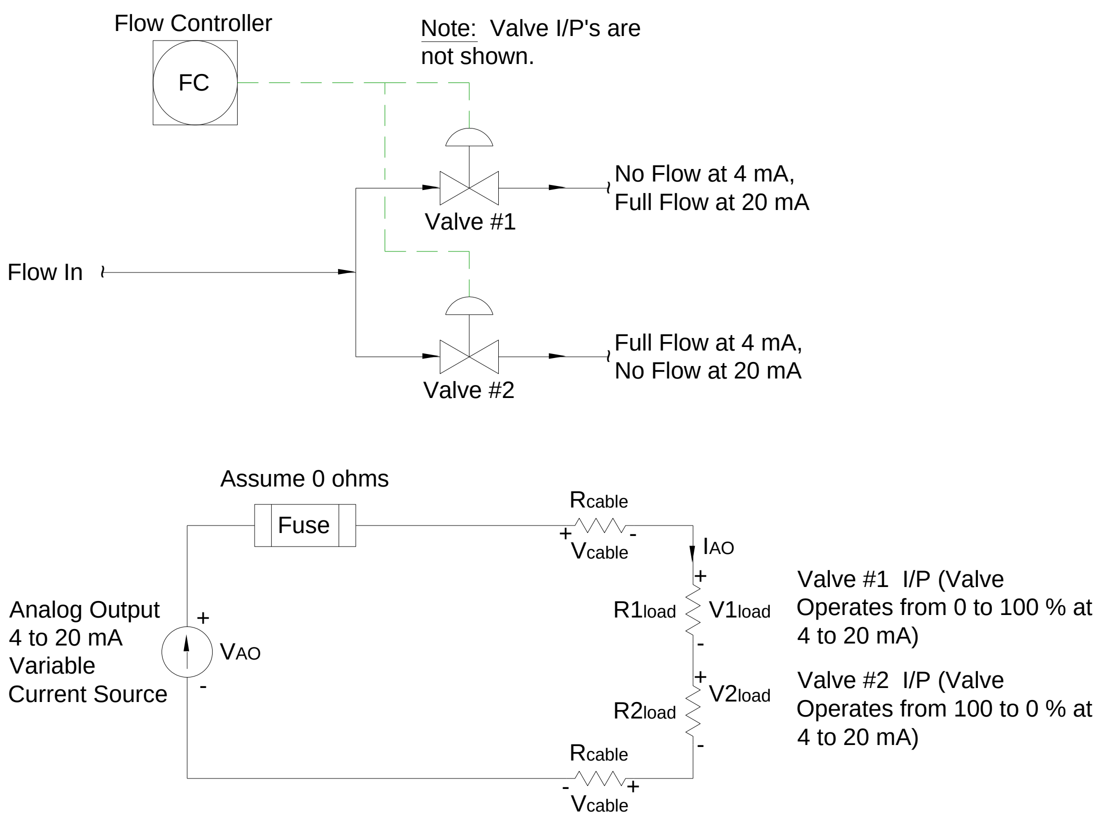
We also know that this 0.32 V change happens over a span of 20 – 4 = 16 mA.

Dividing the 0.32 V by 16 mA yields the resistance of 20 ohms. This is the resistance across which voltage drop V1 occurs. This voltage drop V1 takes place across the 40-ohm resistor in Figure 7(a), the 5-ohm resistor in Figure 7(b), and the 50-ohm resistor in Figure 7(c). In this example, however, we have determined that the resistance value is 20 ohms.

What would be the value of the zener diode voltage in this example? The constant voltage across the zener diodes illustrated in the three examples in Figure 7(a), (b), and (c) are 4 V, 3.8 V, and 5V, respectively. To determine the value of the zener diode voltage in this example, we could use any of the three input resistances to calculate it, but let's use 1,370 ohms at 4 mA, which is a total voltage drop of 5.48V. We have determined that the resistance for V1 is 20 ohms and the current through this resistance is 4 mA, so V1 = 20 * 0.004 = 0.08 V. The total voltage drop at 4 mA is 5.48 V, so the constant voltage drop is 5.48 – 0.008 V = 5.4 V across the zener diode. This is instead of the 4 V zener diode in Figure 7(a), the 3.8 V zener diode in Figure 7(b), and the 5 V zener diode in Figure 7(c). Confirm that this zener voltage value still holds true for 12 mA and 20 mA.

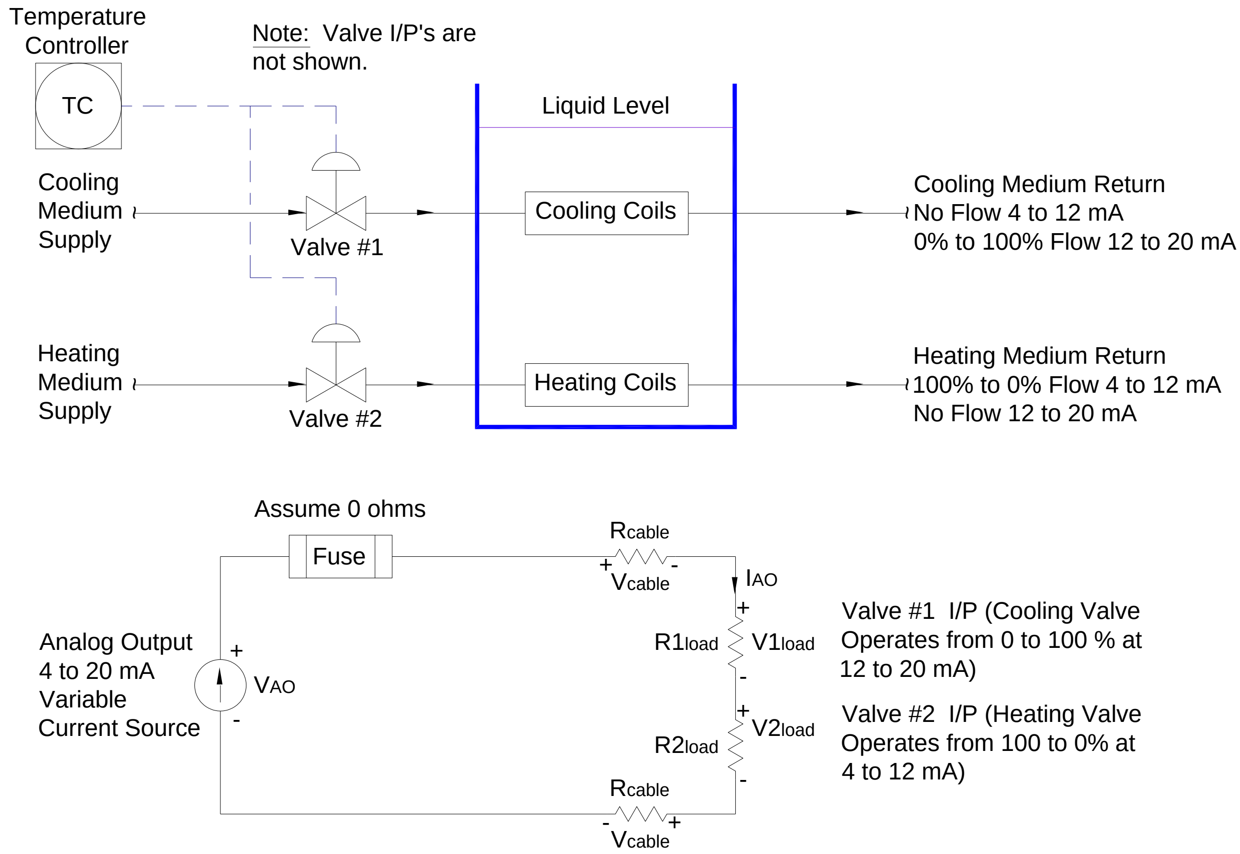
END OF EXAMPLE

It would be unusual, but still possible, to find an analog output (AO) control loop that has more than one load on it. One example that occasionally occurs of an analog output loop with more than one load is a two-valve system that splits the flows in two different directions by using two valves that work in opposite directions while using the same 4 to 20 mA signal. See Figure 9.



Analog Output Loop with Two Loads
Flow Diverting Proportional Control
Figure 9

Another example of an analog output (AO) control loop with two loads is shown in Figure 10. In this scenario, a temperature transmitter (not shown) monitors the temperature in the vessel and the control system outputs one 4 to 20 mA signal to provide either heating or cooling to the liquid in the vessel, or neither heating nor cooling if the current signal is 12 mA. This type of analog output loop is known as "split range" because the valves are using different parts of the 4 to 20 mA range to define their operation, rather than sharing the entire 4 to 20 mA range as in Figure 9.



Analog Output Loop with Two Loads
Split-Range Temperature Control
Figure 10

To reiterate, most analog output 4 to 20 mA current loops only have one load. The examples shown in Figures 9 and 10 are exceptions to the commonplace installation.

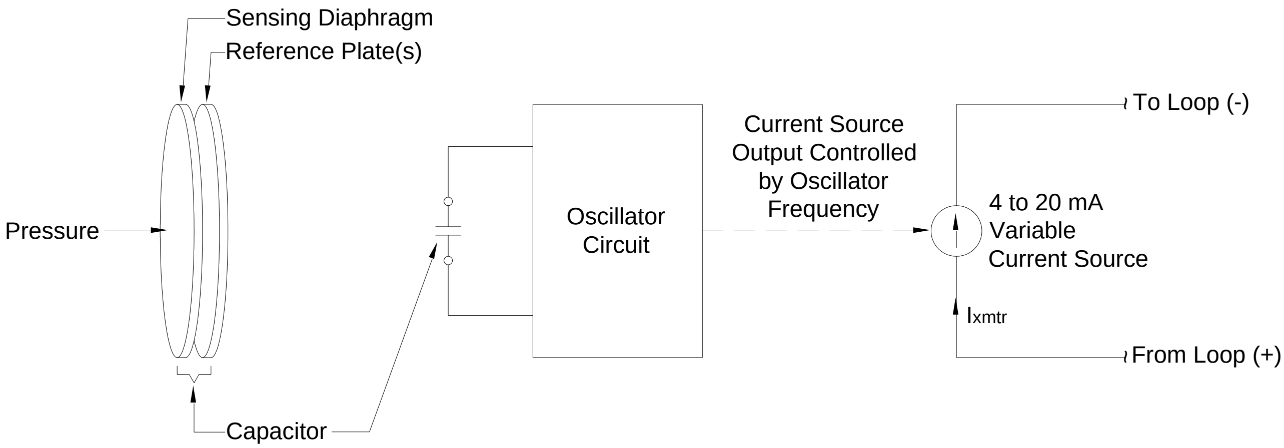
Analog Inputs from Transmitters (Measurement):

An analog input (measurement) is the functional opposite of an analog output (control). An analog input at a DCS, PLC, single loop controller, or other device, accepts an electronic signal, such as 4 to 20 mA or 1 to 5 VDC, and converts it into a digital value. When an analog input module or card is said to accept a 4 to 20 mA signal, it doesn't actually measure the current directly, in most cases. As mentioned previously, most analog inputs measure the current by measuring the resulting voltage drop across a resistor, typically a 250-ohm resistor.

How is the 4 to 20 mA loop current controlled by the transmitter? A typical process transmitter is a combination of a transducer, translation circuitry, and a variable current source. A transducer converts one measurable parameter into a different measurable parameter. For example, a thermocouple converts heat energy into a micro-volt (μV) signal and a resistance temperature device (RTD) converts heat energy into a resistance value. Other everyday transducers include audio speakers, which change electrical energy into acoustic energy, and the neurons in our bodies, which change chemical signals into electrical signals, and then back into chemical signals.

One type of process transmitter is a pressure transmitter, which senses the input pressure and puts out a signal in the range of 4 to 20 mA to represent the sensed pressure. There is more than one way for a transducer to convert pressure into an electrical quantity, but we will consider the method that uses the sensed pressure (one measurable parameter) to change a capacitance value (another measurable parameter).

In the highly simplified illustration in Figure 11, the sensed pressure pushes on the sensing diaphragm, which is one of the plates in a capacitor. The circumference of the sensing diaphragm is fixed and the center of this diaphragm is pushed inward by the pressure and therefore its effective distance from the reference plate(s) of the capacitor changes [there could be more than one reference plate]. The capacitance value of a capacitor changes as the distance between the plates changes, and that change in capacitance causes a change in the frequency of the oscillator circuit. The oscillator frequency controls the output of the variable current source such that the current passing through it is directly related to the pressure on the diaphragm. Other elements in the translation circuitry make corrections for non-linearity in the transducer, for variations due to temperature changes, and for other factors, all to ensure that the 4 to 20 mA signal is accurate, repeatable, and as linear (in most cases) as possible.

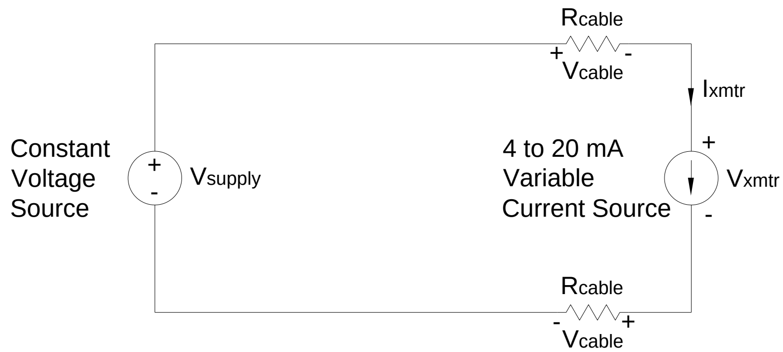


One Type of Pressure Transmitter
Figure 11

Loop Power Supply and Resistance Limitations:

Power is required for the oscillator circuit and current source shown in Figure 11, as well as the other components in the transmitter. In a loop-powered or 2-wire device, such as that illustrated in Figure 11, that power is provided by the 4 to 20 mA loop itself, which is driven by the loop power supply (shown in Figure 12 but not shown in Figure 11). In a loop-powered (2-wire) transmitter, as long as the variable current source in a process transmitter has enough voltage drop (V_{xmtr}) across its terminals, it will produce a 4 to 20 mA current that represents the parameter that is being measured on the process side of the transducer. In the case of 3-wire or 4-wire devices, the loop power and device power requirements are provided from a power source external to the loop. The differences between loop-powered (2-wire), 3-wire, and 4-wire transmitters will be discussed later.

The simplest example of a typical measurement loop is shown in Figure 12. The power is provided by a constant DC voltage source (V_{supply}, which is usually 24V) and the current in the loop (I_{xmtr}) is controlled by the variable current source in the transmitter. Notice that there is no analog input or other monitoring device in this particular loop. This loop could be used to power a transmitter that was being used for local indication only. Most current loops usually include an analog input resistance which is not shown in Figure 12 but which will be added in Figure 28 later on. The two resistances labeled R_{cable} in Figure 12 represent the cable resistance in the conductor going out to the transmitter and the conductor coming back from the transmitter. Both of those resistances are equal, since both of those conductors are equal in length, and the voltage drops (V_{cable}) across those resistances are equal, since the same current (I_{xmtr}) flows through both resistances.



Simple Measurement Loop
without Analog Input
Figure 12

Many technical documents will state that the current signal in a 4 to 20 mA loop is not affected by the total loop resistance or the voltage drops within the loop, but that is not entirely true. Process transmitter cut-sheets will usually have a load limit formula and graph that reveals the maximum loop resistance versus loop power supply voltage. A more correct statement to make would be, the current signal in a 4 to 20 mA loop won't be affected by the total loop resistance and voltage drops within the loop, <u>within defined limits</u>. In order to define those operational limits, there are four basic parameters that must be known:

- The minimum transmitter voltage [V_{xmtr}(min.)] is the minimum voltage required by the transmitter to power its internal circuitry and to produce a 4 to 20 mA output (or other defined current range, such as 3 to 21 mA).

- The maximum transmitter voltage [V_{xmtr}(max.)] is the maximum voltage that the transmitter can tolerate at 20 mA (or other defined high current limit) and still safely dissipate the resulting power.

- The maximum transmitter current [I_{xmtr}(max.)] is the maximum current that the transmitter can output, which could be a value of 20 mA, 21.4 mA, 22 mA, or some other value.

- The minimum transmitter current [I_{xmtr}(min.)] is the minimum current that the transmitter can output, which could be a value of 4 mA, 3.9 mA, 3 mA, or some other value. This last parameter is not used as often as the first three in defining the operational limits of the transmitter.

The first three parameters [V_{xmtr}(min.), V_{xmtr}(max.), and I_{xmtr}(max.)] are revealed in two ways on a transmitter cut-sheet: 1) in the graph called the load limit or maximum loop resistance graph [see Figure 13], and 2) in the formula for maximum loop resistance (see following).

EXAMPLE 4

The general formula for the maximum acceptable loop resistance line on the load limit graph is:

$R_{max} = [V_{supply} – V_{xmtr}(min.)] / I_{xmtr}(max.)$

Consider a transmitter cut-sheet that specifies the maximum acceptable loop resistance in a slightly different arrangement with the following formula:

$R_{max} = 50 * (V_{supply} – 12\ V)$

The 50 in the above formula merely represents dividing the voltage by the current (20 mA) to get the resistance, which is the same as multiplying the voltage by 50, so the above formula can be rewritten as:

$R_{max} = (V_{supply} – 12\ V) / 20\ mA.$

> ***Maximum acceptable loop resistance:***
>
> *In addition to the formats discussed to the left of this sidebar, namely*
>
> $R_{max} = 50 * (V_{supply} – 12\ V)$, and
>
> $R_{max} = (V_{supply} – 12\ V) / 20\ mA$,
>
> *the formula could sometimes be shown in a rearranged form in order to find the minimum acceptable power supply voltage, such as:*
>
> $V_{supply}(min) = 12\ V + (0.02 * R_{total})$,
>
> which is also the same as
>
> $V_{supply}(min) = 12\ V + (R_{total} / 50)$.

The two versions of the formula above represent a transmitter that has a minimum power supply requirement [V_{xmtr}(min.)] of 12 V and a maximum loop resistance graph line based on 20 mA, which is I_{xmtr} (max.). A current of 20 mA gives the maximum loop resistance line a slope of 50 ohms/volt.

Some transmitter cut sheets might use 22 mA to determine the maximum loop resistance, which would change the 50 in the formula to 45.45. Some transmitter cut-sheets will use yet another value for maximum transmitter current which would result in a different slope for the R_{max} line. The formula above is graphed in Figure 13, but only for power supply values 12 V [since this is V_{xmtr} (min.)] or greater. Power supply values less than 12 V are not valid in this case, since they would not provide the minimum V_{xmtr} required for proper operation of the transmitter. Notice that the maximum transmitter voltage [V_{xmtr} (max.)] is also shown, at 36 V in Figure 13.

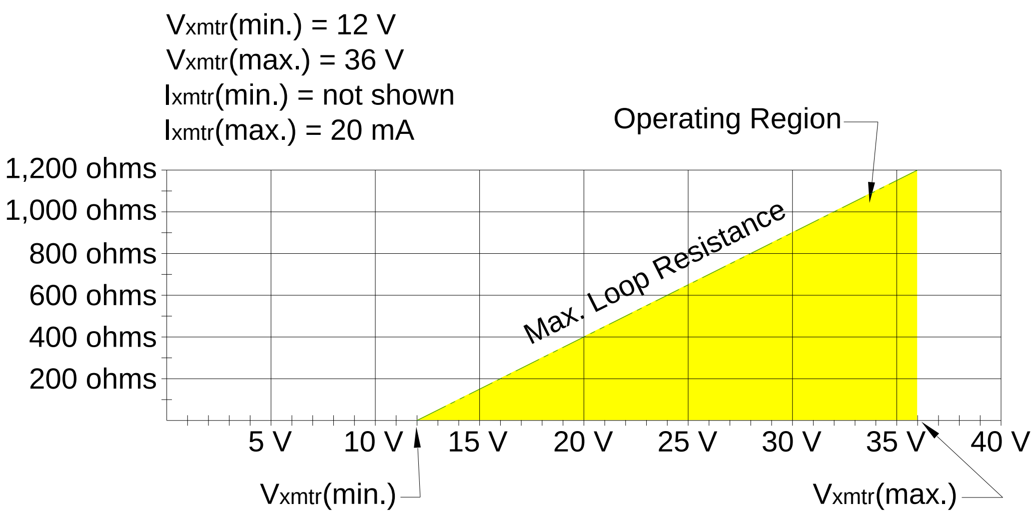


Figure 13

Notice the shaded operating region shown in Figure 13. The operating region says, in effect, if you plot the loop power supply voltage (V_{supply}) as a vertical line and the total loop resistance as a horizontal line and the intersection of those two lines (the operating point) falls within the operating region, the loop should function properly. For example, let's assume a 24 V loop power supply and a total loop resistance of 500 ohms. The result is plotted in Figure 14.

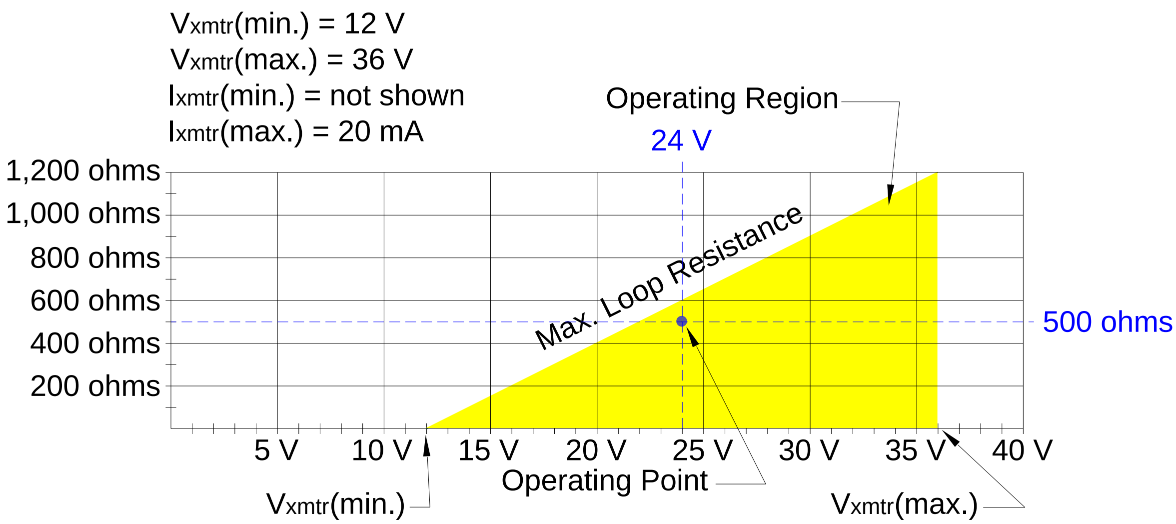


Figure 14

END OF EXAMPLE

From Figure 14, it is clear that, although a total loop resistance of 500 ohms is acceptable, a total loop resistance of 750 ohms would not be acceptable with a loop power supply of 24 V, since the resulting intersection of those two lines (the operating point) would be outside of (above) the operating region. For a total loop resistance of 750 ohms to be acceptable, the loop power supply would have to be increased to 27 V, as calculated in Example 5, and which could also be ascertained from the formulas or graphs above.

EXAMPLE 5

From the above discussion in Example 4, set the total loop resistance equal to 750 ohms to determine the minimum power supply voltage required for this transmitter at this resistance:

$R_{max} = 50 * (V_{supply} – 12\ V)$

$750 = 50 * (V_{supply} – 12\ V)$

$15 = V_{supply} – 12\ V$

$V_{supply} = 27\ V$

END OF EXAMPLE

The voltage of the loop power supply is assumed to remain constant. The total resistance in the loop is assumed to remain constant, though the resistance will vary a little bit, based on temperature. The operating point, which is the intersection of these two parameters, is therefore assumed to remain constant. In general, it is best not to operate near the edge of the operating region where small variations in power supply voltage or total loop resistance could possibly move the operating point outside of the operating region.

In Figures 13 and 14, it is also illustrated that the maximum voltage drop that is acceptable at the transmitter [V_{xmtr}(max.)] is 36 V (this is the lower, right-hand corner of the operating region) for this transmitter. Notice that the graphs in Figures 13 and 14 do not show a minimum loop resistance line, based on the manufacturer's supposition (or perhaps mandate) that the loop power supply will not have a higher voltage than the maximum voltage rating of the transmitter [V_{xmtr}(max.)]. If the minimum loop resistance line were to be shown, as it sometimes is on catalog cut-sheets, it would start at 36 V [V_{xmtr}(max.)] in this example and go up with a slope of 250, which is the reciprocal of 4 mA. There will be more about this later. Many catalog cut-sheet loop resistance / load limitation graphs are presented like Figure 13, truncated at the maximum V_{xmtr} value (36 V in this case), without a minimum load resistance line.

EXAMPLE 6

Consider the example in Figure 15, which is similar to the one shown in Figures 13 and 14, but which uses 22 mA to determine the maximum loop resistance line. The other parameters are the same, so we have:

1. V_{xmtr} (min.) = 12 V

2. V_{xmtr} (max.) = 36 V

3. I_{xmtr} (max.) = 22 mA

4. I_{xmtr} (min.) = not shown

Because of the 22 mA value of I_{xmtr}(max.) current, the formula for maximum loop resistance has changed slightly to:

$R_{max} = 45.45 * (V_{supply} – 12\ V)$

Which can also be written as:

$R_{max} = (V_{supply} – 12\ V) / 22\ mA$.

On the loop resistance graph, the maximum loop resistance line starts at V_{xmtr}(min.) and the slope of this line is the reciprocal of I_{xmtr}(max.). In this example, the starting point of the line is 12 V and the slope of the line is 45.45 ohms / V. See Figure 15.

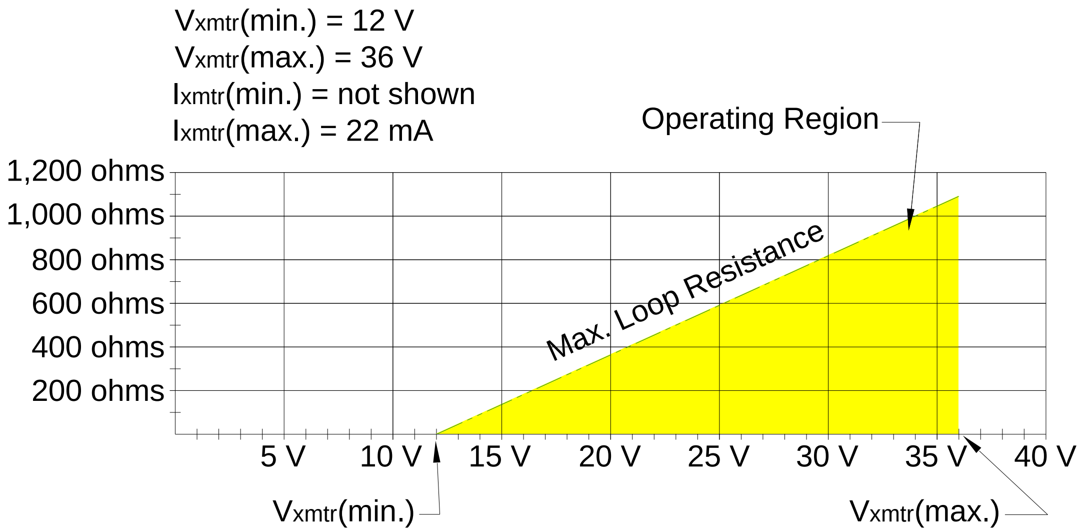


Figure 15

Using the graph in Figure 15, let's determine if a loop power supply of 24 V and a total loop resistance of 500 ohms are still an acceptable combination. These are plotted in Figure 16.

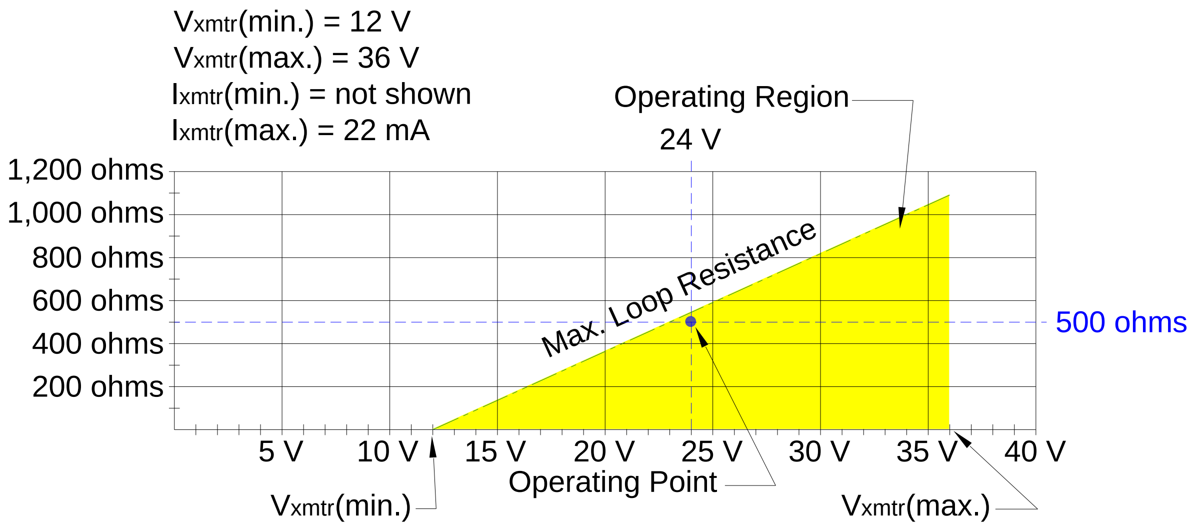


Figure 16

It is clear from Figure 16 that a loop power supply of 24 V and a total loop resistance of 500 ohms are still acceptable, but that the intersection of those two lines (the operating point) is closer to the borderline than it was on Figure 14. Again, it is best not to operate a loop at or near the edge of its operating region. END OF EXAMPLE

As mentioned above, the load limit graph on a transmitter cut-sheet often does not show a minimum resistance line, but let's think about how to show it in the next example.

EXAMPLE 7

Assume that we have a 40 V loop power supply and we'd like to know how much total loop resistance would be required in order to not over-voltage a particular transmitter, which has a V_{xmtr} (max.) of 36 V. The formula for R_{min} is similar to that for R_{max}, but uses V_{xmtr}(max.) instead of V_{xmtr}(min.), and I_{xmtr}(min.) instead of I_{xmtr}(max). The formula is:

$R_{min} = [1 / I_{xmtr}(min.)] * [V_{supply} – V_{xmtr}(max.)]$

$R_{min} = 250 * (V_{supply} – 36\ V)$

$R_{min} = 250 * (40\ V – 36\ V)$

$R_{min} = 250 * 4\ V$

$R_{min} = 1{,}000$ ohms

So, if we have a 40 VDC power supply, we need to ensure that there is always a minimum of 1,000 ohms of total resistance in the loop in order to avoid applying an over-voltage to the transmitter. If the minimum loop resistance line is included on the manufacturer's graph, it would be as shown on Figure 17. On the loop resistance graph, the starting point for the minimum loop resistance line starts at V_{xmtr}(max.) and the slope of this line is the reciprocal of

I_{xmtr}(min.). In this example, the starting point of the line is 36 V and the slope of the line is 250 ohms/volt, which shows (as we calculated above) that a minimum value of 1,000 ohms at for a 40 V loop power supply (V_{supply}). This is on the very edge of the operating region.

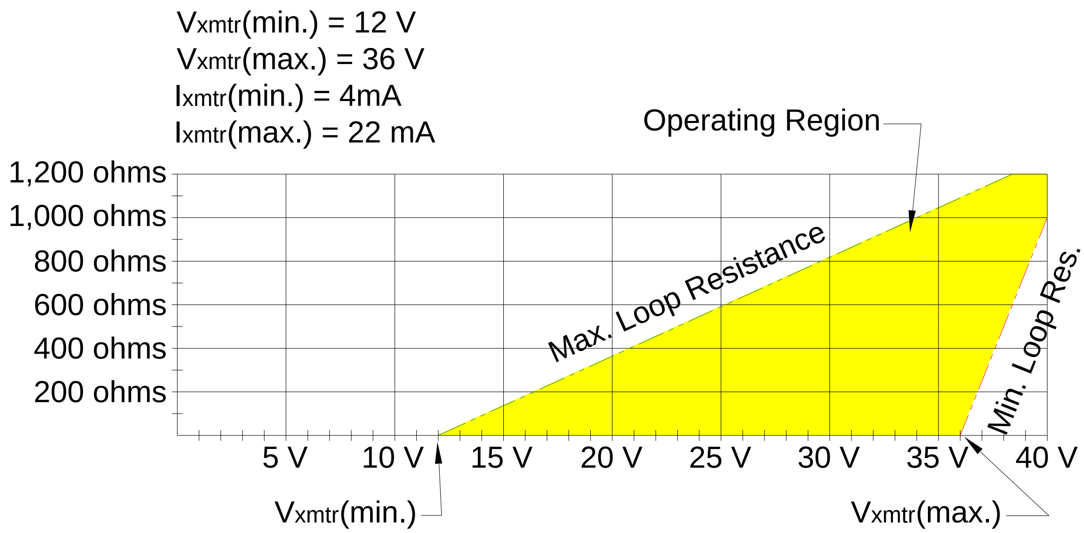


Figure 17

END OF EXAMPLE

Of course, if the manufacturer's cut-sheet does not show a minimum loop resistance line and you decide to apply a power supply voltage greater than V_{xmtr}(max.) [36 V in the last example], you do so at your own risk

Let's look at another representation of Figure 17, which is shown in Figure 18:

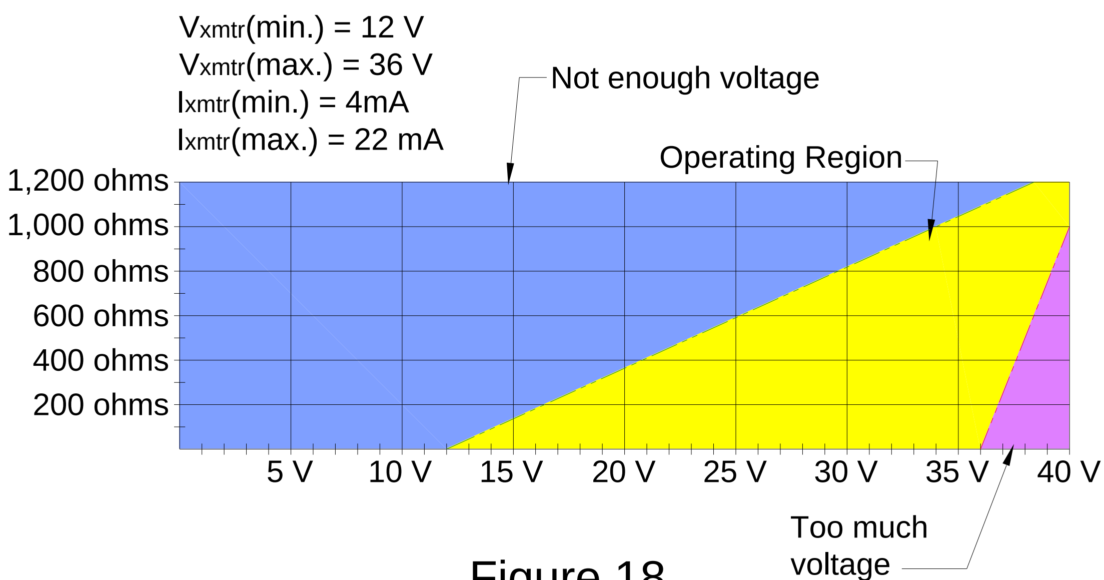


Figure 18

As can be seen in Figure 18, the region to the left of the operating region boundary represents combinations of voltage and resistance that will not provide enough voltage (V_{xmtr}) to the transmitter for it to operate properly. Conversely, the region to the right of the operating region boundary represents combinations of voltage and resistance that will provide too much voltage (V_{xmtr}) to the transmitter for it to operate properly.

EXAMPLE 8

Consider another example that has a transmitter with the following requirements/parameters:

1. V_{xmtr}(min.) = 10.5 V
2. V_{xmtr}(max.) = 31 V
3. I_{xmtr}(max.) = 20 mA
4. I_{xmtr}(min.) = 4 mA
5. Minimum loop resistance of 230 ohms for HART communications
6. Maximum loop resistance of 1,100 ohms for HART communications

Let's derive the formula for the maximum loop resistance for this transmitter, which is based on ensuring we have 10.5 V at the transmitter so that it can operate properly when loop current is at its maximum value:

$R_{max} = (V_{supply} – 10.5\ V) / 20\ mA$, which is the same as:

$R_{max} = 50 * (V_{supply} – 10.5\ V)$ END OF EXAMPLE

EXAMPLE 9

Let's continue the example above and derive the formula for the minimum loop resistance beyond 31 V [V_{xmtr}(max.)], which is based on ensuring that the transmitter does not receive an overvoltage when loop current is at its minimum value:

$R_{min} = (V_{supply} – 31\ V)] / 4\ mA$, which is the same as:

$R_{min} = 250 * (V_{supply} – 31\ V)$

The above two versions of the R_{min} formula are only valid when the power supply voltage (V_{supply}) exceeds the [V_{xmtr}(max.)] of the transmitter. The minimum resistance line is not graphed below this voltage because it would imply negative resistance values.

Let's create a graph to illustrate the maximum and minimum loop resistance requirements for the transmitter we're presently considering. See Figure 19 for the maximum and minimum loop resistance requirements for this particular transmitter, as well as the acceptable loop resistance operating region, which is defined and outlined by these resistance lines.

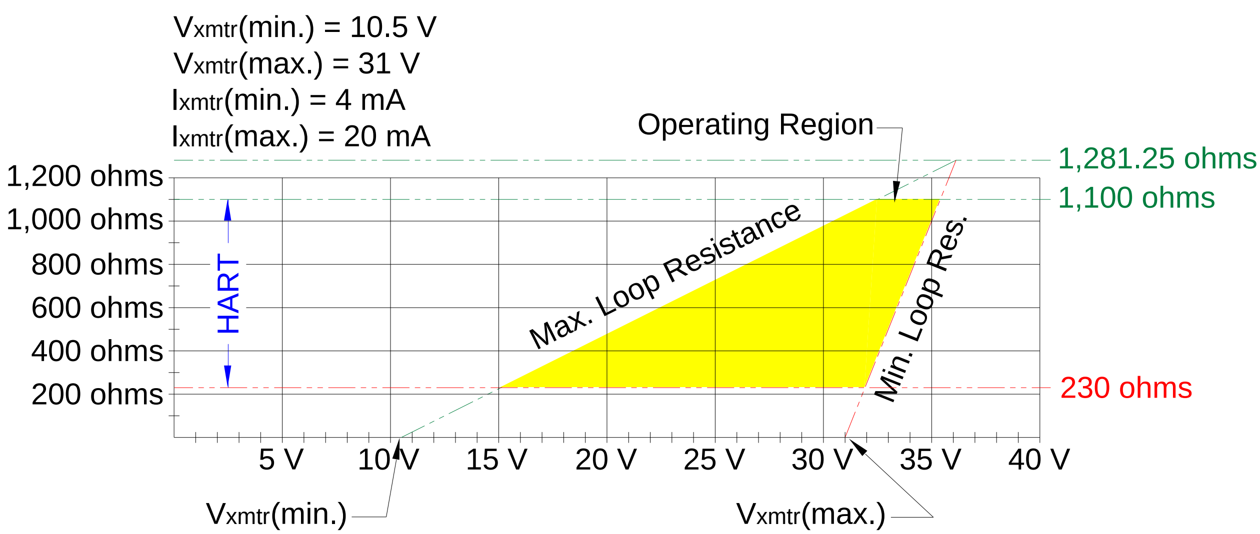


Figure 19

As mentioned previously, the maximum loop resistance line has its starting point on the voltage axis at 10.5 V [V_{xmtr}(min.)] which is the minimum value of V_{xmtr} for the transmitter to operate properly. Since the slopes of the lines on the graph are resistance divided by voltage, which is the reciprocal of current, the slope of the maximum loop resistance line, in this case, is the reciprocal of 20 mA [I_{xmtr}(max.)] or 50.

As also mentioned previously, the minimum loop resistance line has its starting point on the voltage axis at 31 V [V_{xmtr}(max.)], which is the maximum allowable V_{xmtr} at the transmitter when there is a loop resistance of 0 ohms. Since the slope of the lines on the graph is resistance divided by voltage, the slope of the minimum loop resistance line, in this example, is the reciprocal of 4 mA [I_{xmtr}(min.)] or 250.

Let's ignore the maximum resistance limitation (1,100 ohms) of the HART specification for a moment. The intersection of the maximum loop resistance line and the minimum loop resistance line is at 1,281.25 ohms and 36.125 V, which defines the top limit of the operating range. This top limit represents the maximum loop resistance and maximum loop power supply voltage for this particular transmitter. This limit could also be calculated by setting the formulas for R_{max} and R_{min} equal to each other. From the work above:

$R_{max} = 50 * (V_{supply} – 10.5\ V)$, and

$R_{min} = 250 * (V_{supply} – 31\ V)$

When these two lines intersect, the two formulas are equal to each other, so

$50 * (V_{supply} – 10.5\ V) = 250 * (V_{supply} – 31\ V)$

$(V_{supply} – 10.5\ V) = 5 * (V_{supply} – 31\ V)$

$(V_{supply} – 10.5\ V) = 5 * V_{supply} – 155\ V$

$144.5 = 4 * V_{supply}$

$V_{supply} = 36.125\ V$

Plugging this value of V_{supply} back in to the equation for R_{max} gives us:

$R_{max} = 50 * (V_{supply} – 10.5\ V)$

$R_{max} = 50 * (36.125\ V – 10.5\ V)$

$R_{max} = 1{,}281.25$ ohms

We could also have double-checked this resistance value by plugging this value of V_{supply} back in to the equation for R_{min}, which gives us:

$R_{min} = 250 * (V_{supply} – 31\ V)$

$R_{min} = 250 * (36.125\ V – 31\ V)$

$R_{min} = 250 * (5.125\ V)$

$R_{min} = 1{,}281.25$ ohms at the top limit of the operating region.

If we include the maximum resistance limitation (1,100 ohms) of the HART specification required in this example, then the maximum loop power supply voltage (V_{supply}) would be defined by the R_{min} formula when it equals 1,100 ohms:

$R_{min} = 250 * (V_{supply} – 31\ V)$

$1{,}100 = 250 * (V_{supply} – 31\ V)$

$4.4 = V_{supply} – 31\ V$

$V_{supply} = 35.4\ V$ [maximum allowable at 1,100 ohms]

What would be the minimum loop power supply voltage [V_{supply}(min.)] that would be required for the transmitter described above? Remember that we need a minimum resistance of 230 ohms to meet the specification for HART communications, as required in this example. That defines the bottom, horizontal line of the acceptable loop resistance operating range in Figure 19. To determine what the minimum loop power supply voltage requirement would be, we look at the bottom, left-hand corner of the operating range in Figure 19 and estimate that it is around 15.1 V. To double-check, we solve the formula above for V_{supply} where the maximum resistance line has a value of 230 ohms:

$R_{max} = 50 * (V_{supply} – 10.5\ V)$

$230 = 50 * (V_{supply} – 10.5\ V)$

$4.6 = V_{supply} – 10.5\ V$

$V_{supply} = 15.1\ V$ [minimum required] END OF EXAMPLE

EXAMPLE 10

Let's consider another example for loop load limitations in which the transmitter parameters are:

1. Vxmtr (min.) = 11 V
2. Vxmtr (max) = 36 V
3. Ixmtr (min.) = 3 mA (this value indicates an alarm condition)
4. Ixmtr (max.) = 22 mA (this value also indicates an alarm condition)
5. HART communication is required (assume 250-ohm minimum loop resistance, rather than 230 ohms, and 1,100-ohm maximum loop resistance)

Suppose that we work for the transmitter manufacturer and we are tasked with creating the load limit graph and maximum resistance formula for this transmitter. We know that the bottom portion of the operating range will be defined by the 250-ohm minimum loop resistance requirement assumed above for HART communications in this example. We know that the top portion of the operating range will be defined by the 1,100-ohm maximum resistance loop requirement assumed above for HART communications in this example. We also know that the maximum loop resistance line will start at Vxmtr (min.) and have a slope of 45.45, which is the reciprocal of 22 mA. We know that the minimum resistance line will start at Vxmtr (max) and have a slope of 333.3, which is the reciprocal of 3 mA. When we graph these constraints, we have, in Figure 20:

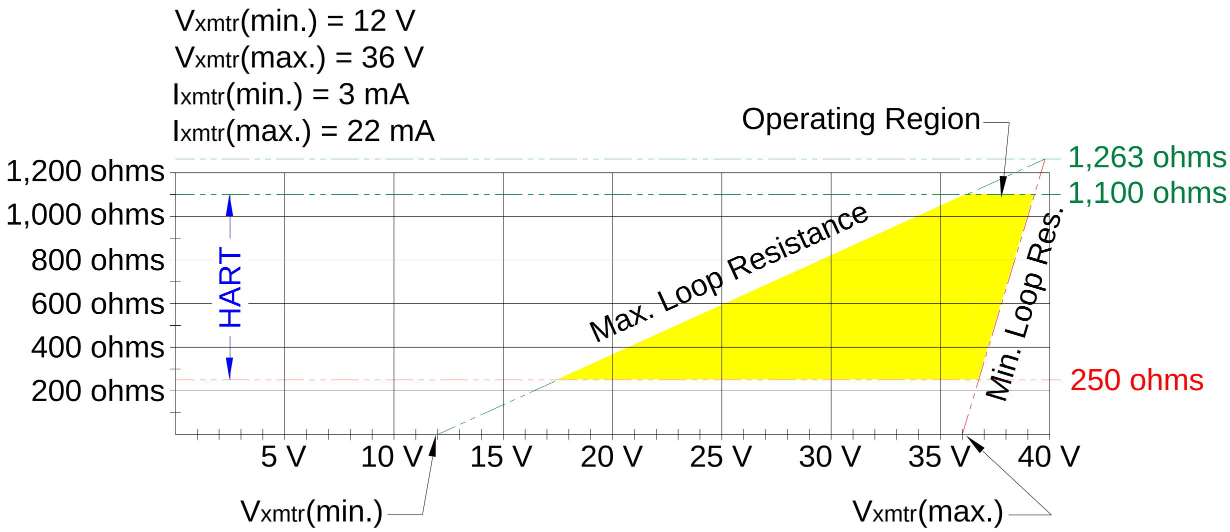


Figure 20

The formula for maximum loop resistance would be:

$R_{max} = [1 / I_{xmtr} (max.)] * [V_{supply} – V_{xmtr} (min.)]$

$R_{max} = 45.45 * [V_{supply} – 12]$

Or we could have written it as:

$R_{max} = [V_{supply} – V_{xmtr} (min.)] / I_{xmtr} (max.)$

$R_{max} = [V_{supply} – 12] / 0.022$

The formula for the minimum loop resistance would be:

$R_{min} = (1 / I_{xmtr} (min.)) * [V_{supply} – V_{xmtr} (max.)]$

$R_{min} = 333.3 * [V_{supply} – 36]$

Or we could have written it as:

$R_{min} = [V_{supply} – V_{xmtr} (max.)] / I_{xmtr} (min.)$

$R_{min} = [V_{supply} – 36] / (0.003)$

As stated in a previous example, the upper right-hand corner of the operating range, where the maximum and minimum resistance lines intersect, is defined when the formulas for R_{max} and R_{min} are equal to each other. Restating the formulas from this example:

$R_{max} = 45.45 * [V_{supply} – 12]$, and

R_{min} = 333.3 * [V_{supply} – 36]

They intersect when they are equal to each other, so:

45.45 * [V_{supply} – 12] = 333.3 * [V_{supply} – 36]

[V_{supply} – 12] = 7.33 * [V_{supply} – 36]

264 – 12 = 6.33 * V_{supply}

V_{supply} = 252 / 6.33

V_{supply} = 39.789 V

This can be verified (approximately) by looking at Figure 20.

Plugging this value for the maximum allowable V_{supply} into the formula for R_{max} give us:

R_{max} = 45.45 * [V_{supply} – 12]

R_{max} = 45.45 * [39.789 – 12]

R_{max} = 45.45 * 27.8

R_{max} = 1,263 ohms, as shown in Figure 20.

We could also have double-checked this resistance value by plugging this value of V_{supply} back in to the equation for R_{min}, which gives us:

R_{min} = 333.3 * [V_{supply} – 36]

R_{min} = 333.3 * [39.789 – 36]

R_{min} = 333.3 * [3.789]

R_{min} = 1,263 ohms at top limit of operating range

The above value for R_{max} is at the upper right-hand corner of the operating region for this particular transmitter. Of course, we should not exceed the HART maximum total loop resistance limitation, which is defined as 1,100 ohms in this example.

What would be the minimum power supply voltage required for proper operation of this transmitter with HART communication? From the graph in Figure 20, we can tell that it is around 17.5 V, based on where the maximum loop resistance line and the 250-ohm resistance line intersect. We could find the value more accurately by solving the above formula for R_{max} =

250 ohms, which is where the maximum loop resistance line and the 250-ohm resistance line intersect.

$R_{max} = 45.45 * [V_{supply} – 12]$

$250 = 45.45 * [V_{supply} – 12]$

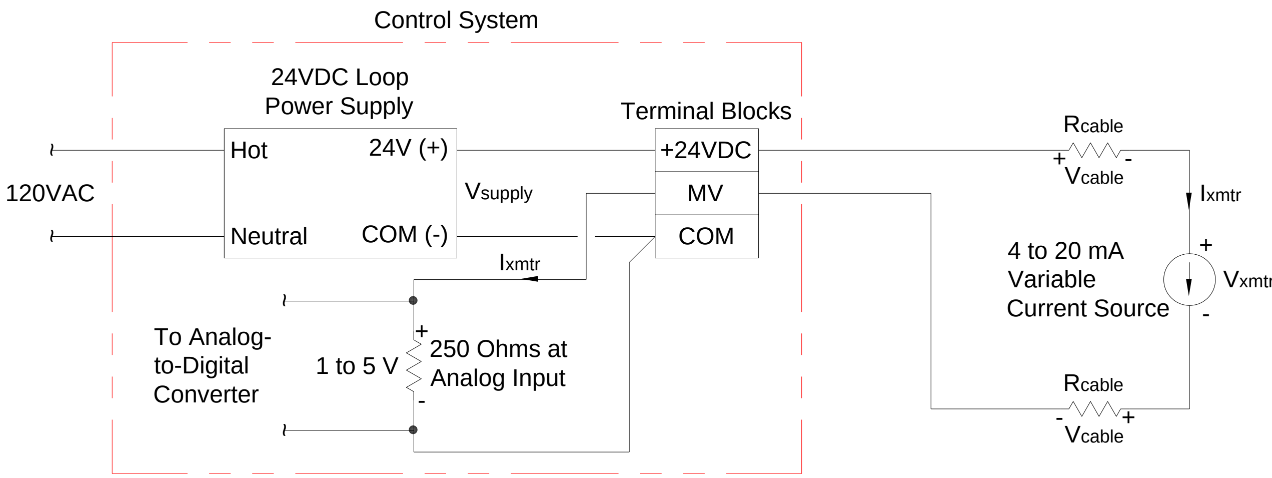
$5.5 = V_{supply} – 12$

$V_{supply} = 17.5$ V [minimum requirement for HART communication]

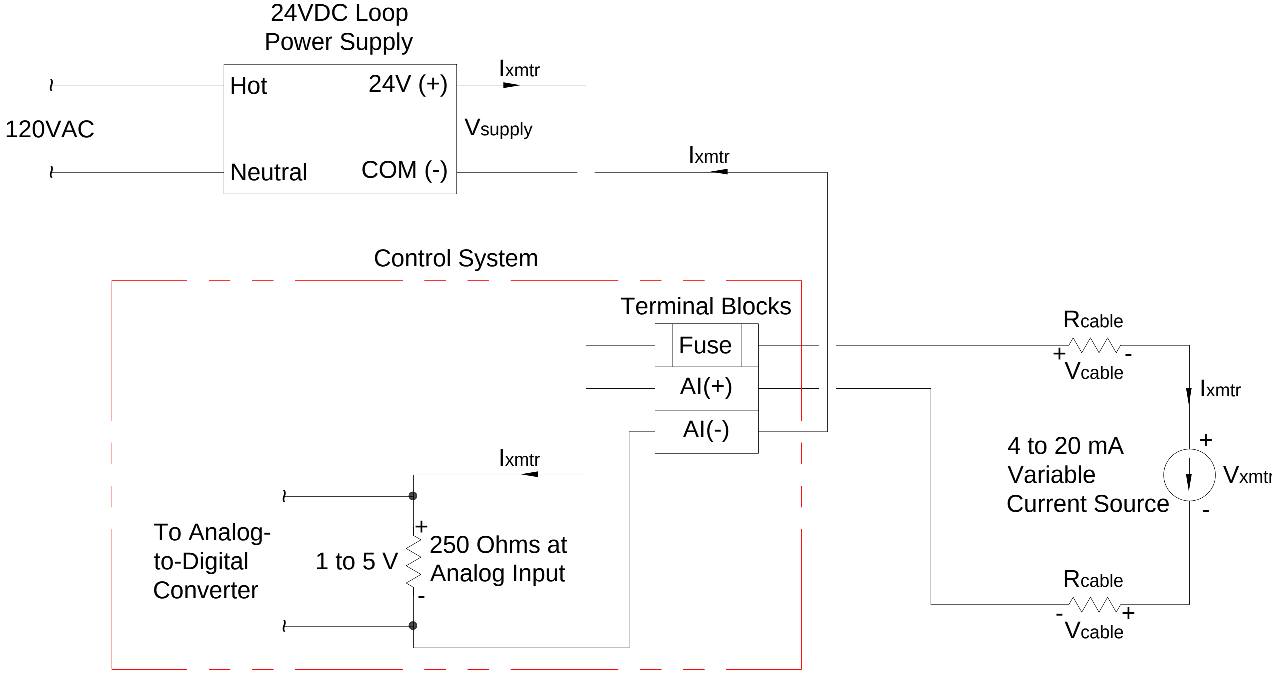
END OF EXAMPLE

2-Wire Transmitters:

As mentioned numerous times previously, most analog inputs have a 250-ohm precision resistor to convert the 4 to 20 mA current signal to a 1 to 5 V voltage signal. For a 2-wire transmitter loop, the loop power supply could be provided within the control system (Figure 21) or external to the control system (Figure 22).



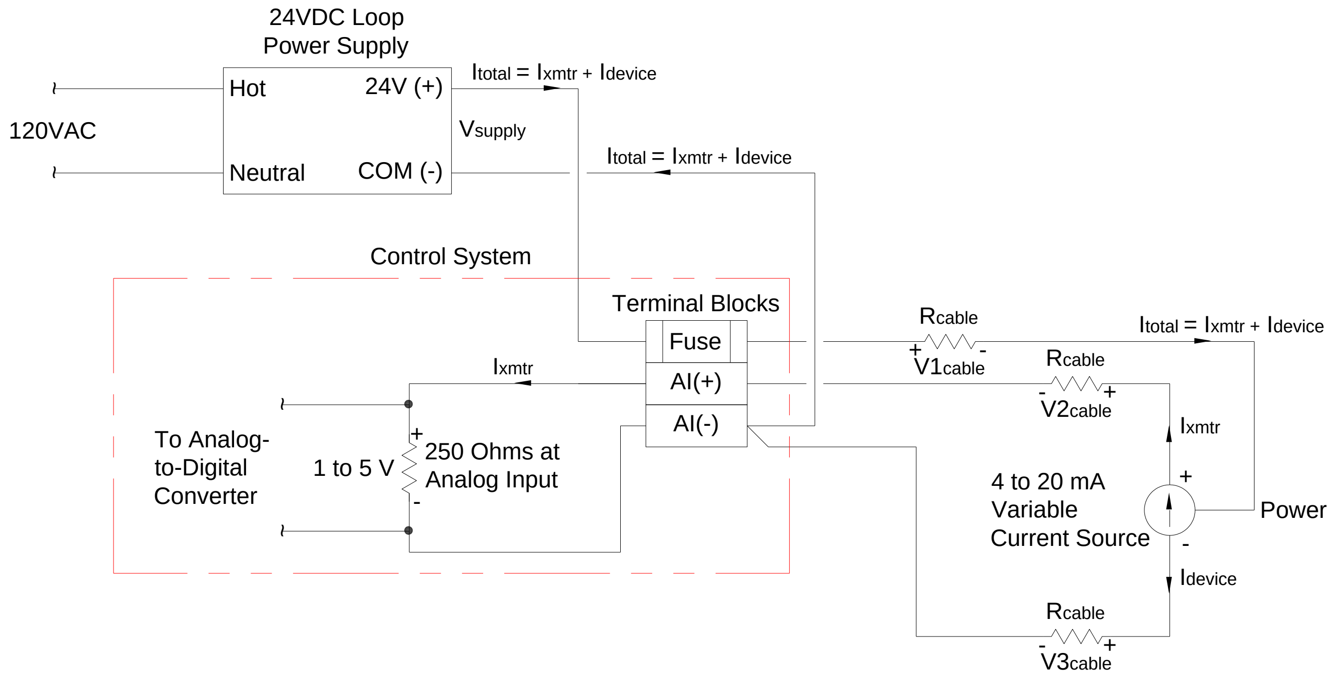
2-Wire Analog Input
Loop Power Supply Internal to Control System
Figure 21



2-Wire Analog Input
Loop Power Supply External to Control System
Figure 22

3-Wire Transmitters:

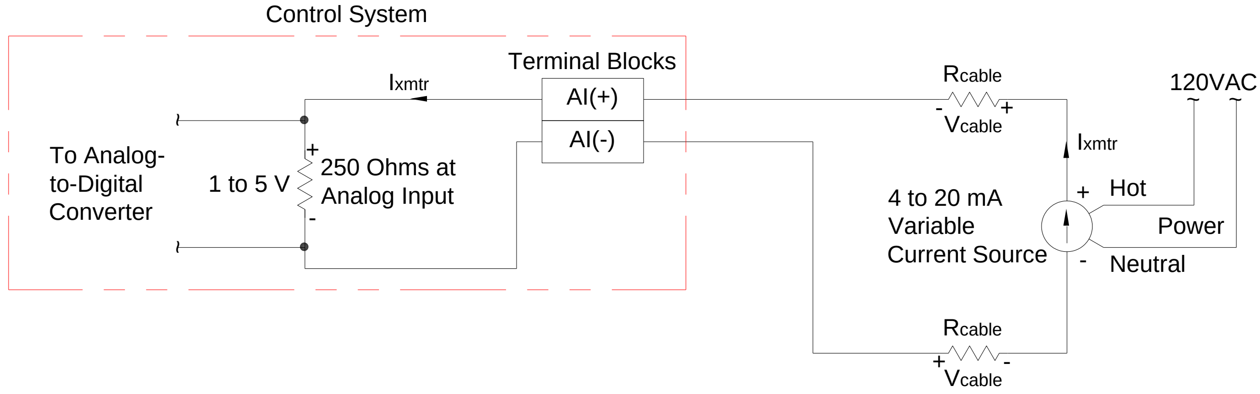
Three-wire transmitters require a third wire to provide enough operating current (in excess of 20 mA) for the transmitter to operate properly. This third wire typically provides the same voltage as the loop power supply, such as 24 VDC, and carries the total current required for the device operation and the loop current. See Figure 23.



3-Wire Analog Input
Loop Power Supply External to Control System
Figure 23

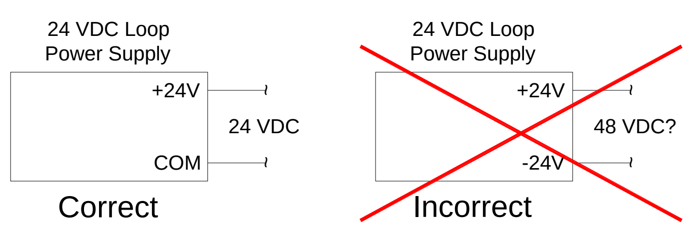
4-Wire Transmitters:

Four-wire transmitters typically require 120 VAC or 230 VAC, which powers the transmitter's internal circuitry and internal loop power supply. It is called 4-wire because it has two wires for the loop and two wires for power (ignoring the ground conductor for the AC power). See Figure 24.



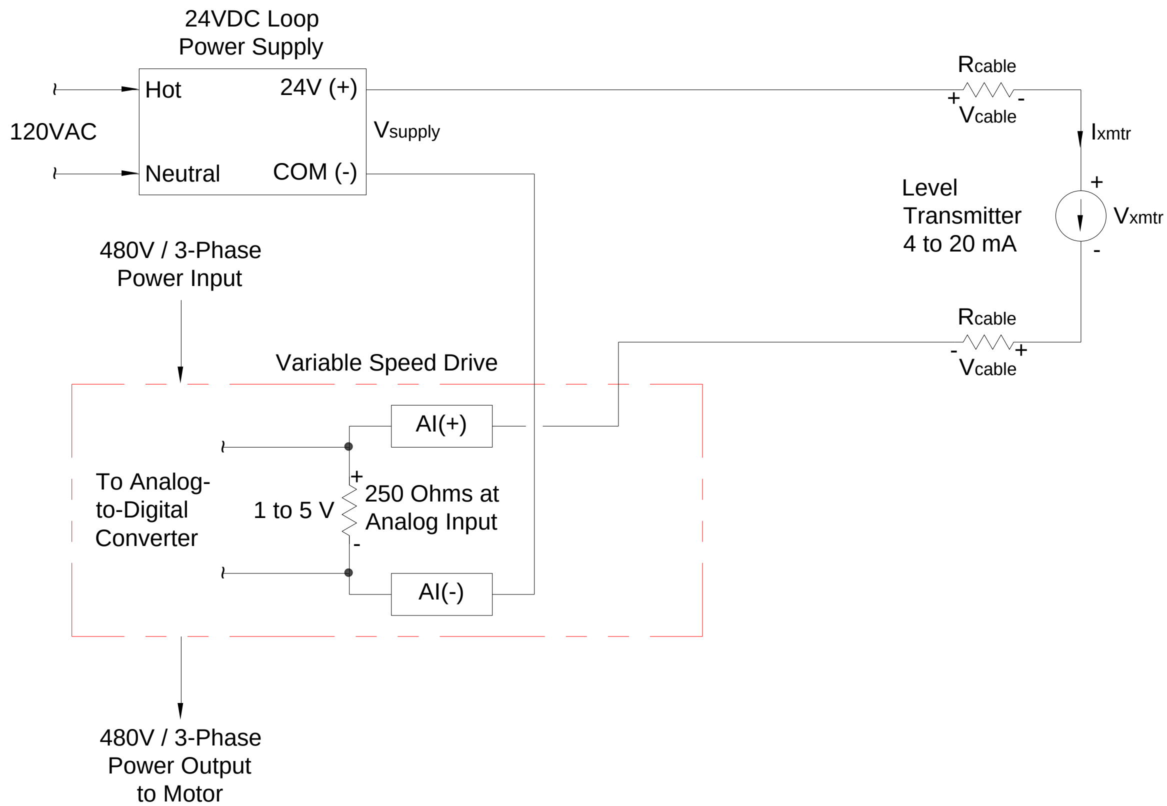
4-Wire Analog Input
Loop Power Supply Inside Transmitter
Figure 24

Loop Power Supply Terminal Designations:
Oftentimes, the positive terminal of a 24 VDC power supply is represented as "+24VDC" or some similar designation. Occasionally, the common or return terminal of a 24 VDC power supply is incorrectly represented as as "-24VDC". The latter designation is incorrect because it implies that there is a 48 VDC difference between the +24VDC and -24VDC terminals.



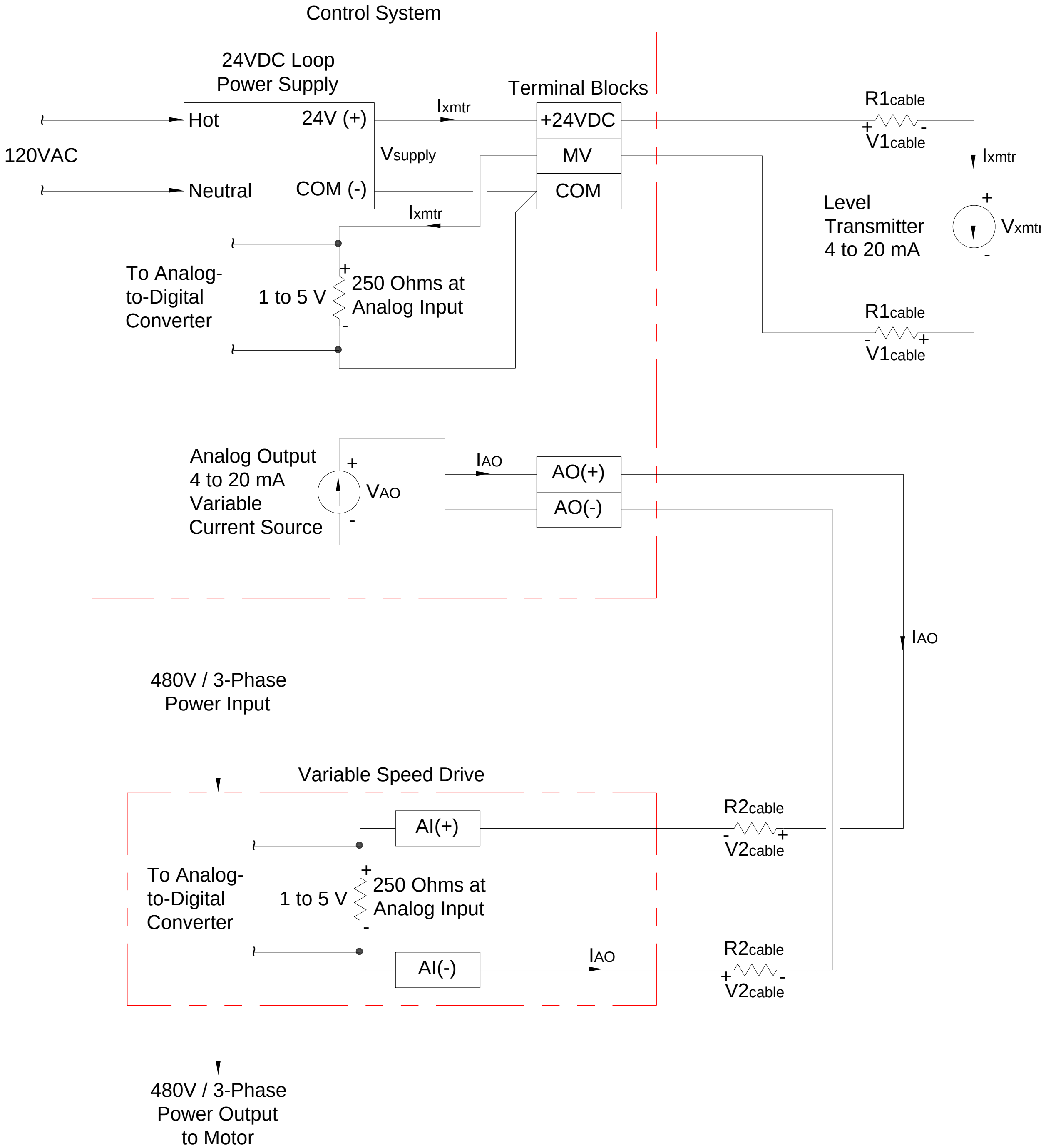
Other Considerations:

On rare occasions, a transmitter might be wired directly to a final control element, such as a variable speed drive (see Figure 25). Most modern variable speed drives have enough computing power to apply a control algorithm (such as PID) to the incoming 4 to 20 mA signal and control the connected motor properly, without the intervention of an external control system.



2-Wire Analog Input to Loop Controller in VFD
Loop Power Supply External to VFD
Figure 25

Most of the time, however, a transmitter is wired to a PLC, DCS, or other controller and the controller calculates and outputs the 4 to 20 mA loop to the final control element (see Figure 26). In the case illustrated in Figure 25, there is an analog loop that is measurement only, and the control loop is within the variable speed drive. In the case illustrated in Figure 26, there is a measurement portion of the loop and a control portion of the loop.



2-Wire Analog Input
Loop Power Supply Internal to Control System
Analog Ouput to VFD
Figure 26

Wiring

Most often, the instrumentation wiring between the controller and the instruments is run separately from the 480 VAC power wiring and 120 VAC power and control wiring. This is because the 480 and 120 VAC electrical fields can induce voltage on the instrumentation wiring and this higher-voltage noise can 'swamp' or obscure the low-voltage signal in the instrumentation wiring.

The separation between power and instrumentation wiring can be accomplished in several different ways, including:

- Physical distance separation, such as a minimum of 12" between the two types of wiring; and

- Ferromagnetic (such as iron or steel) enclosure of one of the wiring types, such as putting the instrumentation wiring in steel conduit or steel wireway.

If the two wiring types have to pass through the same location, such as within a control panel, it is generally better to have them cross each other perpendicularly, in order to minimize the amount of induction. When cables run parallel to each other, it maximizes the amount of noise that can be induced from one cable to the other.

Cable Types:

In addition to the physical separation methods discussed above, the construction techniques of the instrumentation cables can also afford some immunity to electrical noise. The type of cable that is typically used for 2-wire 4 to 20 mA signals is a shielded twisted pair (STP) cable (see Figure 27). For 3-wire 4 to 20 mA transmitters, shielded triad is the usual choice. For 4-wire 4 to 20 mA transmitters, shielded twisted pair is typically used for the 4 to 20 mA signal and 3/C #12 multi-conductor cable is typically used for the 120 VAC power, using the precautions mentioned above to avoid voltage induction.

Color Codes:

There are different opinions as to which color codes should be applied to the positive and negative leads of an analog loop. Two of the most popular color code options for twisted shielded pair cables are a) Black & White and b) Red & Black. In the case of Black & White conductors, Black is usually Positive and White is usually Negative [see Figure 27(b)], since the negative terminal of a DC power supply can be considered to be similar in function to the neutral terminal in AC power systems (the neutral conductor is color-coded with white or gray). In the case of Red & Black conductors, Red is sometimes argued as being the best choice for Positive [See Figure 27(a)] because it matches the color code in most American automobiles, but others might suggest that Black is the best choice for positive if there are also Black & White conductor cables used at the same jobsite. In other words, if there are both Black & White and Red & Black conductor cables used at the jobsite [see Figures 27(b) and (c)], then it could be said that using Black for positive in both cases would eliminate some confusion. Again, there is a variety of opinions on this topic.

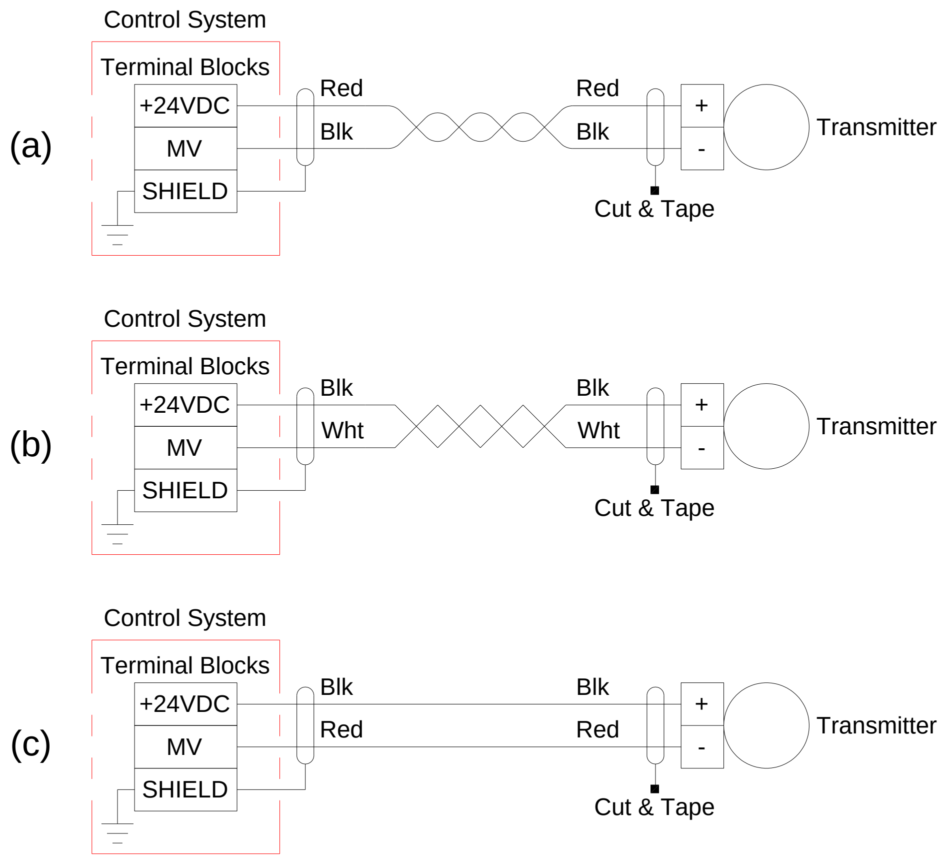
Grounding of Shields:

Industrial installations have numerous sources of electrical noise, such as motors, generators, hand-held radios, cellular phones, lighting ballasts, computers, and electrical power cables. If preventative steps are not taken, this electrical noise can find its way into the low-voltage DC signal cables that are carrying the 4 to 20 mA current. The cables that are used for 4 to 20 mA signals are usually shielded twisted pair cables. The shield tends to prevent electrical noise from getting to the enclosed pair of conductors, due to the Faraday cage effect of the shield. If electrical noise still makes it to the twisted pair, it appears as common-mode electrical noise, which will be rejected inherently by the differential measurement technique at the analog input.

In order to drain off any induced electrical noise voltage that is captured on the shield, it is required to ground one end of the shield. Technically, it does not matter whether the shield is grounded at the transmitter (field) end or the controller (PLC or DCS) end, but the shield grounding connections are usually already present at the controller end, in the form of terminal blocks (see Figure 27). This is one reason that the shields of shielded cables are usually grounded at the controller end. This philosophy is sometimes reversed in some types of intrinsically safe installations, which occasionally call for the shields to be grounded at the instrument end.

It is not desirable to ground both ends of the shield because it is possible that the two different ground points are at different potentials. There could be a voltage difference of a few volts or more between a grounding point at the transmitter in the field and a grounding point hundreds of feet away at the PLC control panel or DCS marshalling cabinet near the control room. This voltage difference between the two ends of the shield will cause a current to flow in the shield. This current will be a source of electrical noise that might affect the signal carried on the conductors within the shield.

On loop sheets and other instrumentation wiring drawings, it is common to use a symbol at the transmitter end of the shielded twisted cable that says “Cut & Tape” (see Figure 27), which means that the shield at this end is to be cut back and the leftover stub is to be taped with electrical tape to ensure that the shield does not become grounded by coming into contact with the enclosure’s back panel or the terminal block mounting rail or does not become energized by coming into contact with an energized terminal block or exposed portion of wire. In practice, the shield is sometimes merely bent back along the cable and taped in place, being covered completely by the tape.



Various Representations of
Shielded Twisted Pair Cable
Figure 27

It is common to have 4 to 20 mADC and 120 VAC wiring within the same cabinet or enclosure, but still physically separated from each other as much as possible. However, it is not the best practice to use the 120 VAC grounding bus as the grounding point for the shields of shielded 4 to 20 mA cables. The 4 to 20 mA cable shields are typically grounded to a DC ground bus, which has its own terminals. The 120VAC equipment grounding conductors are typically terminated to an AC ground bus, which has its own terminals. The DC and the AC ground buses are both at the same electrical potential, typically through connections to the metallic enclosure, so they are not electrically isolated from each other, but keeping the two types of grounding connections physically separated from each other will diminish the opportunity of 120 VAC noise infecting the 4 to 20 mADC loops.

Fusing:

Fusing philosophy for 4 to 20 mA loops can vary from site to site, but it is common to fuse the positive lead going from the control system to the 2-wire transmitter, as shown in Figure 22, and the power lead to a 3-wire transmitter, as shown in Figure 23. It is also common to fuse the positive lead of an analog output loop, as shown in Figure 5. Some models of DCS and PLC analog input and output cards also have internal fuses.

Cable Resistance and Total Loop Resistance:

It is generally suggested that 24 AWG be the smallest gauge wire selected for 4 to 20 mA loops. Many installations improve on this by using larger gauge wires, such as 20, 18, or 16 AWG for single-pair, multiple-pair, single-triad, and multiple-triad cables.

The larger the number of the wire gauge, the smaller the diameter of the wire, and the larger the resistance of the wire, due to the smaller the cross-sectional area of the wire. See Table 1, which lists some typical resistance values for the most common wire gauges for shielded twisted pair cables:

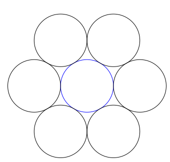
Table 1

Wire Gauge	Approximate Ohms / 1,000 feet	Typical Area per Wire (cir. mil.)	Qty. and Gauge of Strands per Wire	Typical Area per Strand (cir. mil.)
16 AWG	3.7	2,580	7 X 24 AWG	404
18 AWG	5.8	1,620	7 X 26 AWG	253
20 AWG	9.5	1,024	7 X 28 AWG	159
22 AWG	15.0	640	7 X 30 AWG	100
24 AWG	23.7	404	7 X 32 AWG	64

Always check the resistance values for the cable that is actually installed, rather than refer to a typical example like Table 1.

Stranded Conductors and Cross-Sectional Area:

Most conductors used in industrial facilities are stranded, rather than solid, due to the fact that stranded conductors are more flexible, less difficult to pull through conduits, and easier to bend into place inside of enclosures. Each stranded conductor is composed of several smaller solid conductors. In the case of the wire gauges discussed in this document, the number of strands per conductor is usually seven. This is because seven conductors naturally form the stable shape of one conductor surrounded by six conductors, as shown here:

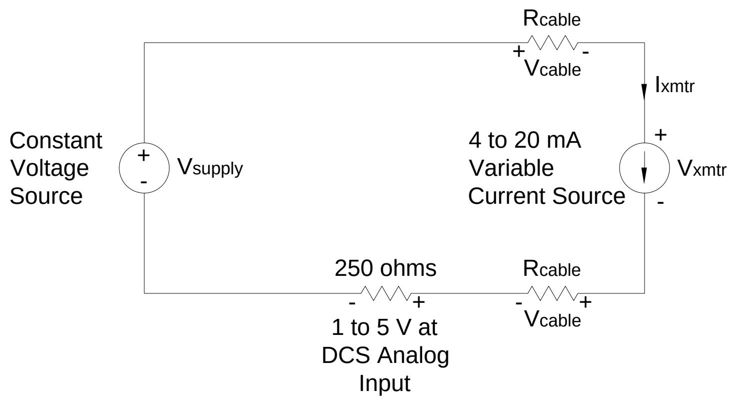


You can lay seven identical coins on a flat surface to confirm the seven-strand arrangement shown above. Notice in Table 1 that each of the stranded conductors is composed of seven smaller conductors that are eight gauges smaller than the gauge of the stranded conductor. For example, a stranded 16 AWG conductor is composed of seven 24 AWG solid conductors, while a stranded 24 AWG conductor is composed of seven 32 AWG conductors.

As mentioned previously, the cable resistance is one part of the total loop resistance. In a typical 2-wire loop, such as shown in Figure 28, the resistance of the cable is factored in to the voltage drop two times, once on the way out to the transmitter and once on the way back. That's why the voltage drop formula for DC and single-phase AC circuits (ignoring inductance and capacitance) is:

$V_{drop} = 2 * R * I$

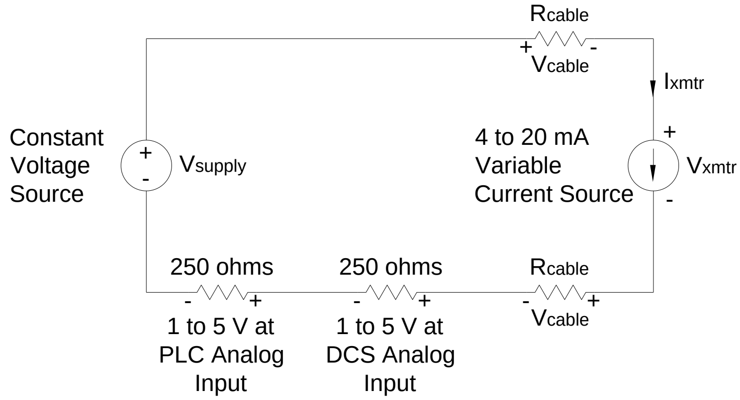
In addition to the cable resistance, there will most likely be at least one analog input resistance, which is typically 250 ohms, as shown in Figure 28.



Analog Input Loop
with One Analog Input
Figure 28

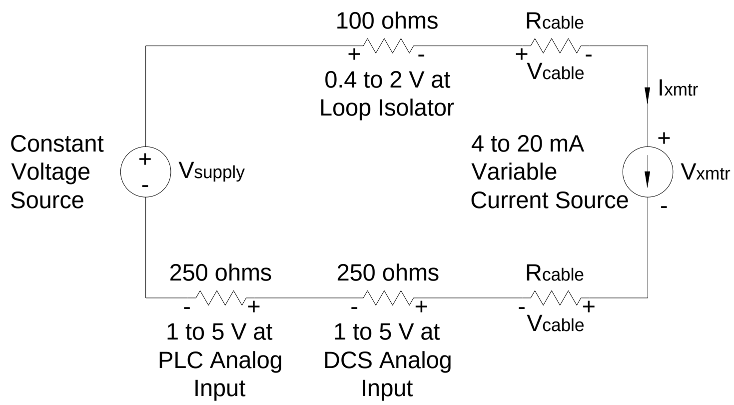
Figure 28 shows an analog input at the DCS, but there are occasions when it is also desired to have the same signal at a PLC, as shown in Figure 29.

What is a circular mil?
*A circular mil is a unit of cross-sectional area that is equal to the area of a circle that is one mil (0.001 inches) in diameter. A circular mil is therefore equal to PI * (0.001)^2 / 4 = 7.85 x 10^{-7} sq. in. The advantage of using circular mils is that the cross-sectional area of a solid conductor is the diameter of that conductor squared. For example, a solid conductor with a diameter of 0.0808 inches (80.8 mils) has a circular mil area of (80.8)^2 or 6,529 circular mils.*



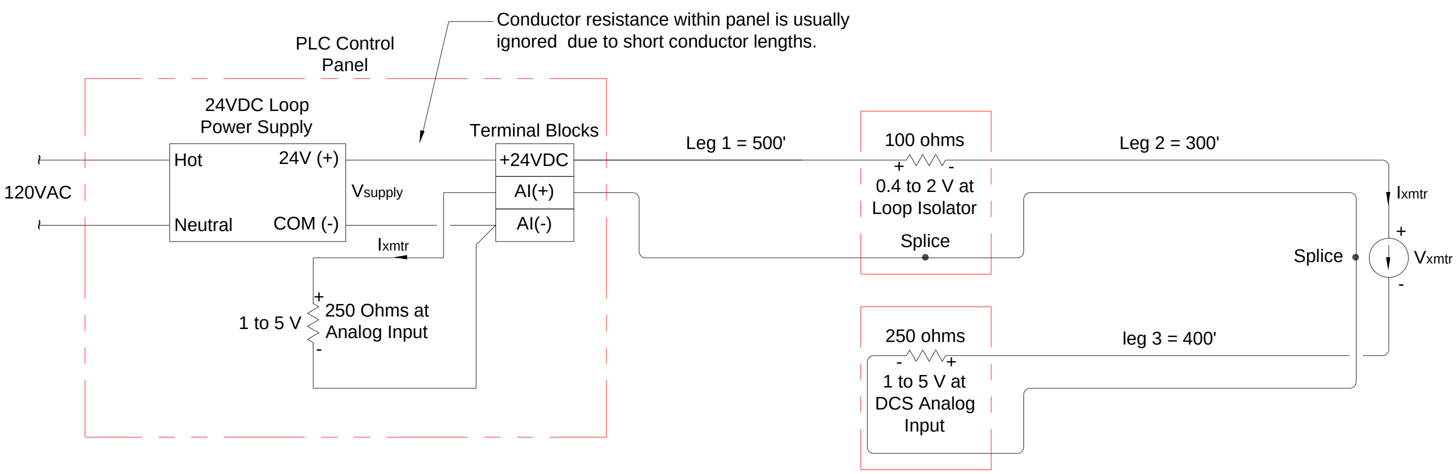
Analog Input Loop
with Two Analog Inputs
Figure 29

Most analog inputs are 250-ohm resistances, but some types of analog input devices have other resistances. For example, some signal conditioners or loop isolators have 100-ohm (or smaller) resistors on their inputs in order to lessen the total resistance on the loop, as compared to having a 250-ohm input resistance. See Figure 30.



Analog Input Loop
with Three Analog Inputs
Figure 30

The shielded twisted pair cable run shown in Figure 30 would actually snake through the factory, plant, or mill with many changes of direction as shown in Figure 31, but the total one-way length is used to calculate the one-way cable resistance.



Total One-Way Length = 1,200'
Figure 31

EXAMPLE 11

Looking at Figure 31, assume the shielded twisted pair cable is 18 AWG and has a total one-way (either going out or coming back) length of 1,200 feet. What would be the total resistance in the loop?

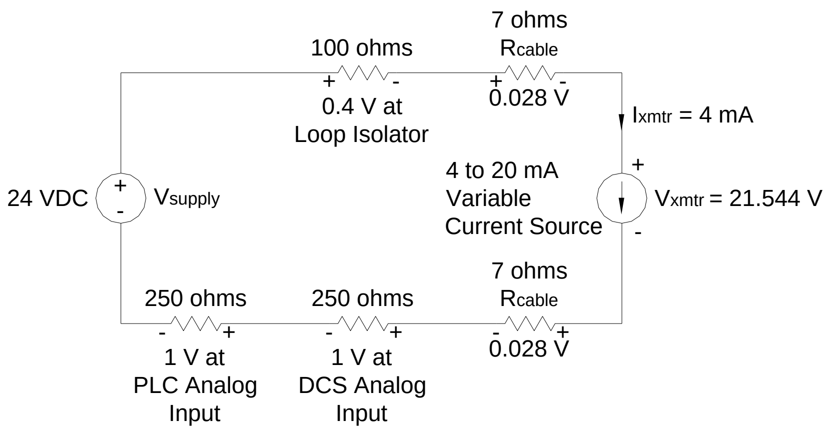
From Table 1, the resistance of 18 AWG shielded twisted pair cable is approximately 5.8 ohms per 1,000 feet. Since we have 1,200 feet one-way, the cable will have a total one-way resistance of 6.96 ohms. This one-way resistance appears twice, once on the way out and once on the way back, so the total cable round-trip resistance is 2 * 6.96 = 13.92 ohms. We'll simplify the rest of this example by saying that the total cable resistance is 2 * 7 = 14 ohms.

The total loop resistance from Figure 31 (also illustrated in Figure 32) is:

100 + 7 + 7 +250 + 250 = 614 ohms END OF EXAMPLE

EXAMPLE 12

Continuing the last example, let's assume a loop power supply (V_{supply}) of 24 VDC and calculate the voltage available at the transmitter (V_{xmtr}) when the loop current (I_{xmtr}) is at 4 mA and 20 mA. See Figure 32 for the 4 mA case:



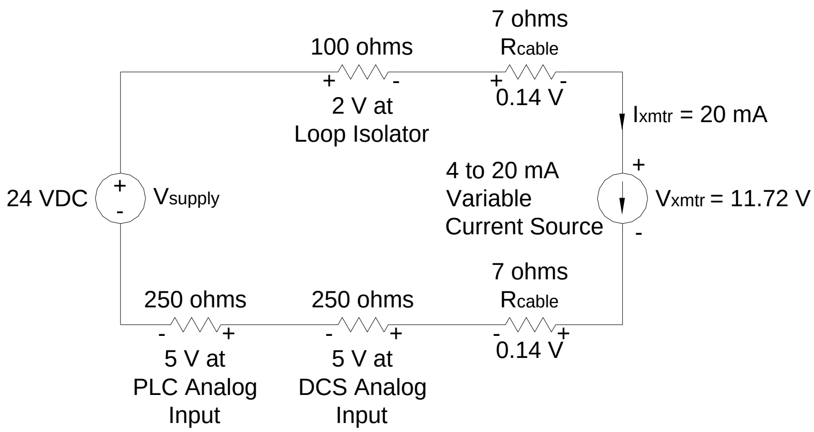
Analog Input Loop at 4 mA
with Three Analog Inputs
Figure 32

The voltage drops around the loop in Figure 32 must add up to equal the 24 V power supply (see Appendix for further explanation). The voltage drops are:

$24 = 0.4 + 0.028 + V_{xmtr} + 0.028 + 1 + 1$

$V_{xmtr} = 21.544$ at 4 mA

When the loop current is 4 mA, the voltage drop across the transmitter (V_{xmtr}) will be 21.544 V, as shown in Figure 32. See Figure 33 for the 20 mA case:



Analog Input Loop at 20 mA
with Three Analog Inputs
Figure 33

The voltage drops around the loop in Figure 33 must add up to equal the 24 V power supply. The voltage drops are:

$24 = 2 + 0.14 + V_{xmtr} + 0.14 + 5 + 5$

$V_{xmtr} = 11.72$ at 20 mA

So, when the loop current is 20 mA, the voltage drop across the transmitter (V_{xmtr}) will be 11.72 V, as shown in Figure 33. This would be sufficient voltage for some transmitters to operate properly, but other transmitters might require at least 12 V to operate properly.

END OF EXAMPLE

EXAMPLE 13

Let's continue the two examples above by considering a transmitter with the following operating parameters:

1. Minimum transmitter voltage [V_{xmtr}(min.)] of 12 V
2. Maximum transmitter voltage [V_{xmtr}(max.)] of 31 V
3. Minimum loop current [I_{xmtr}(min.)] of 4 mA
4. Maximum loop current [I_{xmtr}(max.)] of 20 mA

When we plot the load limit graph for this transmitter and add a horizontal line for the total loop resistance and a vertical line for the 24 VDC power supply, the result is the graph shown in Figure 34. Notice that the intersection of the 614-ohm and 24 V line (the operating point) is slightly outside of the operating region, indicating that there is not enough voltage for the transmitter specification of V_{xmtr}(min.) = 12 V (see similar graph in Figure 18). This result agrees with Example 12, in which the available voltage at the transmitter (V_{xmtr}) was found to be only 11.72 V, as illustrated in Figure 33.

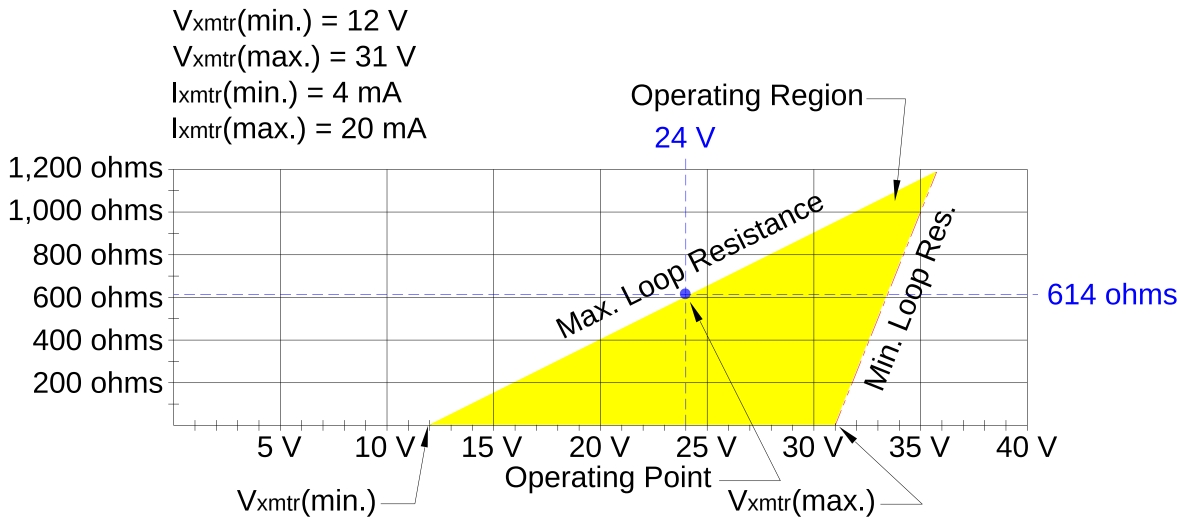


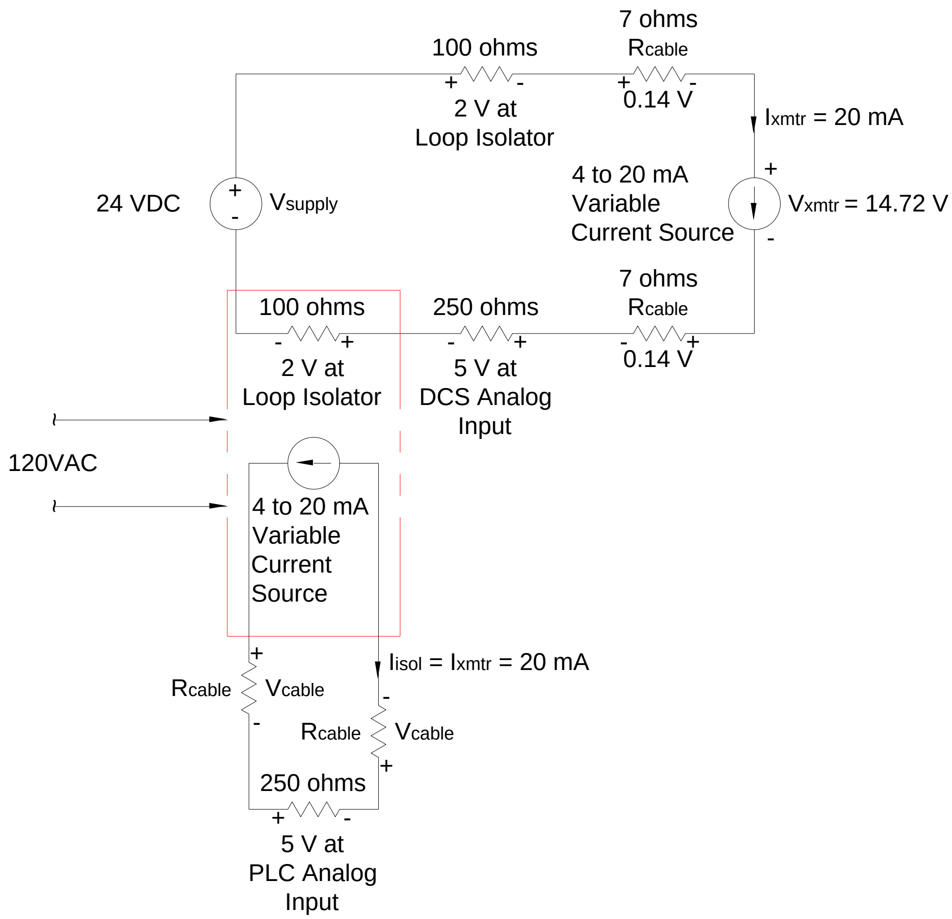
Figure 34

One solution to get the total loop resistance to move down into the operating region for a 24 V power supply is to replace the 250-ohm PLC AI with a 100-ohm loop isolator, as shown in Figure 35. Notice in Figure 35 that the voltage available at the transmitter is now 14.72V at 20 mA. This is because the voltage drops are:

$24 = 2 + 0.14 + V_{xmtr} + 0.14 + 5 + 2$

$V_{xmtr} = 14.72$ at 20 mA, which is illustrated in Figure 35.

Notice also that the current output from the loop isolator (I_{isol}) is equal to the current output from the transmitter (I_{xmtr}). The loop isolator is powered from a different source (120 VAC, in this example) and its internal circuitry acts as a repeater to duplicate the current going through its sense resistor (100 ohms, in this example). This separately-powered loop isolator replicates the 4 to 20 mA signal and sends it to the PLC analog input, but only puts a 100-ohm load on the transmitter's 4 to 20 mA loop.



Analog Input Loop at 20 mA
with Three Analog Inputs
Figure 35

Now, the total loop loop resistance is

100 + 7 + 7 +100 + 250 = 464 ohms.

If we plot the 464-ohm horizontal line on the graph from Figure 34 and see where it intersects the vertical 24 VDC power supply line, we will have a graph as shown in Figure 36.

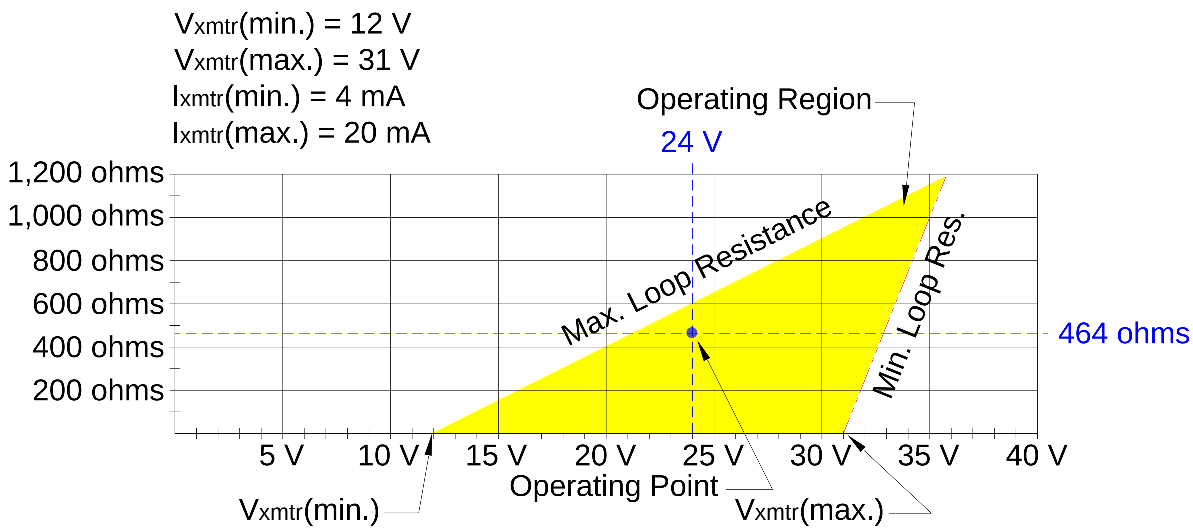


Figure 36

Clearly, reducing the total loop resistance has enabled us to be in the operating region of the transmitter at a loop power supply value of V_{supply} = 24 V. We could have moved the operating point to the right to be within the operating region by increasing the loop power supply voltage (V_{supply}) to 25 V or higher, but that might have required a lot of additional work, such as confirming existing fuse sizes, re-calculating minimum loop resistances for existing loops, and confirming V_{xmtr}(max.) ratings for existing instruments.

END OF EXAMPLE

EXAMPLE 14

Another interesting thing we can do with the graph in Figure 36 is to copy the maximum loop resistance line (since it represents a loop current of 20 mA) over to the intersection of the 464-ohm horizontal line and the 24 VDC power supply vertical line (which is the operating point) to find out how much voltage will be available at the transmitter at a loop current of 20 mA [I_{xmtr}(max.)]. This is done in Figure 37.

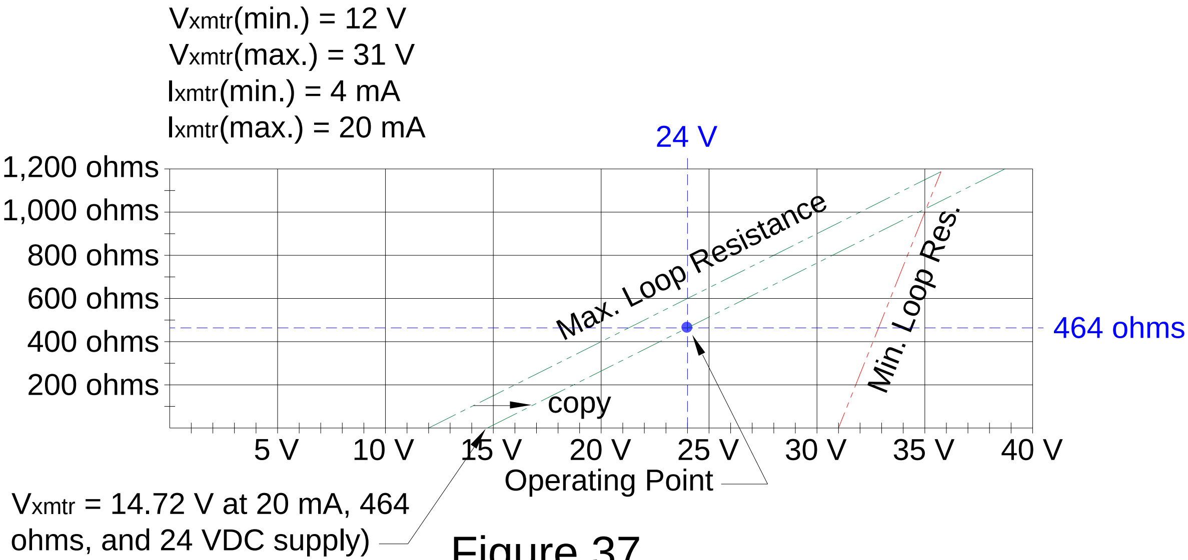


Figure 37

The maximum resistance line that we copied over to the intersection of the 464-ohm line and the 24 V line (the operating point) gives us a transmitter voltage of 14.72 V on the horizontal axis of the graph, which matches the transmitter voltage shown on Figure 35. This is another method that can be used to determine the voltage (V_{xmtr}) available at the transmitter at maximum current [I_{xmtr}(max.)], as defined by the maximum loop resistance line. END OF EXAMPLE

EXAMPLE 15

Would that same technique work for 4 mA [I_{xmtr}(min.)]? What if we slid the minimum loop resistance line (since it represents a loop current of 4 mA) over to the same intersection? Would it tell us the voltage available at the transmitter at a loop current of 4 mA? Let's try it in Figure 38.

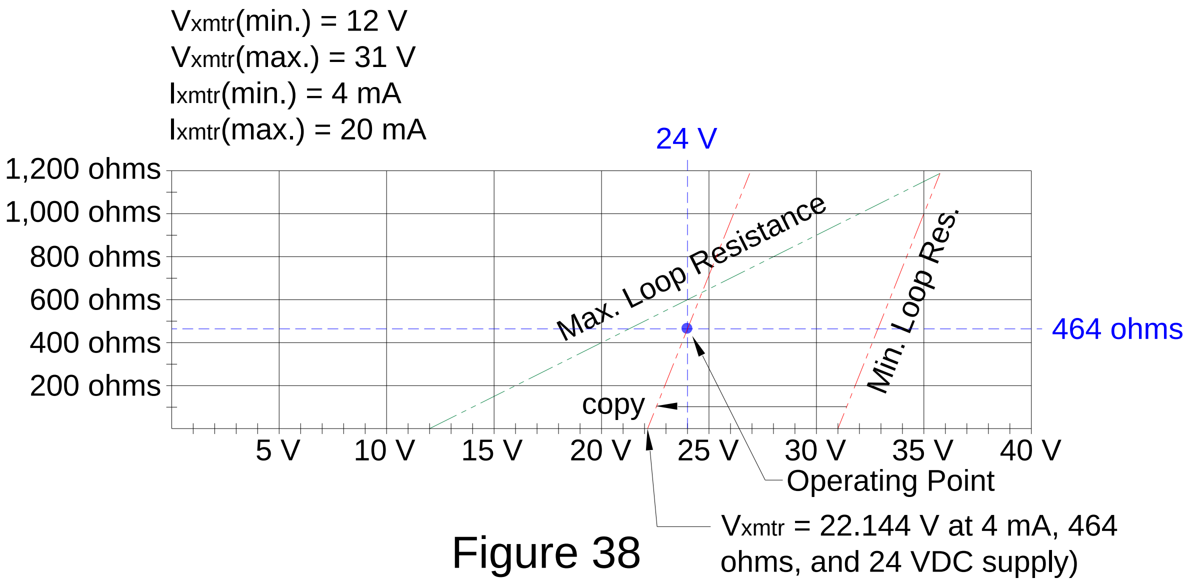
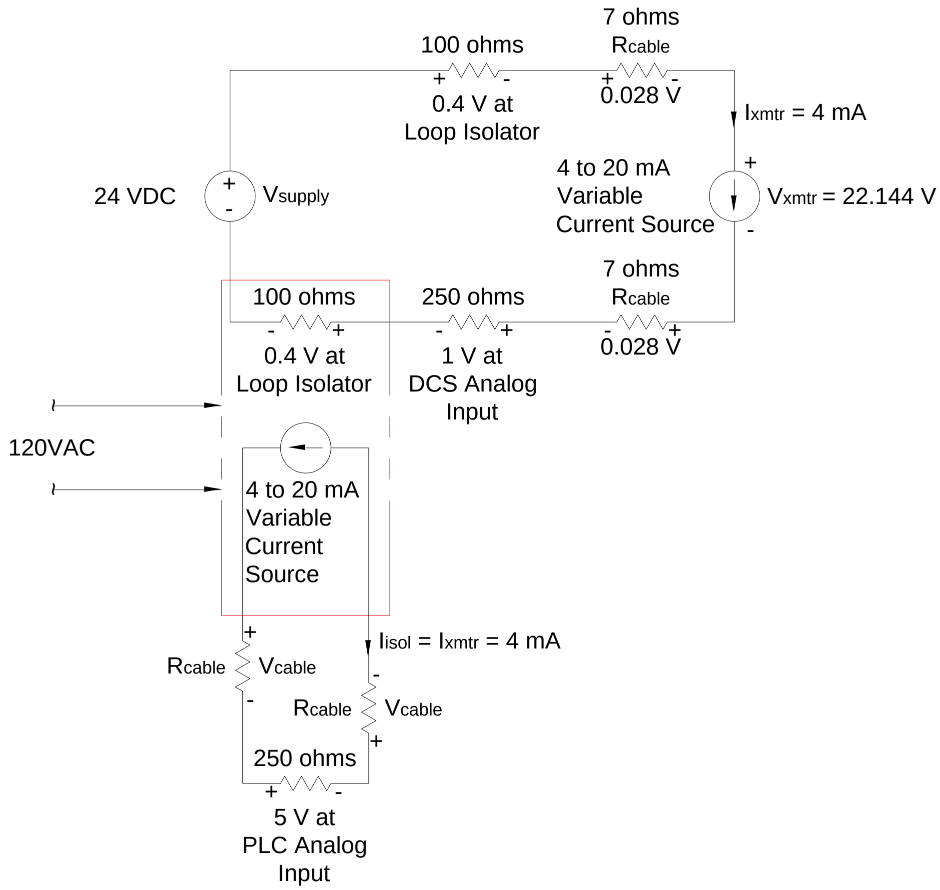


Figure 38

According to Figure 38, when the current is 4 mA, the voltage at the transmitter should be 22.144 V. Let's check that using Figure 39. The voltage drops are:

$24 = 0.4 + 0.028 + V_{xmtr} + 0.028 + 1 + 0.4$

$V_{xmtr} = 22.144$ V at 4 mA



Analog Input Loop at 4mA
with Three Analog Inputs
Figure 39

Clearly, this method of plotting the current through the operating point also works for 4 mA. Would it work for any current value from 4 to 20 mA? Let's try 12 mA.

END OF EXAMPLE

EXAMPLE 16

The slope of a line representing 12 mA would be 1 / 12 mA or 83.3 ohms / V. If we plot a line with that slope through the same operating point, we get Figure 40.

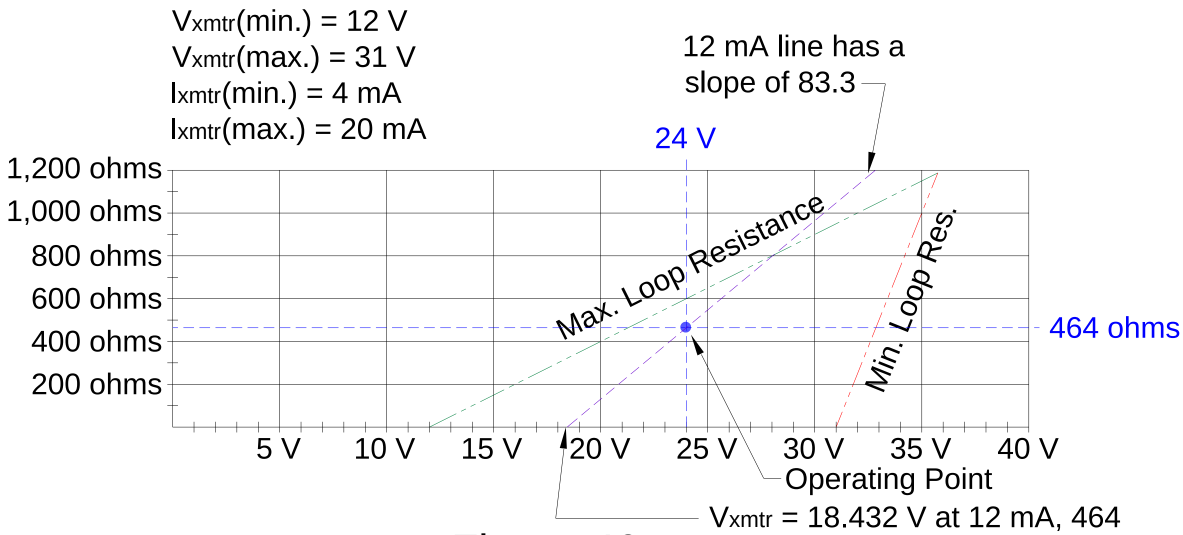
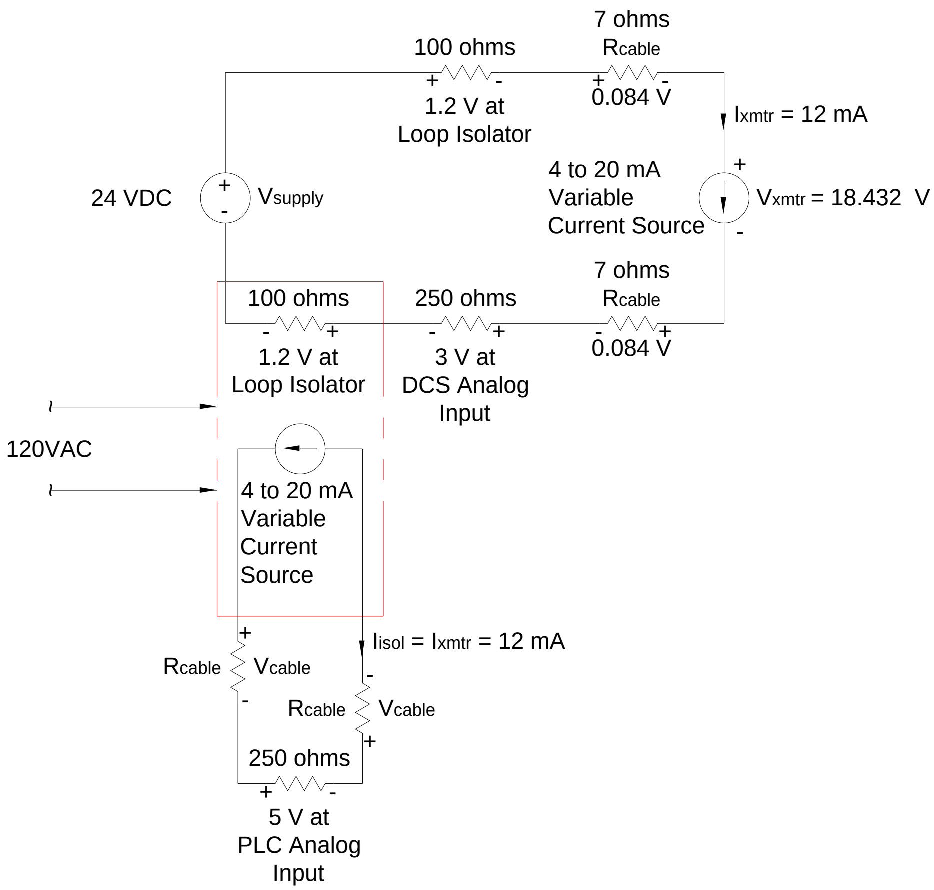


Figure 40

According to Figure 40, when the current is 12 mA, the voltage at the transmitter should be 18.432 V. Let's check that using Figure 41. The voltage drops are:

$24 = 1.2 + 0.084 + V_{xmtr} + 0.084 + 3 + 1.2$

$V_{xmtr} = 18.432$ V at 12 mA



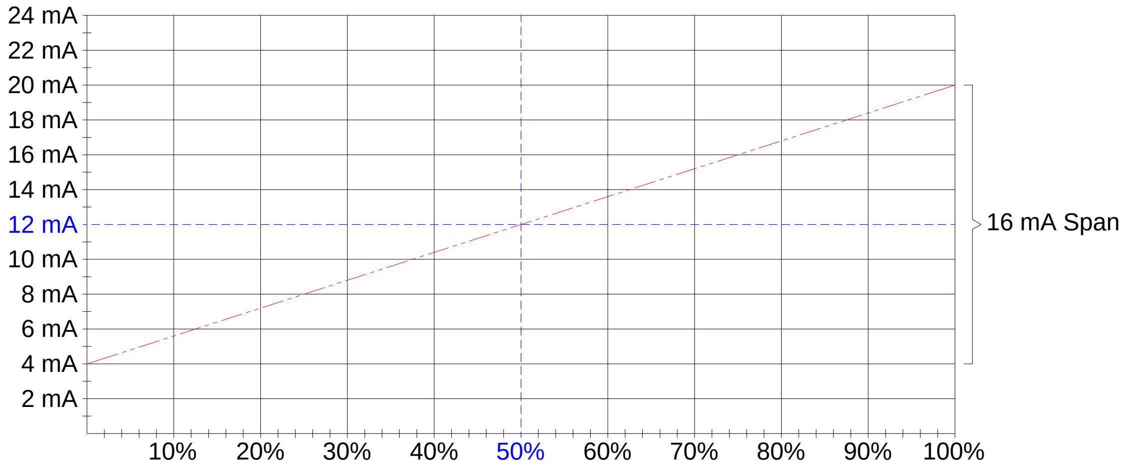
Analog Input Loop at 12 mA
with Three Analog Inputs
Figure 41

END OF EXAMPLE

As we have seen in the three examples above, we can plot any valid value of current through the operating point and determine what the voltage at the transmitter would be by looking at the intersection of that line with the voltage axis.

4 to 20 mA = Measured Range:

At first glance, it might seem that 10 mA would be the mid-point or 50% value of the 4 to 20 mA signal, but such is not the case. The mid-point or 50% value of the 4 to 20 mA signal is 12 mA. This is because the span of the 4 to 20 mA signal is 20 – 4 = 16 mA. Half of 16 mA is 8 mA. Add this 8 mA to the bottom of the 4 to 20 mA range to get 4 + 8 = 12 mA as the mid-point of the range. See Figure 42.



4 to 20 mA = 0 to 100%
Figure 42

EXAMPLE 17
What is the ratio of % to mA? Divide one span by the other:

100% / 16 mA = 6.25% / mA

What is the ratio of mA to %? Divide one span by the other, or take the reciprocal of the number directly above:

16 mA / 100% = 0.16 mA / % END OF EXAMPLE

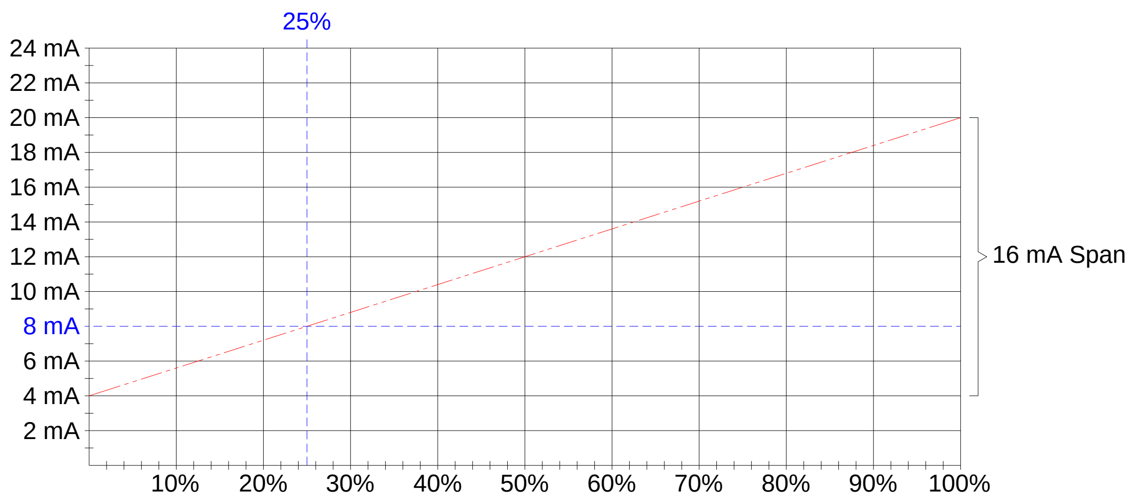
You can think of a 4 to 20 mA signal as being a 16 mA span with a 4 mA offset or bias.

EXAMPLE 18
What would be the mA reading for 25% of the 4 to 20 mA signal?

25% * 0.16 mA / % = 4 mA, but we have to add this 4 mA to the bottom of the 4 to 20 mA range to get:

4 + 4 = 8 mA

This can be verified on Figure 43. END OF EXAMPLE



25% of 4 to 20 mA Range
Figure 43

EXAMPLE 19

What percentage of the 4 to 20 mA signal would be represented by a current reading of 13.5 mA?

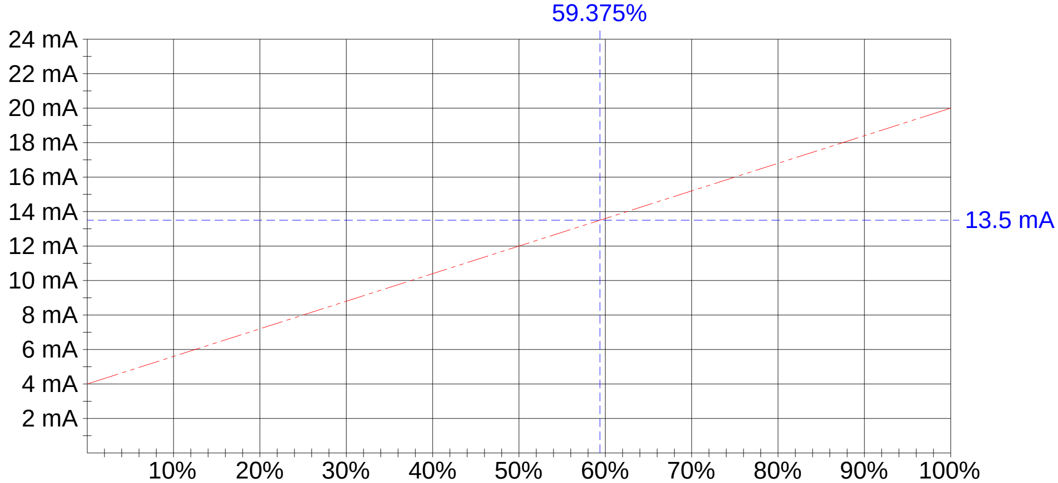
First, subtract 4 mA from the 13.5 mA reading to get

13.5 mA – 4 mA = 9.5 mA

Then divide the result by the span (16 mA) to find out which percentage of the range is represented by the current reading.

9.5 mA / 16 mA = 59.375 %.

This can be verified on Figure 44. END OF EXAMPLE



13.5mA = X%
Figure 44

EXAMPLE 20

Suppose we are monitoring how many widgets per hour are being produced at the widget factory. The selected transmitter will output a current reading of 4 mA to represent 0 widgets per hour (w/h) and a current reading of 20 mA to represent 500 widgets per hour. What would be the current reading that represents 200 widgets per hour?

Divide the spans to get mA per w/h:

16 mA / 500 w/h = 0.032 mA / w/h

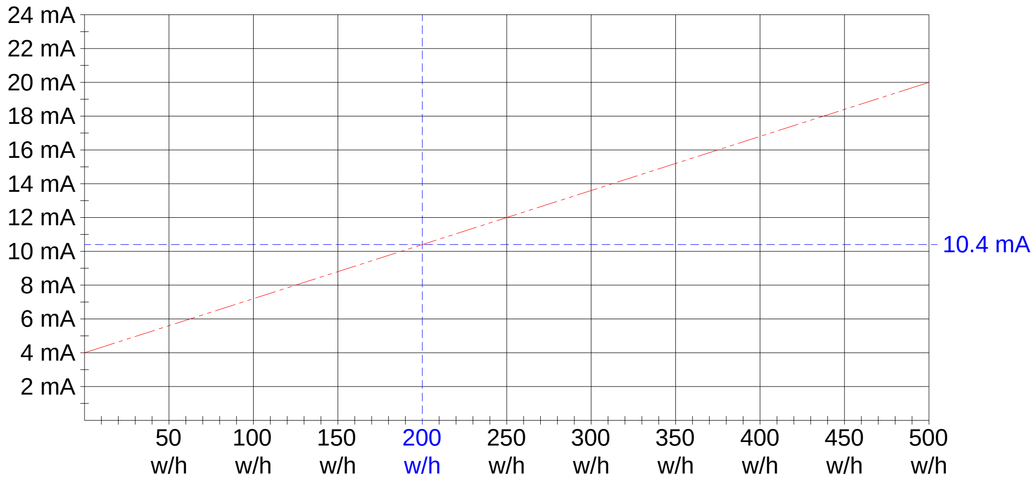
For 200 w/h, multiply

200 w/h * 0.032 ma / w/h = 6.4 mA

Add this mA value to the bottom of the 4 to 20 mA range

6.4 mA + 4 mA = 10.4 mA.

This can be verified on Figure 45. END OF EXAMPLE



4 to 20 mA = 0 to 500 w/h
Figure 45

EXAMPLE 21

The lowest mA value (4 mA) doesn't always have to represent the lowest measured quantity and, therefore, the highest mA value (20 mA) doesn't always have to represent the highest measured quantity. The opposite could be true in some cases, such that 4 mA would represent the highest measured quantity and 20 mA would represent the lowest measured quantity (see Figure 46). In other words, 4 mA could represent 500 widgets per hour and 20 mA could represent 0 widgets per hour. For this case, what would be the current reading for 200 widgets per hour?

Divide the spans to get mA per w/h (which we did in the previous example):

16 mA / 500 w/h = 0.032 mA / w/h

For 200 w/h, multiply

200 w/h * 0.032 mA / w/h = 6.4 mA

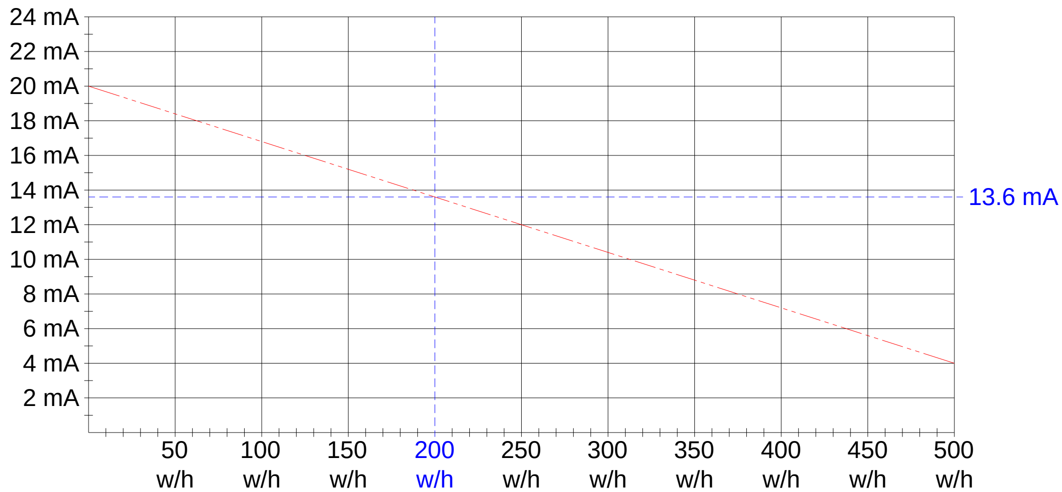
Subtract this from the top of the 4 to 20 mA range (since 20 mA = 0 w/h)

20 mA – 6.4 mA = 13.6 mA

Alternatively, we could have multiplied (500 w/h – 200 w/h) * 0.032 mA / w/h = 9.6 mA, and added this result to 4 mA to get 13.6 mA.

This can be verified by looking at Figure 46. Compare Figure 46 to Figure 45.

END OF EXAMPLE



4 to 20 mA = 500 to 0 w/h
Figure 46

EXAMPLE 22

What if there were no possible way that the widget factory could produce less than 50 widgets per hour? Therefore, let's say that 4 mA represents 50 widgets per hour and 20 mA represents 500 widgets per hour (this is a 450 w/h span with a 50 w/h offset or bias). Which current reading would represent 200 widgets per hour?

Divide the spans to get mA per w/h:

16 mA / 450 w/h = 0.0356 mA / w/h

We can't multiply by 200, since the bottom of the w/h range is 50, not zero, so we have to multiply by (200 – 50), which is 150:

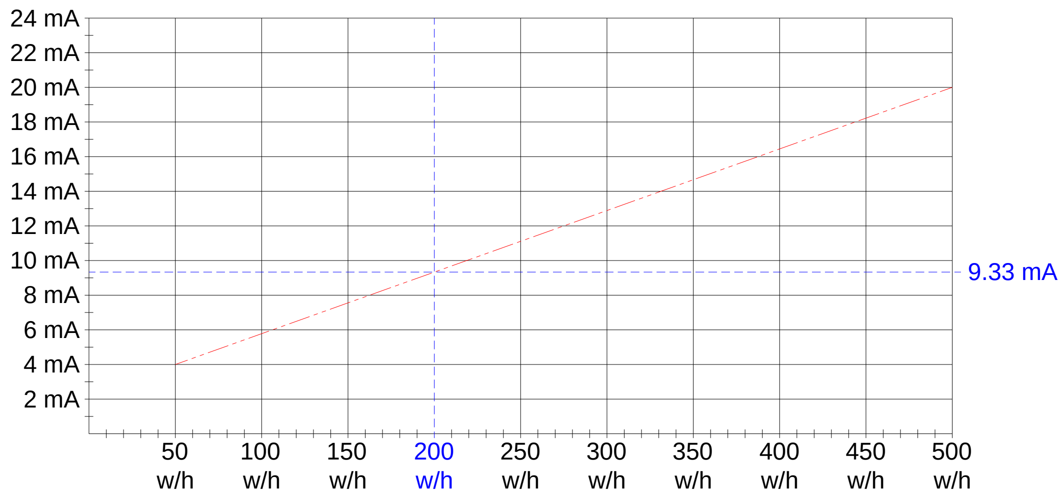
150 w/h * 0.0356 mA / w/h = 5.33 mA

Add that result to 4 mA to get

5.33 mA + 4 mA = 9.33 mA

This can be verified on Figure 47. Compare Figure 47 to Figure 45.

END OF EXAMPLE



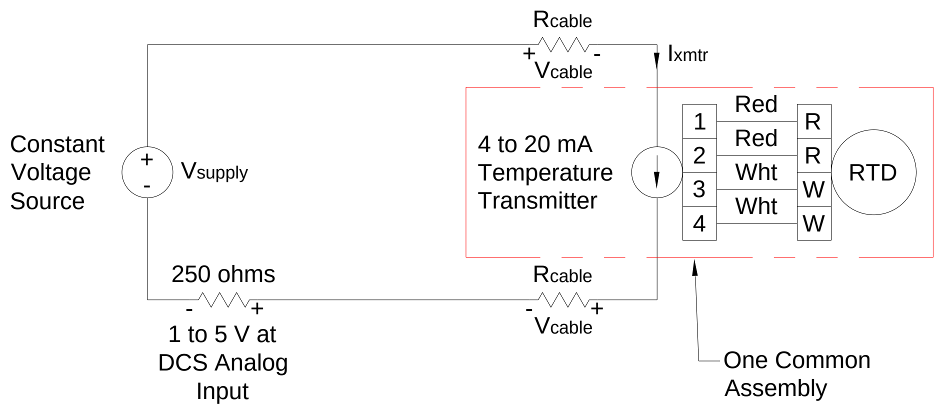
4 to 20 mA = 50 to 500 w/h
Figure 47

Examples of 4 to 20 mA Loops:

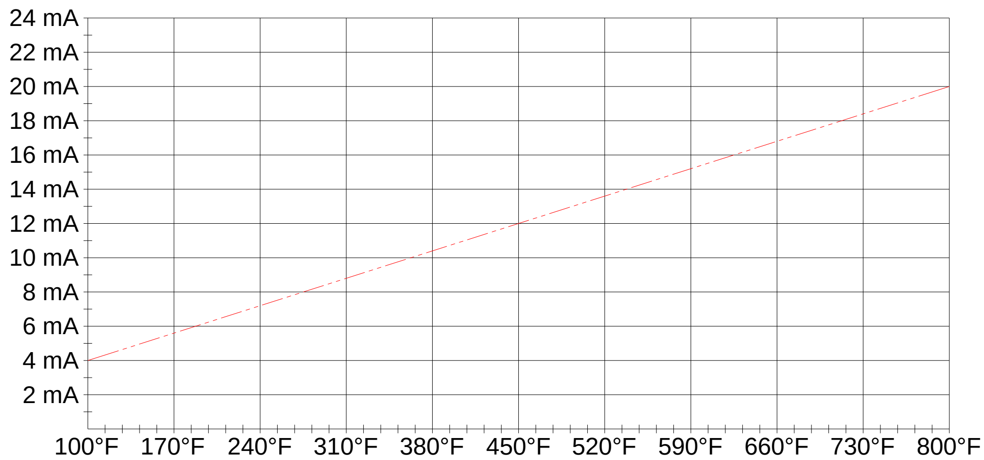
To merely say that we have a 12 mA signal without knowing what that means in the physical world is like having the answer without knowing the question. For each of the measurement loop types in this section, we will discuss how the measurements are made, and what they mean in the real world, in order to gain a better understanding of what the 4 to 20 mA signal actually represents. In the illustrations in this section, isolation valves, drain valves, impulse tubing, manifolds, thermowells, and other required accessories are not shown in order to keep the illustrations simple.

Temperature Transmitter:

In most industrial installations, temperature is usually measured using thermocouples or RTDs. These types of temperature measurement devices can be wired directly to some models of controllers and recorders, but they are often wired to a 4 to 20 mA transmitter instead. Converting the thermocouple or RTD signals to 4 to 20 mA makes the resulting signal more robust and able to be transmitted a longer distance. Very often, the 4 to 20 mA transmitter is mounted inside the connection head of the thermocouple or RTD assembly (see Figure 48). The 4 to 20 mA transmitter also has built-in linearization for whichever type of thermocouple or RTD it is wired to and provides a linear 4 to 20 mA output (see Figure 49). Please note that the 4 to 20 mA transmitter shown in Figure 48 would actually be mounted in a remote connection head, away from the heat of the process, if it were being used for the temperature range shown in Figure 49.



Analog Input Loop
RTD Temperature Element with Integral Transmitter
Figure 48



Temperature Loop
4 to 20 mA = 100 to 800 °F
Figure 49

EXAMPLE 23
Which temperature would be represented on Figure 49 by current readings of 10.5 mA and 18.5 mA?

Divide the spans to get °F per mA (this is a 700 °F span with a 100 °F offset or bias):

700 °F / 16 mA = 43.75 °F / mA

We expressed the ratio in terms of °F / mA to make it easy to multiply by the mA readings, such as:

(10.5 mA – 4 mA) * 43.75 °F / mA =

6.5 mA * 43.75 °F / mA = 284.375 °F

Add that result to 100 °F to get

284.375 °F + 100 °F = 384.375 °F @ 10.5 mA

Now, let's work out 18.5 mA:

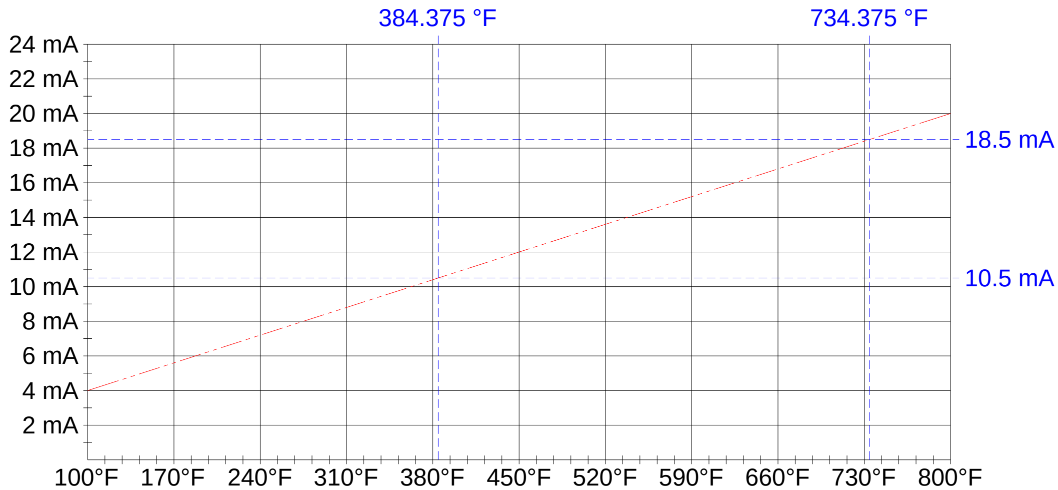
(18.5 mA – 4 mA)* 43.75 °F / mA =

14.5 mA * 43.75 °F / mA = 634.375 °F

Add that result to 100 °F to get

634.375 °F + 100 °F = 734.375 °F @ 18.5 mA

Both results are verified in Figure 50. END OF EXAMPLE

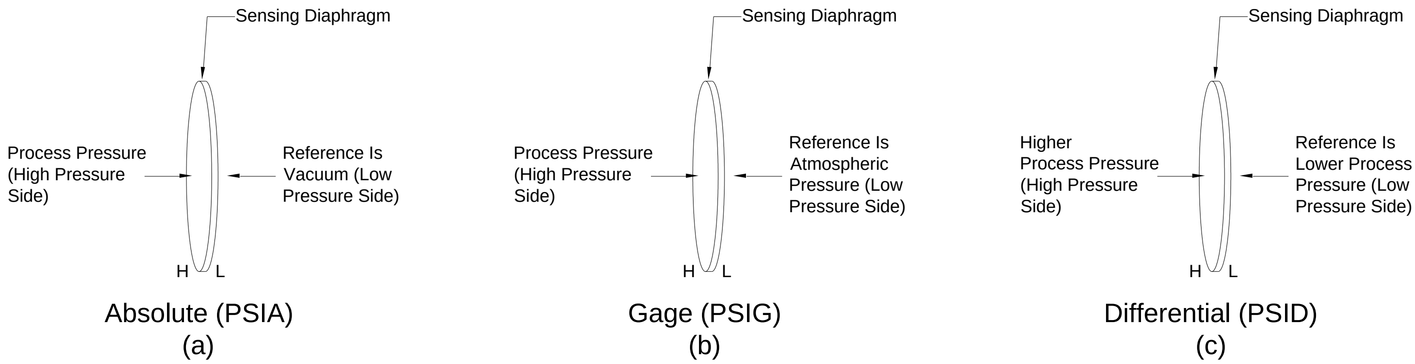


Temperature Loop
4 to 20 mA = 100 to 800 °F
Figure 50

Pressure Transmitter:

There are three types of pressure measurement: Absolute (PSIA), Gage (PSIG), and Differential (PSI or PSID) [it can be argued that Vacuum (PSIV) and Sealed (PSIS) measurements fall into one of these three types]. All pressure measurements are actually differential in nature, but the two types of pressure measurements that have a more-specific meaning are Absolute (PSIA) and Gage (PSIG).

An **absolute** pressure measurement has **one** external pressure connection and compares the process pressure to a near-perfect vacuum [see Figure 51(a)]. This means that one side (the low pressure side) of the pressure diaphragm is a factory-sealed, evacuated chamber that is as close to a perfect vacuum as is commercially feasible. The other side (the high pressure side) of the pressure diaphragm is connected by the installer to the process to be measured.



Pressure Measurement Types
Figure 51

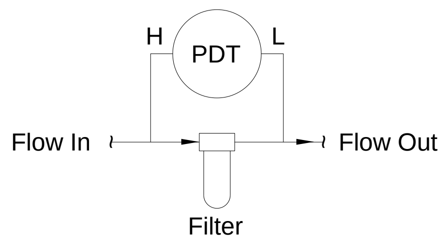
At sea level, atmospheric pressure is taken to be 14.7 PSIA (1 atmosphere), which means it is 14.7 pounds per square inch higher in pressure than an absolute (unchanging) vacuum. An absolute pressure measurement is the only one of these three types in which the reference pressure can not change, since it is a constant vacuum. In contrast, the reference pressure is allowed to change for gage and differential pressure measurements.

A **gage** pressure measurement has **one** external pressure connection and compares the process pressure to the local ambient atmospheric pressure at that moment in time [see Figure 51(b)]. The low pressure side of the pressure sensing diaphragm is exposed to the open air at the transmitter location (this is an opening made in the unit at the factory, it is not a physical, external connection). The other side (the high pressure side) is connected by the installer to the process to be measured.

In a gage pressure measurement, if the local atmospheric pressure changes (a very common event), then the point of reference for the pressure measurement changes. That is not a problem, since vessels and piping are rated for gage pressure, such as 200 PSIG, not for absolute pressure.

ISA Nomenclature for Pressure Transmitters:
Absolute and Gage Pressure Transmitters, which have one pressure connection, are labeled as PTs when using the ISA standards (or PITs when they have local indication). Differential Pressure Transmitters, which have two pressure connections, are labeled as PDTs (Or PDITs when they have local indication) to distinguish them from Absolute and Gage pressure transmitters.

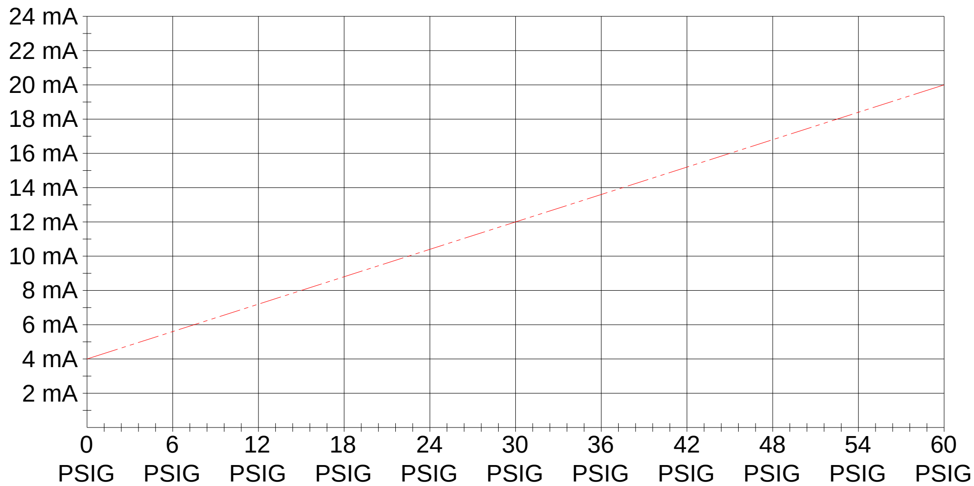
As stated previously, all pressure measurements are differential. When a pressure measurement is referred to as being differential, however, it means that it is neither an absolute nor a gage pressure measurement. A **differential** pressure measurement has **two** external pressure connections and compares the two pressures to each other [see Figure 51(c)]. A typical differential pressure measurement application is to monitor the pressure drop across a filter, as shown in Figure 52. In this application, when the differential pressure gets too high, it is time to replace the filter.



Differential Pressure Monitoring
Figure 52

The pressure measurement value for all three types (Absolute, Gage, and Differential) is determined by subtracting the low pressure from the high pressure. This is illustrated in Figure 51 by virtue of the low process pressure pushing on one side of the pressure sensing diaphragm while the high process pressure pushes on the opposite side of the sensing diaphragm. It is, therefore, the difference between the high and low pressures that determines the deflection of the sensing diaphragm and the resulting pressure reading.

A differential pressure transmitter can easily be used as a gage pressure transmitter by exposing the low pressure side (or high pressure side for certain applications) to the local atmosphere. It is not practical to use a differential pressure transmitter as an absolute pressure transmitter because it is difficult to create and maintain a constant and near-perfect vacuum to be used as the reference pressure.



Pressure Loop
4 to 20 mA = 0 to 60 PSIG
Figure 53

EXAMPLE 24

What would be the mA current reading of a 36 PSIG pressure in Figure 53?

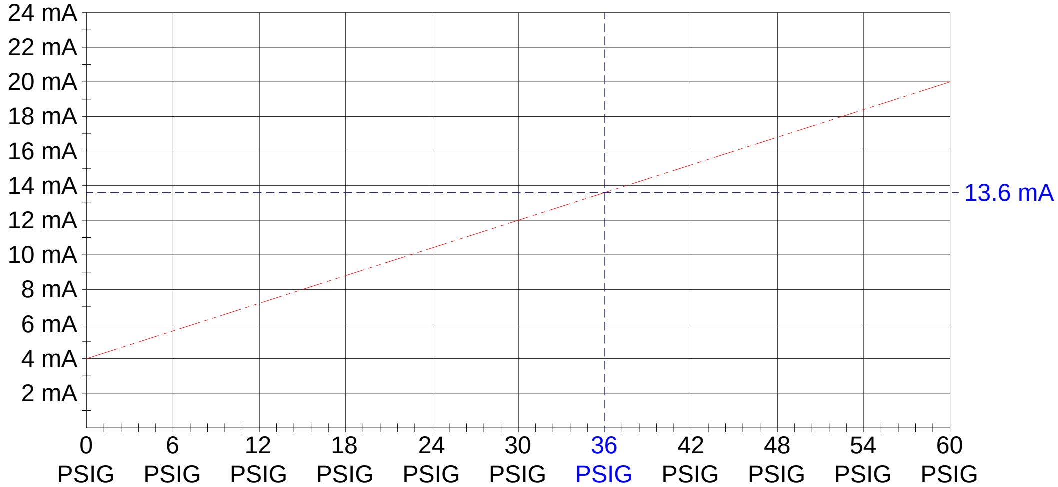
Dividing the spans:

16 mA / 60 PSIG = 0.2667 ma / PSIG

0.2667 mA / PSIG * 36 PSIG = 9.6 mA

9.6 mA + 4 mA = 13.6 mA

Confirm this with Figure 54. END OF EXAMPLE



Pressure Loop
4 to 20 mA = 0 to 60 PSIG
Figure 54

EXAMPLE 25

What change in pressure would be represented by a 2 mA change in Figure 53?

Dividing the spans:

60 PSIG / 16 mA = 3.75 PSIG / mA

3.75 PSIG / mA * 2 mA = 7.5 PSIG

So, if the mA signal increases by 2 mA, it represents a change of +7.5 PSIG in the measured pressure. Likewise, if the mA signal decreases by 2 mA, it represents a decrease of 7.5 PSIG in the measured pressure. END OF EXAMPLE

Level Using Gage Pressure Transmitter:

There are many ways to measure level, including gage pressure, differential pressure, ultrasonic, radar, time domain reflectometry, nuclear, and a host of other technologies. Let's build on the previous discussion of pressure transmitters by considering liquid level measurement techniques that employ pressure transmitters to infer level.

The gage pressure at any point within an open vessel or tank of liquid (see Figure 55) is dependent on two things:

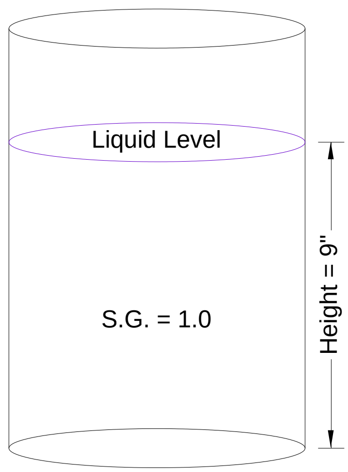
- The height of the liquid level above that point, and
- The specific gravity of the liquid.

This is summarized in the formula for pressure at a certain level and specific gravity:

P = S.G. * H (H represents the height of the liquid above the measurement point)

S.G. at a Certain Temperature and Pressure:
The specific gravity of water is usually defined as 1.0 at 4°C (39°F) and 1 atmosphere (0 PSIG) since the density of water is highest at this temperature, but corrections to the specific gravity value are often not made for different temperatures and pressures. In other words, the specific gravity is usually assumed to be constant at reasonable temperatures and pressures.

The pressure at a certain point within an open container of liquid can be expressed in a wide variety of units, such as PSIG, millimeters of mercury, pascals, or inches of water column, to name a few. Let's start with inches of water column, since it is one of the easier units to understand. Figure 55 illustrates an open container of liquid that has the same specific gravity as water (S.G. = 1.0 at a certain temperature and pressure – see sidebar). Since the height of the liquid is 9", the pressure at the bottom of the container will be 9" of water column (usually abbreviated 9" w.c.). If the measuring point were 1" above the bottom of the container, the pressure at that point would be 8" w.c.



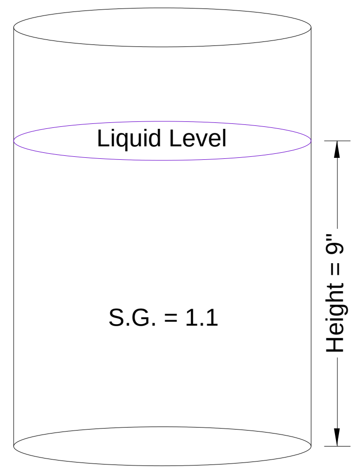
The Pressure of Liquid
Open Vessel
Figure 55

EXAMPLE 26

Consider the open container of liquid illustrated in Figure 56. It is the same as that shown in Figure 55, but the specific gravity has increased to 1.1. For a liquid height of 9", the pressure at the bottom of the container will be:

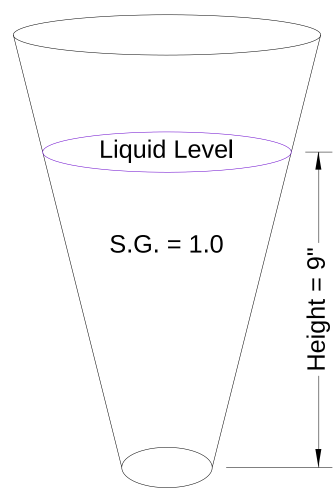
1.1 * 9" w.c. = 9.9" w.c.

END OF EXAMPLE



The Pressure of Liquid
Open Vessel
Figure 56

The shape of the vessel has no effect on the pressure of a liquid at any point within the liquid. As previously discussed for Figure 55, the pressure at the bottom of the open container shown in Figure 57 will be 1.0 * 9" w.c. = 9" w.c. If the measuring point were at 3" above the bottom of the container, the pressure at that point would be 6" w.c.



The Pressure of Liquid
Open Vessel
Figure 57

If the specific gravity of the liquid changes, the pressure transmitter won't be aware of it. The 4 to 20 mA signal will still be an accurate measure of pressure but it will no longer be an accurate representation of level. For example, if a tank contains a liquid at a height of 9.2' but the specific gravity has changed from 1.0 to 1.1, then the 4 to 20 mA signal would report that the height is 9.2' * 1.1 = 10.12', rather than the actual 9.2'.

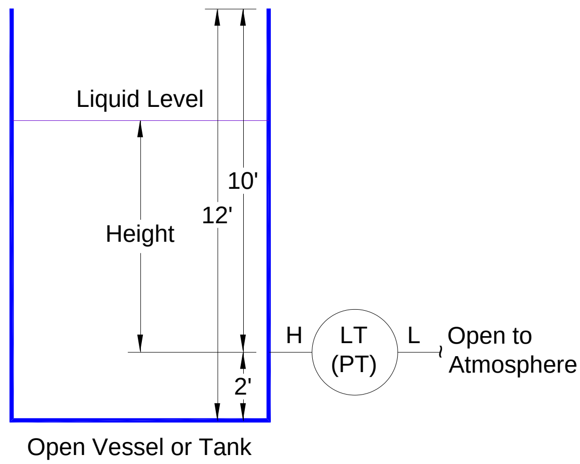
In the United States, in addition to inches of water column, another common unit of pressure is pounds per square inch, or PSI. In order for the pressure reading to be meaningful, we must know what the reference pressure is. Is the reference pressure a vacuum (PSIA) or atmospheric pressure (PSIG)? Our current discussion is about an open tank or vessel and the measurement of gage pressure (PSIG) to infer level. A column of water (S.G. = 1.0) that is 27.7" in height will have a pressure of 1 PSIG at the bottom of that column of water. If the water column is 55.4" in height, it will have a pressure of 2 PSIG at the bottom. Another common unit of pressure is 'feet of water column' or 'feet of head' (used in pump and piping calculations, 'head' is another term for pressure based on the height of water or other liquid). Since 27.7" / 12 = 2.3', a column of water (S.G. = 1.0) that is 6.9 feet in height will have a pressure of 3 PSIG at the bottom of that column.

EXAMPLE 27

Gage pressure is often used to infer the height of a liquid in an open vessel, based on an assumed specific gravity and also the assumption that the specific gravity is unchanging. If the 4 to 20 mA signal indicates a pressure of 5.5 PSIG, and the specific gravity is assumed to be 0.76, then the height of the liquid above the measuring point is:

(5.5 PSIG * 27.7" w.c. / PSIG) / 0.76 = 200.5" or 16.7' END OF EXAMPLE

Refer to Figure 58 and notice that the height of the water above the bottom of the tank is 2' more than the 0% reading of the pressure transmitter. To state this differently, since the measuring point is 2' above the bottom of the vessel, if the pressure transmitter in Figure 58 measures 3' of level, it actually means that there is 5' of liquid in the vessel, since our measuring point is 2' above the bottom of the vessel in this case. When there is no liquid at the pressure transmitter level, it has to be assumed that there is no more liquid in the tank, even though there may be 23" of liquid lurking beneath the measurement point. We don't know how much liquid is in the tank after it falls below the measuring point, so there is not a valid measurement below this point. The control scheme should control the liquid flow into the vessel to make sure that the level never goes down to the measuring point.

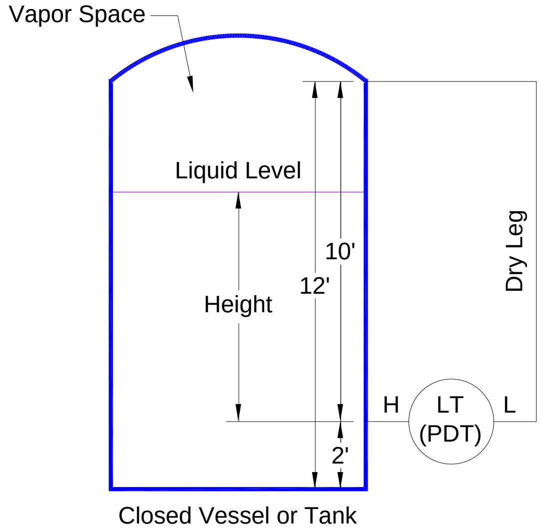


Level Transmitter
Open Vessel
Figure 58

Level Using Differential Pressure Transmitter:

Many tanks and vessels in industrial installations are closed or pressurized, as illustrated in Figure 59, rather than being open or atmospheric containers, as illustrated in Figure 58. The measurement of pressure in order to infer liquid level still works in basically the same way, except that a gage pressure transmitter can't be used for a closed vessel. Instead, a differential pressure transmitter is used, one connection point being within the liquid (as in an open vessel) and the other connection point being within the vapor space at the top of the vessel (see Figure 59, which illustrates a pressurized vessel with a dry reference leg). Since the closed vessel can be pressurized (at a different pressure than the surrounding atmosphere), the vapor space could be at a certain pressure, let's say 10 PSIG (10 pounds per square inch higher than the surrounding atmosphere) for discussion purposes. The 10 PSIG of pressure will push against the top and the walls of the vapor space, but it will also push against the liquid, adding that pressure value of 10 PSIG to the inherent pressure of the liquid level at the pressure measurement point. Since the 10 PSIG pressure is being applied to both the vapor space and the liquid, it is applied to both the high process pressure and low process pressure connection points of the differential pressure transmitter. This has the effect of canceling out the 10 PSIG of pressure such that it does not affect the level reading.

The fact that the vapor pressure in the vapor space of the closed vessel cancels out by being applied to both the high and low pressure connections of the differential pressure transmitter is analogous to the fact that the local atmospheric pressure at an open vessel is cancelled out by being applied to both the high connection (via the liquid) and low pressure factory opening of the gage pressure transmitter.

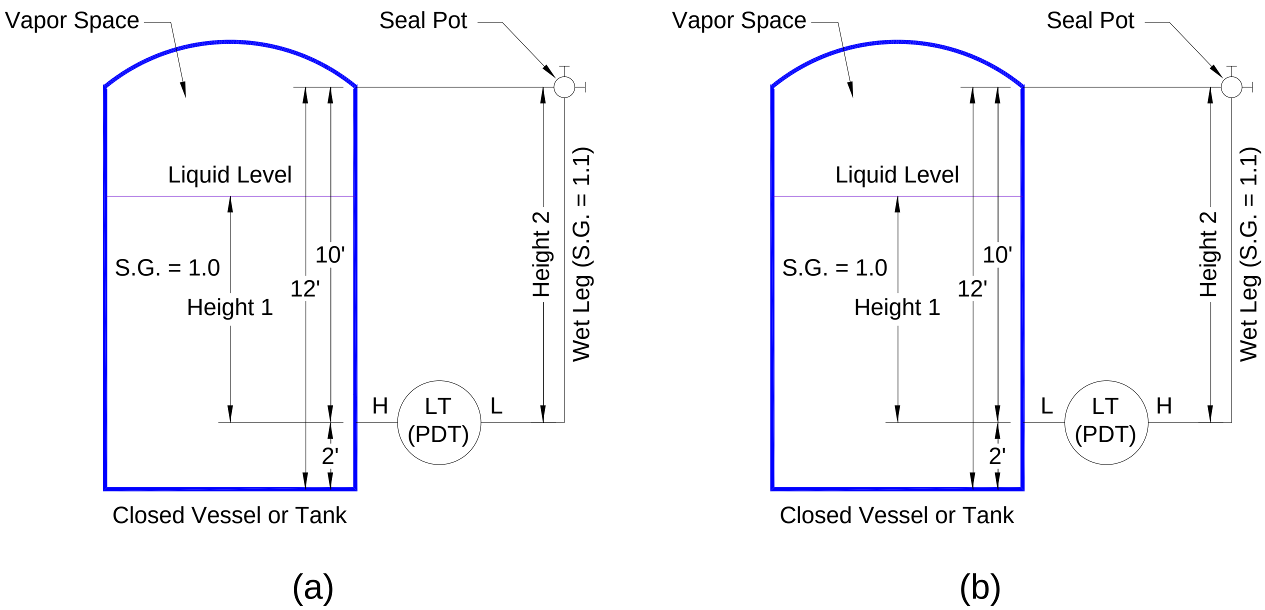


Level Transmitter
Closed Vessel - Dry Reference Leg
Figure 59

The dry reference leg shown in Figure 59 is used on vessels that contain liquids that won't evaporate and then condense in the reference leg. As the name implies, the dry reference leg will contain gas only (from the vapor space) at the same pressure as the vapor space.

As opposed to the dry reference leg, the wet reference leg illustrated in Figure 60(a) and (b) is used on closed vessels that have liquids that could evaporate and then condense in the reference leg (such as water in a steam drum), which would put a varying amount of pressure (based on the height and specific gravity of the condensate) on the vapor space connection at the differential pressure transmitter. If this height and specific gravity are not known, then the wet leg head pressure will result in an inaccurate reading of the level in the tank. For this reason, the wet reference leg is usually filled up to the top of the pipe (at the seal pot) and then the known and constant head pressure at the differential pressure transmitter is accounted for in the pressure reading. There are two techniques illustrated in Figure 60: Figure 60(a) has the liquid level connected to the high pressure connection of the differential pressure transmitter, and Figure 60(b) has the liquid level connected to the low pressure connection of the differential pressure transmitter. The pressure in the wet leg is therefore accommodated in two different ways, as described in the next two examples.

> *The pressure in the vapor space is assumed to be the same everywhere within the vapor space:*
> *While it is true that the pressure in a column of gas will be higher at the bottom than at the top (one example of which is atmospheric pressure at sea level versus the atmospheric pressure at the top of a tall mountain), the gas pressure in the relatively small vapor space of a closed vessel is assumed to be the same everywhere within the vapor space.*



Level Transmitter
Closed Vessel - Wet Reference Leg
Figure 60

EXAMPLE 28

In Figure 60(a), where the liquid level is connected to the high pressure connection, assume the wet leg Height 2 is 10’, the tank liquid level Height 1 is 6’ and the specific gravities are as shown. The pressure measurement at the differential pressure transmitter will be the high pressure (H) minus the low pressure (L), which will be:

[(6’) * (1.0)] – [(10’) * (1.1)] = 6’ – 11’ = -5’ at 13.6 mA

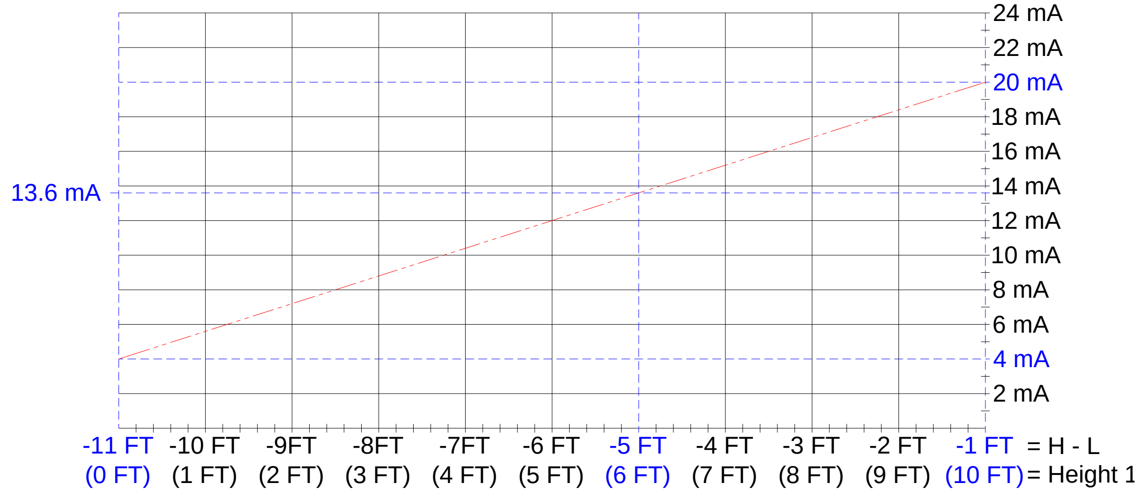
At the lowest measurable level, when Height 1 is 0’, the pressure measurement is:

[(0’) * (1.0)] – [(10’) * (1.1)] = 0’ – 11’ = -11’ at 4 mA

At the highest level, when Height 1 is 10’, the pressure measurement is:

[(10’) * (1.0)] – [(10’) * (1.1)] = 10’ – 11’ = -1’ at 20 mA

These three level readings are illustrated in Figure 61. The tank levels in parentheses represent Height 1 as it changes from 0 to 10 feet. Notice that the highest differential pressure, at -11’, is represented by 4 mA and the lowest differential pressure, at -1’, is represented by 20 mA, but it could have been the other way around, if desired. END OF EXAMPLE



Level Loop (Wet Leg)
4 to 20 mA = -11 to -1 ft (0 to 10 ft)
Figure 61

EXAMPLE 29

In Figure 60(b), where the liquid level is connected to the low pressure connection, assume the wet leg Height 2 is 10’, the tank liquid level Height 1 is 6’ and the specific gravities are as shown. The pressure measurement at the differential pressure transmitter will be the high pressure (H) minus the low pressure (L), which will be:

[(10’) * (1.1)] – [(6’) * (1.0)] = 11’ – 6’ = 5’ at 13.6 mA

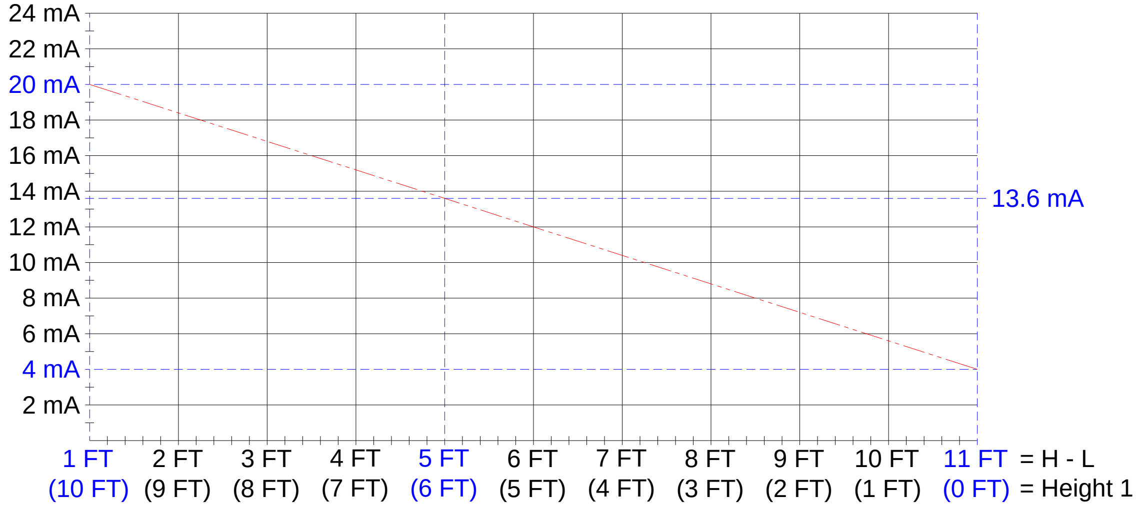
At the lowest measurable level, when Height 1 is 0’, the pressure measurement is:

[(10’) * (1.1)] – [(0’) * (1.0)] = 11’ – 0’ = 11’ at 4 mA

When Height 1 is 10’, the pressure measurement is:

[(10’) * (1.1)] – [(10’) * (1.0)] = 11’ – 10’ = 1’ at 20 mA

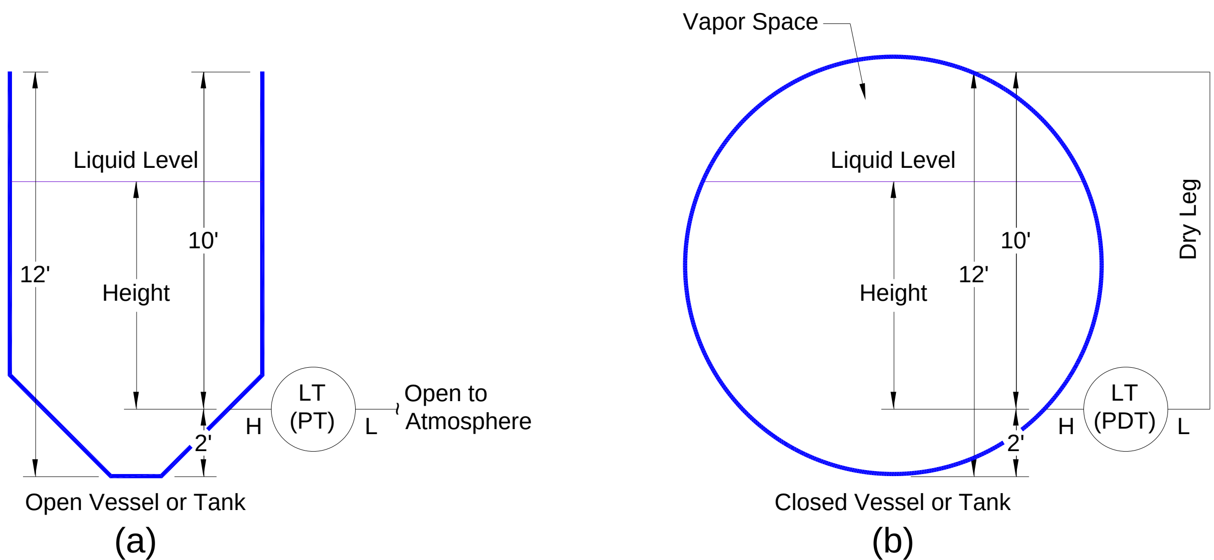
These three level readings are illustrated in Figure 62. The tank levels in parentheses represent Height 1 as it changes from 0 to 10 feet. Notice that the highest differential pressure, at 11’, is represented by 4 mA and the lowest differential pressure, at 1’, is represented by 20 mA, but it could have been the other way around, if desired. END OF EXAMPLE



Level Loop (Wet Leg)
4 to 20 mA = 11 to 1 ft (0 to 10 ft)
Figure 62

As mentioned previously, even when the differential pressure transmitter indicates that the level in the tank is at its lowest, there is still a level of 2' of liquid in the tank in the previous examples, due to the connection point of the differential pressure transmitter being 2' above the bottom of the tank.

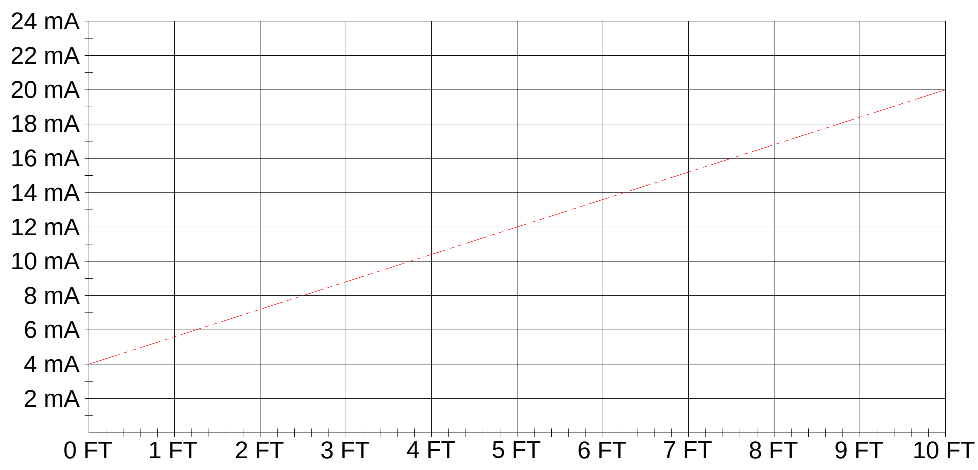
If we know the liquid level height in the vessel or tank, and if the vessel or tank has straight sides or walls, such as shown in Figures 58 through 60, it is a simple matter to infer the volume of liquid above the measuring point. If, however, the sides or walls of the vessel are sloped or otherwise non-uniform (see Figure 63), calculating the volume based on height is not a straightforward task. It can still be done, but will require a little bit of computing power in the control system.



Level Transmitter
Vessels with Non-Uniform Sides
Figure 63

Obviously, in Figure 63(a), if the pressure tap were above the sloped portion (cone) of the vessel (in the straight wall), then the vessel would be a straight-walled tank, as far as calculating the volume above the measuring point is concerned. On the other hand, to calculate the volume of the sphere or cylinder represented by Figure 63(b) would require a formula of some complexity, when compared to a straight-walled tank, but it certainly could be done, if the controller or inventory system has sufficient calculating power.

Let's consider a few more examples of level loops.



Level Loop
4 to 20 mA = 0 to 10 ft (0 to 120" w.c.)
Figure 64

EXAMPLE 30

Which tank levels would be represented by current readings of 8 mA and 18 mA in Figure 64?

Dividing the spans:

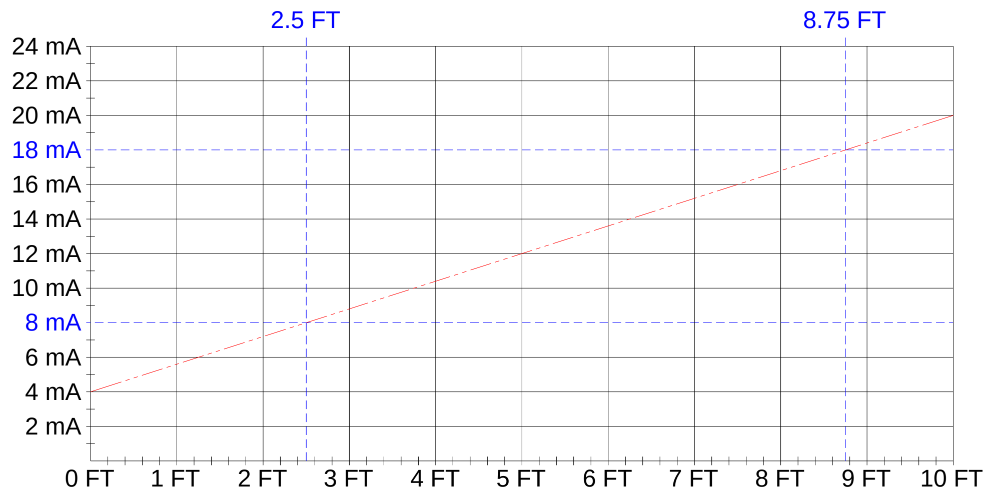
10 ft / 16 mA = 0.625 ft / mA

0.625 mA / ft * (8 mA - 4mA) = 2.5 ft at 8 mA

This can be verified by looking at Figure 65.

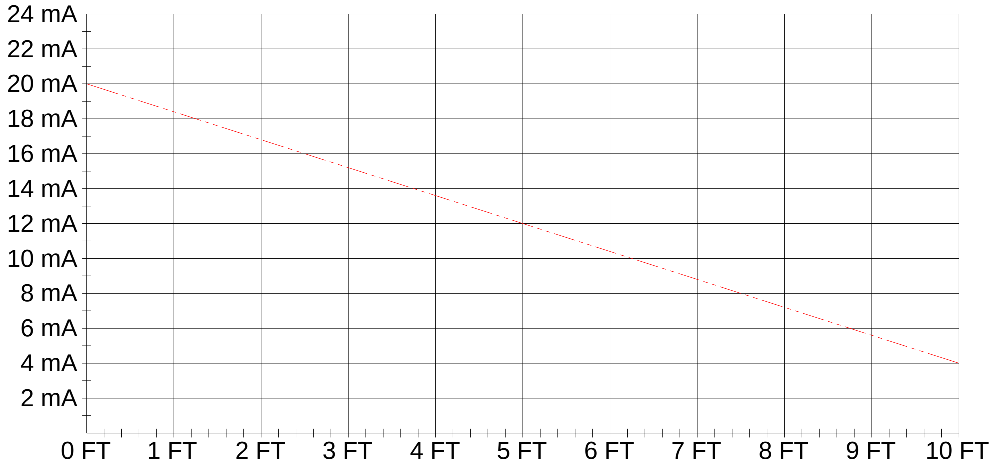
0.625 mA / ft * (18 mA - 4mA) = 8.75 ft at 18 mA

Verify this by looking at Figure 65. END OF EXAMPLE



Level Loop
4 to 20 mA = 0 to 10 ft (0 to 120" w.c.)
Figure 65

Consider a level transmitter that is calibrated to output 20 mA when the level is at 0% and output 4 mA when the level is at 100% (see Figure 66). This 'reverse' type of calibration would be well-suited to control a variable speed drive that is filling a tank. As the level in the tank rises, the 4 to 20 mA signal drops in value.



Level Loop
4 to 20 mA = 10 to 0 ft (120 to 0" w.c.)
Figure 66

EXAMPLE 31

Which tank levels would be represented by current readings of 8 mA and 18 mA in Figure 66?

Dividing the spans:

10 ft / 16 mA = 0.625 ft / mA

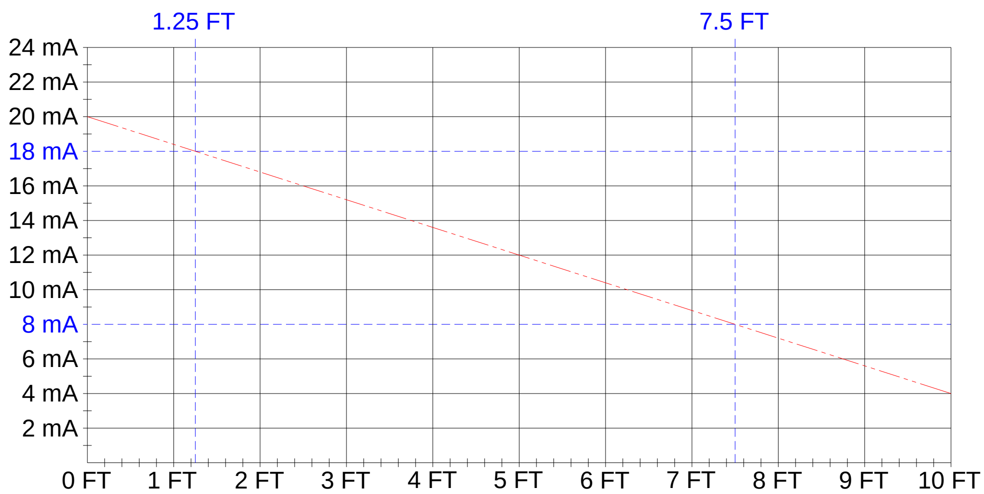
0.625 mA / ft * (20 mA - 8mA) = 7.5 ft at 8 mA

This can be verified by looking at Figure 67.

0.625 mA / ft * (20 mA - 18mA) = 1.25 ft at 18 mA

Confirm this with Figure 67. Compare Figure 67 to Figure 65.

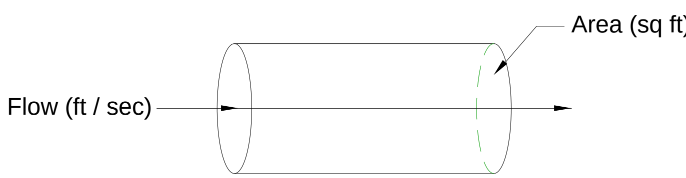
END OF EXAMPLE



Level Loop
4 to 20 mA = 10 to 0 ft (120 to 0" w.c.)
Figure 67

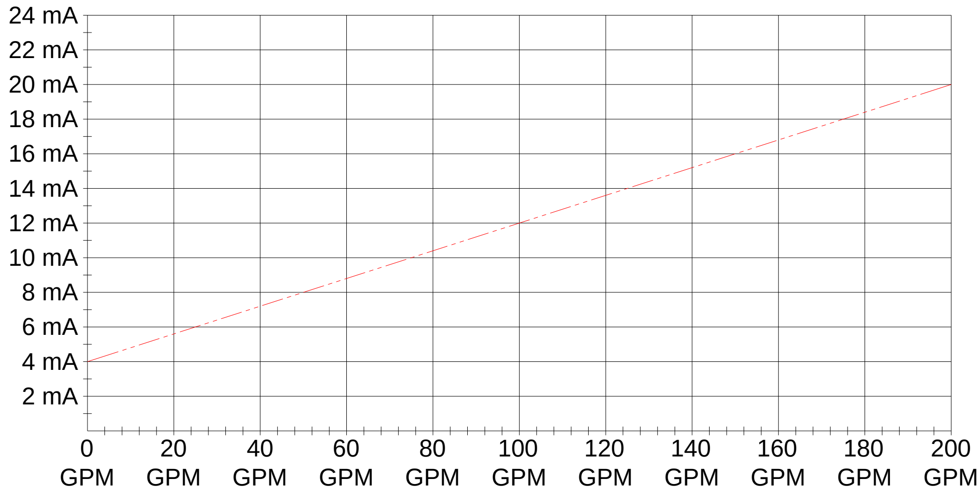
Flow Using Magnetic Flow Element and Transmitter:

There are many ways to measure flow, but let's consider a method that uses the conductive properties of water (or other liquids) and how it is affected by a magnetic field. A magnetic flow meter (sometimes called mag-meter) operates by inducing a magnetic field in a fluid flowing through a cylindrical flow tube (see Figure 68). The flowing conductive fluid is a conductor that is moving through a magnetic field. This produces an electrical field, an effect known as Faraday's Law. The electrical field thus produced is measured in order to determine the velocity of the fluid as it flows through the flow tube. The higher the velocity of the fluid, the higher the magnitude of the electrical field. The flow converter/transmitter determines the velocity of the fluid and the flow is calculated based on the assumption that the flow tube is full (there are some models that can operate with partially-filled flow tubes). Measuring flow based on velocity is a linear function (see Figure 69), since the volumetric flow of fluid is based on the cross-sectional area of the tube (which remains constant) multiplied by the velocity of the fluid (see Figure 68).



Magnetic Flow Meter Element
Figure 68

This type of flow meter measures the velocity of the fluid in order to infer the volumetric flow. It is called volumetric flow because it is measuring the volume of the fluid (water, in our example), rather than mass. As can be seen in Figure 68, if the fluid velocity is 5 ft / sec and the internal cross-sectional area of the flow tube is 0.2 ft^2, then the volumetric flow through the tube is 5 ft/sec * 0.2 ft^2 = 1 ft^3/sec or 60 ft^3/min or 3,600 ft^3/hr. One cubic foot is approximately equal to 7.48 gallons, so a flow rate of 60 ft^3/min is approximately equal to 448.8 gal/min (or 448.8 GPM).



Magnetic Flow Meter Loop
4 to 20 mA = 0 to 200 GPM (linear)
Figure 69

EXAMPLE 32

What would the flow through the meter be in Figure 69 for a current reading of 6.35 mA?

Dividing the spans gives us:

200 GPM / 16 mA = 12.5 GPM / mA

(6.35 mA – 4mA) * 12.5 GPM / mA =

2.35 mA * 12.5 GPM / mA = 29.375 GPM

This can be confirmed with Figure 70.

What would be the 4 to 20 mA current reading or the meter in Figure 69 at a flow of 137.5 GPM?

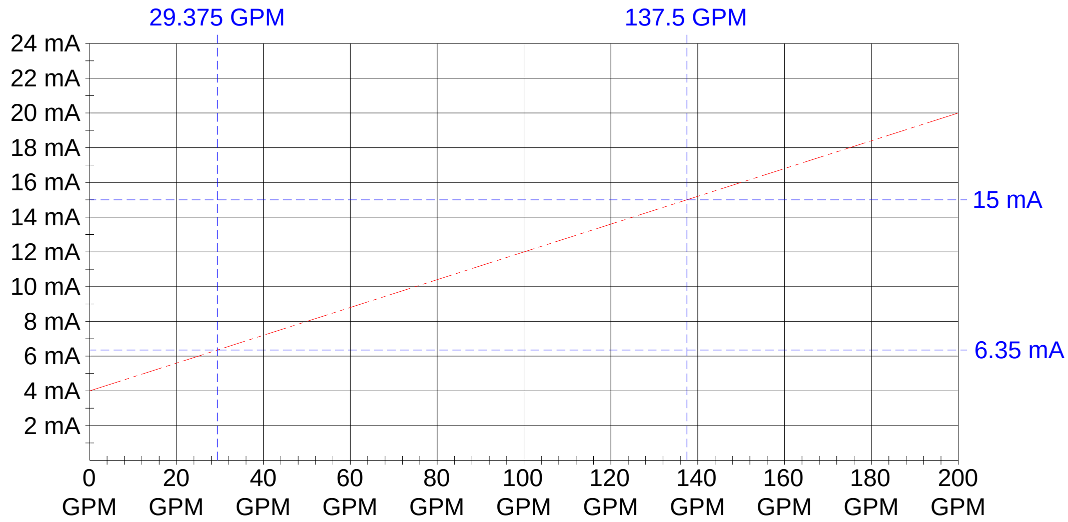
Dividing the spans:

16 mA / 200 GPM = 0.08 mA / GPM

137.5 GPM * 0.08 mA / GPM = 11 mA

11 mA + 4 mA = 15 mA

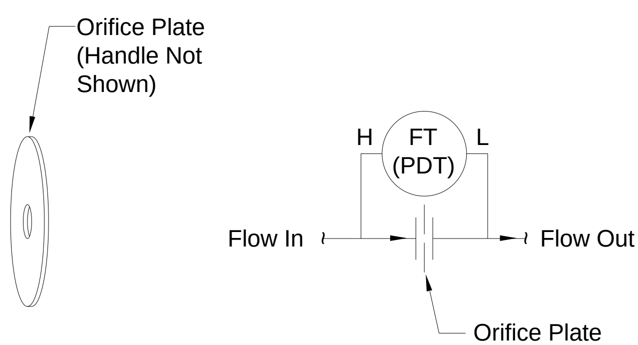
Confirm this with Figure 70. END OF EXAMPLE



Magnetic Flow Meter Loop
4 to 20 mA = 0 to 200 GPM (linear)
Figure 70

Flow Using Differential Pressure Flow Element and Transmitter:

The magnetic flow loop above used a linear type of flow measurement to determine the velocity, then infer the volumetric flow through the flow element. Another type of flow measurement relies on the fact that the change in flow rate through a restriction is proportional to the square root of the change in differential pressure across the restriction (Bernoulli's Principle). Figure 71 shows an illustration of an orifice plate and the symbology used to represent it on a P&ID. The diameter or bore of the hole that is in the center (usually) of the orifice plate determines the pressure drop across the orifice plate at different flow rates.



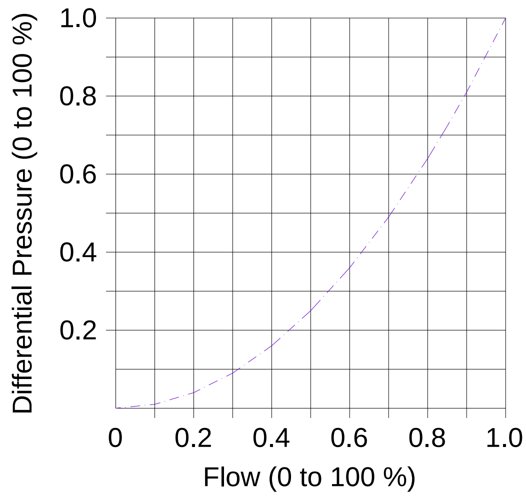
Differential Pressure Flow Meter
Figure 71

As the velocity of the measured fluid through the orifice changes, the differential pressure across the orifice changes as a function of the square of the change in velocity. Stated differently, we can measure the differential pressure across the orifice and calculate the change in velocity through the orifice by taking the square root of the change in differential pressure.

The square root function of differential pressure versus flow is shown in Figure 72. Since the values are less than 1.0, as the percentage of flow increases, the percentage of differential pressure increases more slowly, being based on the square of the percentage of flow, more specifically:

$[Flow(\%)]^2 = DP(\%)$, which also means

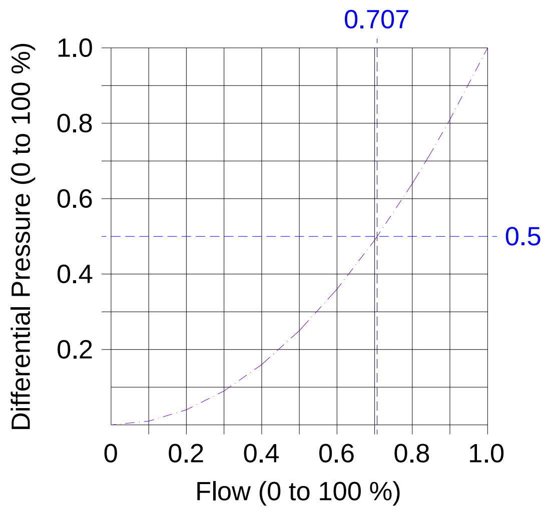
$Flow(\%) = \sqrt{DP(\%)}$



Y = X² Function
[DP(%) = Flow(%)²]
Figure 72

EXAMPLE 33

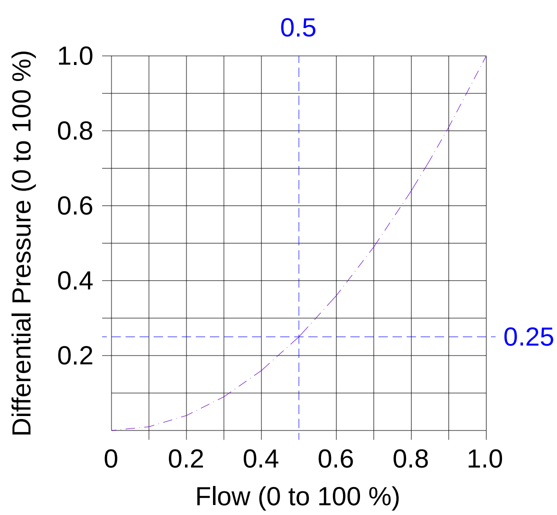
The flow (in %) is equal to the square root of the differential pressure (in %). For example, if the differential pressure is at 50%, the flow is at √0.5 or 70.7%. See Figure 73.



Y = X² Function
[DP(50%) = Flow(70.7%)²]
Figure 73

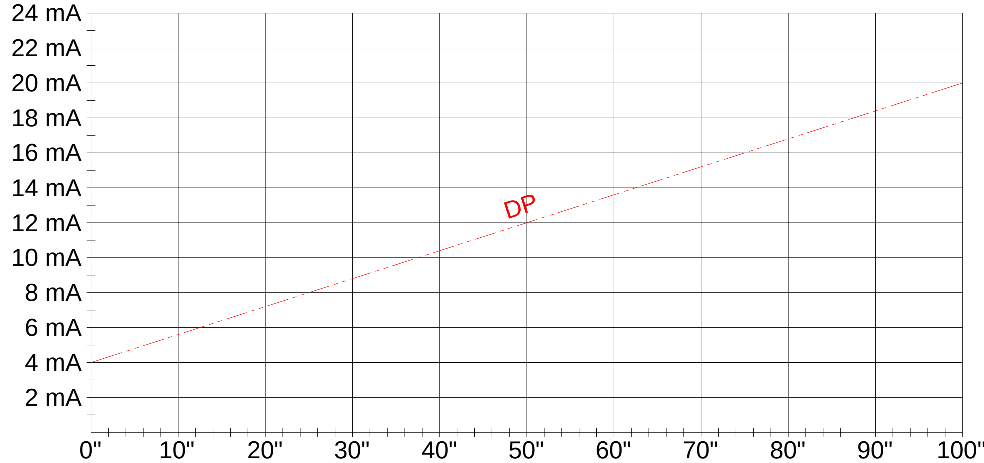
Conversely, if the flow is at 50%, then the differential pressure will be $(0.5)^2 = 0.25$ or 25%. See Figure 74.

END OF EXAMPLE



Y = X² Function
[DP(25%) = Flow(50%)²]
Figure 74

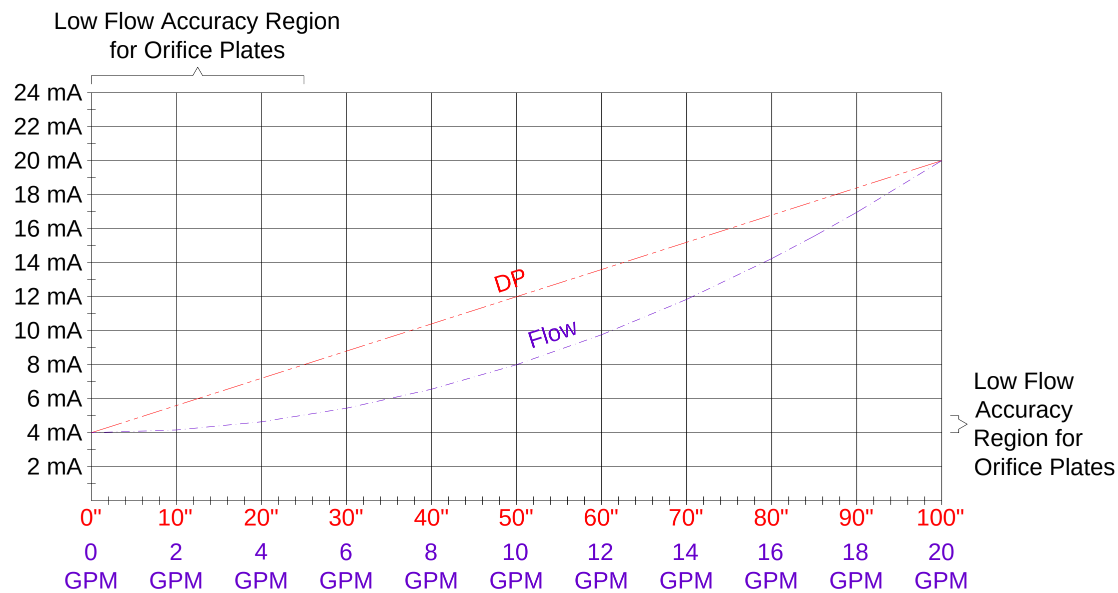
The differential pressure (flow) transmitter in Figure 71 will typically output a 4 to 20 mA signal as shown in Figure 75. Notice in Figure 75 that the 4 to 20 mA signal is a linear function of the differential pressure measured across the orifice plate. The flow through the orifice plate is not a linear function of differential pressure, but is a function of the square root of the differential pressure. The flow curve is added to the differential pressure curve in Figure 76.



Differential Pressure Loop
4 to 20 mA = 0 to 100" w.c. (linear)
Figure 75

The turn-down of an orifice plate is in the neighborhood of 5:1 or 4:1. This means that the accuracy of the flow reading based on differential pressure across an orifice plate is not as good when the flow drops down below 20 to 25% of the flow signal (4 to 6.25% of the DP signal). There are other types of differential pressure flow elements that have higher turn-downs.

In order to extract the flow (in %), the square root of the differential pressure (in %) must be calculated. Figure 75 is reproduced as Figure 76 with the addition of the flow function graph. The shape of the flow function graph is somewhat stretched out in Figure 76 when compared to Figure 72 because the units along the axes in Figure 76 are spaced at a different ratio, not at the same ratio as in Figure 72.



Flow (Differential Pressure) Loop
4 to 20 mA = 0 to 100" w.c. (linear)
4 to 20 mA = 0 to 20 GPM (square root)
Figure 76

EXAMPLE 34

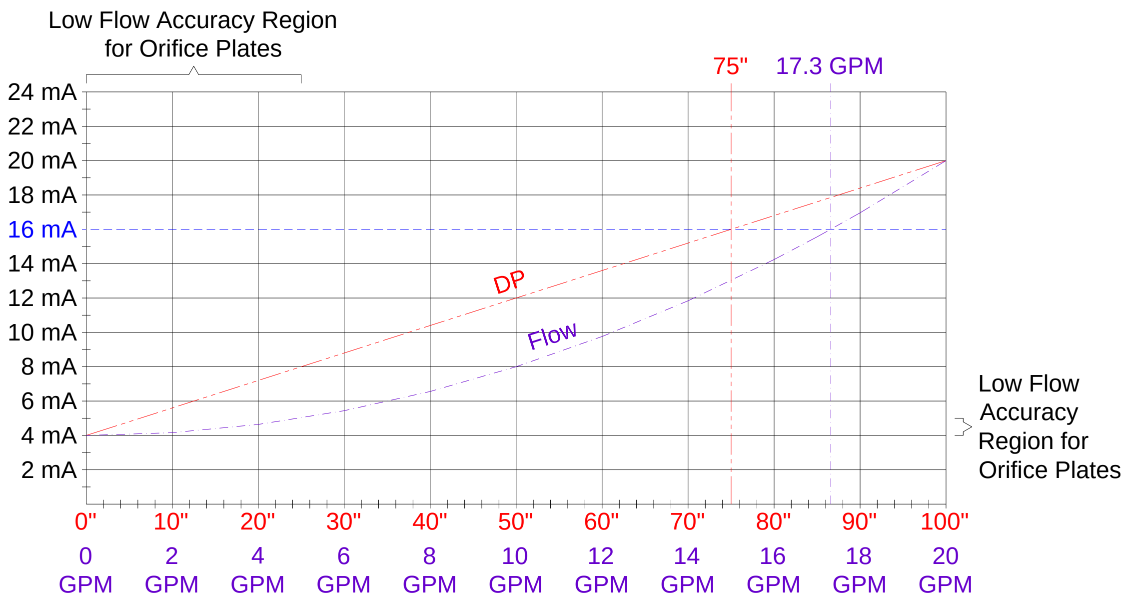
75% of the 4 to 20 mA signal representing differential pressure in Figure 76 is 75" w.c. at 16 mA. The square root of 75% is:

$\sqrt{0.75} = 0.866$

So the flow represented by 75% of the differential pressure signal is 86.6% of the flow span, which is:

0.866 * 20 GPM = 17.3 GPM, which can be verified by looking at Figure 77. As you follow the horizontal 16 mA line across the graph, it hits the DP line at 75" w.c. and then hits the Flow line at 17.3 GPM. END OF EXAMPLE

The purpose of the two sets of units along the horizontal axis of Figures 76, 77, 78, and 79 is not to imply that 60" w.c. = 12 GPM (because it doesn't), but to show the two different functions (DP and flow) on the same graph, since they are related to each other by the same current (mA) reading.



Flow (Differential Pressure " w.c.) Loop
4 to 20 mA = 0 to 100" w.c. (linear)
4 to 20 mA = 0 to 20 GPM (square root)
Figure 77

EXAMPLE 35

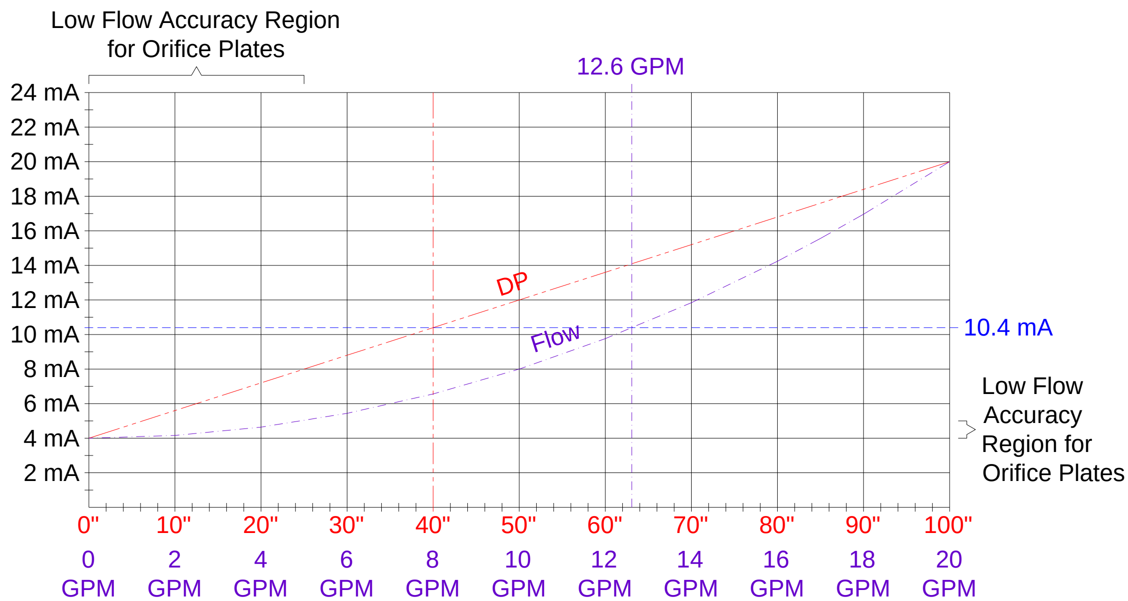
Let's try another example in a different way. We know the flow at a differential pressure of 75" w.c. is 17.3 GPM, so what would the flow be at a differential pressure of 40" w.c.? We'll use X to represent the new flow and do a ratio of the new flow divided by the known flow:

X GPM / 17.3 GPM = (√40" w.c.) / (√75" w.c.)

X / 17.3 = 0.73

X = 12.6 GPM

This can be confirmed with Figure 78.



Flow (Differential Pressure " w.c.) Loop
4 to 20 mA = 0 to 100" w.c. (linear)
4 to 20 mA = 0 to 20 GPM (square root)
Figure 78

To confirm the above answer by using Figure 78, observe where the vertical 40" w.c. line hits the DP line, then draw a horizontal line at this intersection. Follow the horizontal line (which happens to be 10.4 mA) until it intersects with the Flow line, which is at 12.6 GPM in this example.

END OF EXAMPLE

EXAMPLE 36

Let's try the opposite of the previous example. We know the flow at a differential pressure of 75" w.c. is 17.3 GPM, so what would the differential pressure at a flow of 18 GPM? We'll use Y to represent the new differential pressure and do a ratio of the √(new DP) divided by the√(known DP):

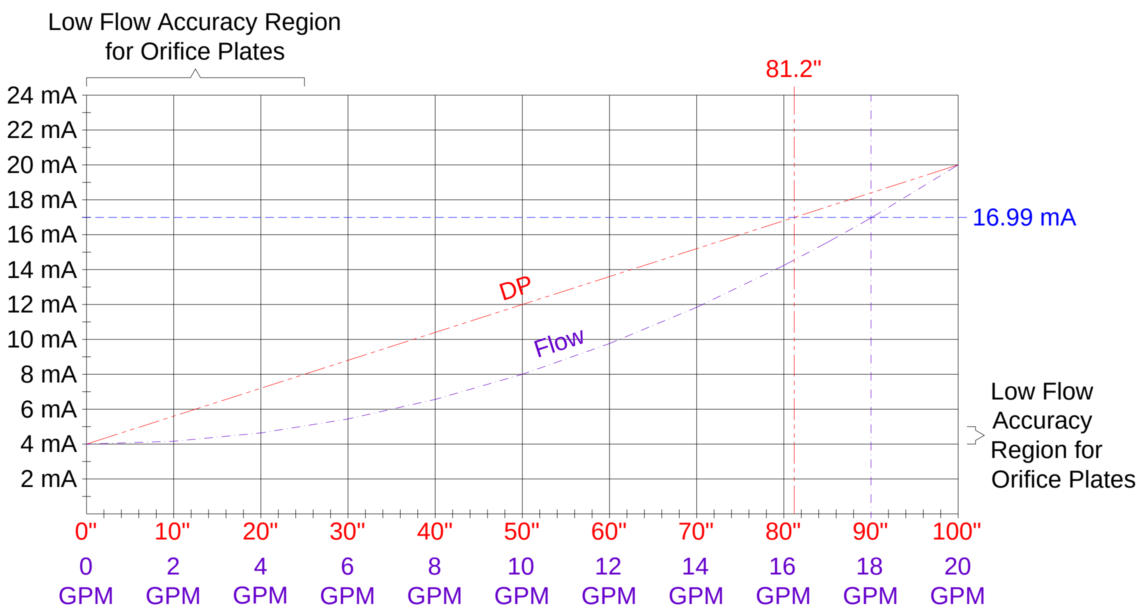
$(\sqrt{Y}\text{" w.c.}) / (\sqrt{75}\text{" w.c.}) = 18 \text{ GPM} / 17.3 \text{ GPM}$

$(\sqrt{Y}) / (8.66) = 1.04$

$(\sqrt{Y}) = 9.01$

$Y = 81.2\text{" w.c.}$

Confirm this by looking at Figure 79.



Flow (Differential Pressure " w.c.) Loop
4 to 20 mA = 0 to 100" w.c. (linear)
4 to 20 mA = 0 to 20 GPM (square root)
Figure 79

To confirm the above answer by using Figure 79, observe where the vertical 18 GPM line hits the Flow line, then draw a horizontal line at this intersection. Follow the horizontal line (which happens to be 16.99 mA) until it intersects with the DP line, which is at 81.2" w.c. in this example.

END OF EXAMPLE

The 4 to 20 mA output of the differential pressure transmitter usually represents differential pressure. The square root extraction function to convert differential pressure to flow can be built in to the calibration of the transmitter, or it can be accomplished by the DCS or other control system. If the square root extraction is built in to the transmitter, then the 4 to 20 mA output will represent the flow, rather than the differential pressure, and will be a linear function of flow, such as that shown in Figure 69 for a magnetic meter.

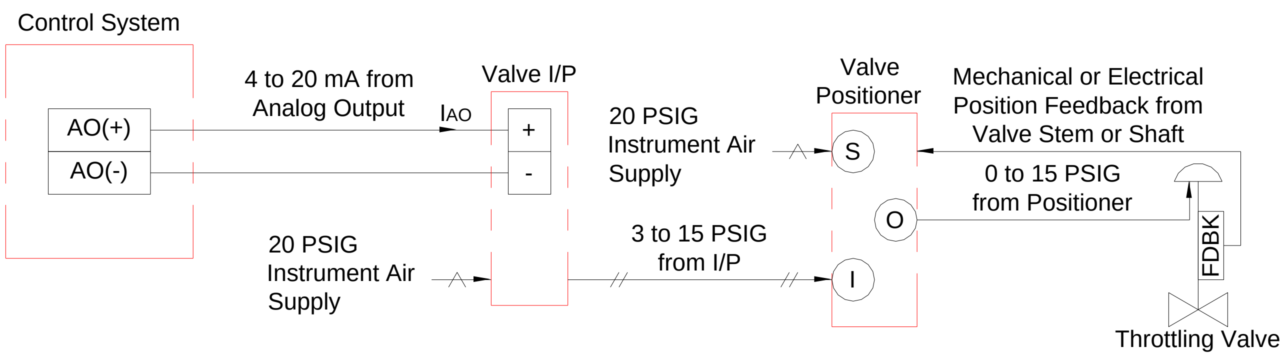
Modulating (Throttling) Control Valve:

We are changing the topic from analog input loops to analog output loops. We begin by discussing modulating control valves.

The type of valve that is called modulating or throttling has more to do with the way in which the valve is controlled or actuated, rather than the construction of the valve body and internal trim. While it is true that some valve construction types, such as globe, butterfly, and ball (opinions vary), lend themselves more readily to modulating applications, almost any construction type of valve, including knife, plug, and others, can be used as modulating valves by adding a positioner (with associated position feedback sensors) to control the position of the actuator.

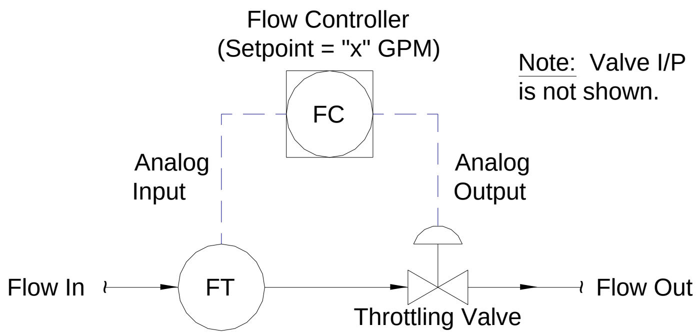
Prior to 4 to 20 mA electronic control, a 3 to 15 PSIG pneumatic signal would be sent from the loop controller in the control room to the valve in the field. This signal would not typically go directly to the actuator but would go to a valve-mounted positioner. The positioner would compare the position of the valve stem or shaft to the 3 to 15 PSIG signal from the loop controller and would output the correct pressure to the valve actuator to position the valve in the exact location defined by the 3 to 15 PSIG signal from the loop controller.

The method is basically the same nowadays, but a 4 to 20 mA signal is sent from the loop controller to the current-to-pressure (I/P) converter, which then presents a 3 to 15 PSIG signal to the valve-mounted positioner, which operates as was just described (see Figure 80). Some models of positioner have built-in I/Ps (these are also referred to as electro-pneumatic positioners). Some manufacturing sites prefer to have the I/Ps mounted remotely from the valve, due to vibration, temperature, plant standards, or some other concern.



Valve I/P and Positioner
Figure 80

Consider the simplified example of a flow measurement and control loop shown in Figure 81. The flow controller's job is to adjust the percentage opening of the throttling valve (via the analog output) to whatever extent is required for the flow transmitter (via the analog input) to measure "x" GPM (gallons per minute). If the setpoint is 10 GPM and the flow transmitter reports a flow of 9 GPM, then the flow controller will open the valve a little bit more (the exact amount being based on the control algorithm). If the setpoint is 10 GPM and the flow transmitter reports a flow of 11 GPM, then the flow controller will close the valve a little bit (again, the amount of change is based on the control algorithm).



Flow Measurement and Control
Figure 81

Different construction types of valves, such as ball, segmented ball, triple-offset butterfly, etc., have different inherent flow characteristics. The inherent flow characteristics (see Figure 82) are those that are observed when the valve has a constant pressure drop across it. The installed flow characteristics will typically push the curve up and to the left, due to changes in pressure drop across the valve at different flow rates and other variations in the process. For example, in many processes, a valve with a linear inherent flow characteristic will have an installed flow characteristic that resembles a quick-opening inherent flow characteristic. Similarly, in many processes, a valve with an equal-percentage inherent flow characteristic will have an installed flow characteristic that resembles a linear inherent flow characteristic.

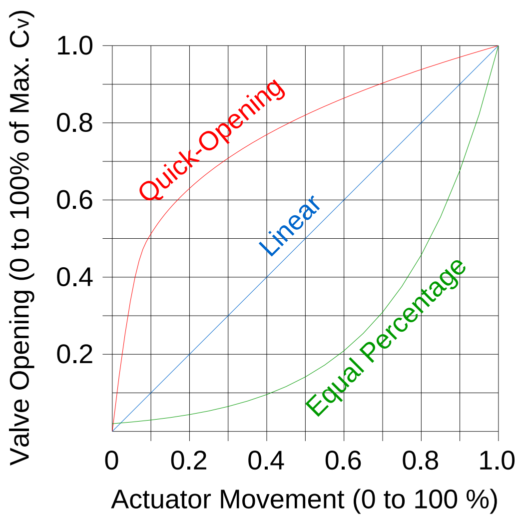
Looking at it another way, the inherent flow characteristics of a valve are determined in a test setup wherein the differential pressure is kept constant across the valve being tested. If the differential pressure across the valve is constant and the fluid is a liquid (such as water), then the flow through the valve will follow the curve of the inherent flow characteristics of the valve, since the formula for liquid flow through a valve is:

$Cv = Q * \sqrt{(G / DP)}$ {for liquids}

When G (the specific gravity of the liquid) and DP (the differential pressure across the valve) are kept constant, the flow through the valve will be equal to the Cv of the valve at that point, multiplied by a constant [$\sqrt{(G / DP)}$]. This is how the inherent flow characteristic of a valve is determined.

In real life, however, the differential pressure across the valve will change as the flow rate through the valve changes. This will cause the installed flow characteristics of a valve to be significantly different from the inherent flow characteristics.

The three most common types of valve inherent flow characteristics are: 1) Quick-Opening, 2) Linear, and 3) Equal-Percentage, which are illustrated in Figure 82. Other types of valve inherent flow characteristics (not shown) include Square Root, Modified Parabolic, and Hyperbolic.



Valve Inherent Flow Characteristics
Figure 82

The formulas for the three types of valve inherent flow characteristics illustrated in Figure 82 are (with % being a value from 0.0 to 1.0):

Quick-Opening:
(% of maximum C_v) = (% Actuator Movement)$^{1/\alpha}$ {α = 3.5 in Figure 82}

Linear:
(% of maximum C_v) = (% Actuator Movement)

Equal-Percentage:
(% of maximum C_v) = $R^{[(\text{\% Actuator Movement})-1]}$ {R = Rangeability = 50 in Figure 82}

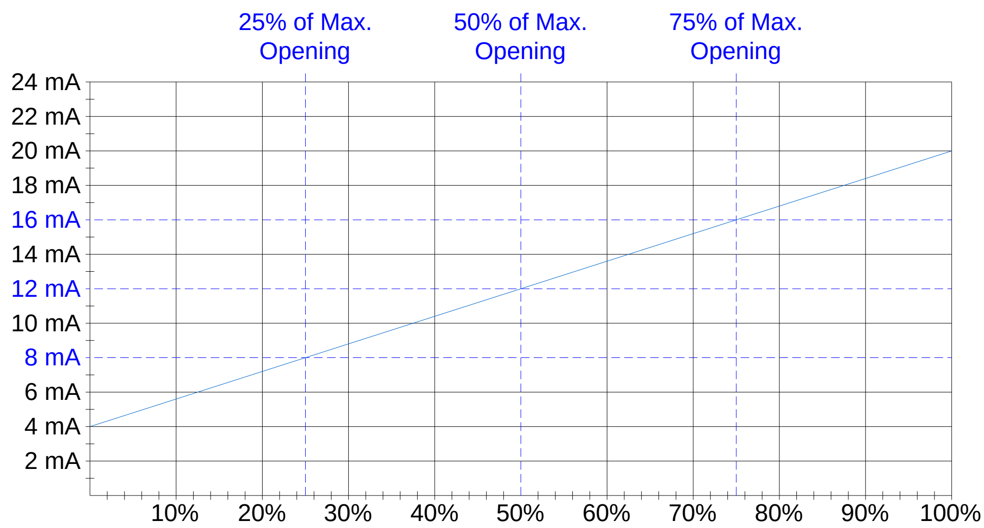
The graphs in Figure 82 are based on the formulas above, but the flow characteristic curves for actual valves might vary somewhat. In particular, the formula above for the equal-percentage flow characteristic will never allow the valve opening to reach 0% (closed), as is evident in the equal-percentage formula above and illustrated in Figure 82. From the formula above, when (% actuator movement) = 0, the % of maximum C_v = 50^{-1} = 0.02 or 2%. This would be quite a disadvantage for a control valve, so these valves are actually provided with "approximate equal-percentage" or "modified equal-percentage" flow characteristics (see Figure 84). That way, the inherent flow characteristic will allow the valve to be completely closed at 0% actuator movement and the inherent flow characteristic curve can then follow an approximation of the equal-percentage formula.

All three of the above formulas allow the valve to be at 100% of maximum C_v at 100% actuator movement. This is also illustrated in Figure 82 and is evident in the three formulas.

As discussed above, different construction types of valves have different inherent flow characteristics, but they can all have customized flow characteristics by using several different methods, including:

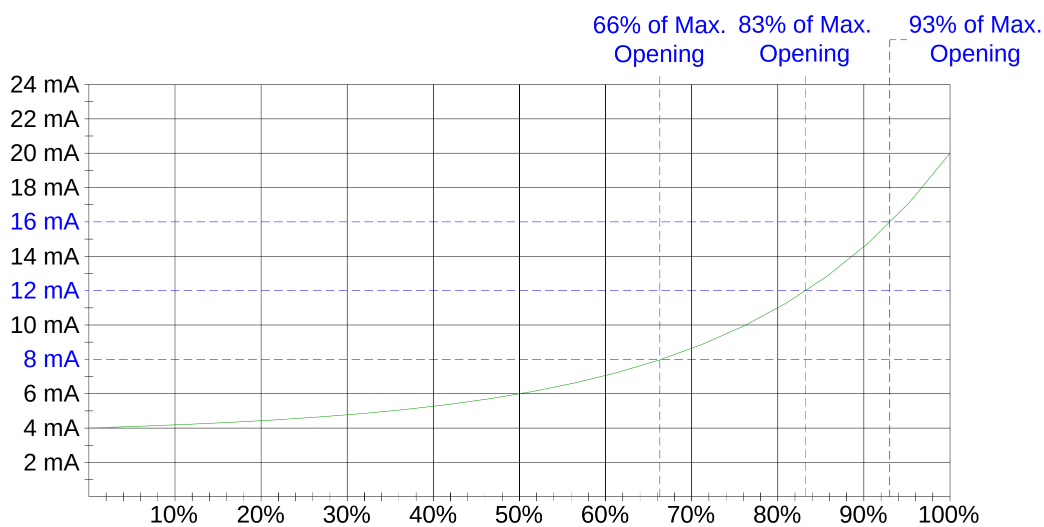
- Specially characterized trim installed in the valve body
- Specially characterized cams in the positioner
- Smart / digital positioners that use internal software to emulate specially characterized cams in the actuator
- Characterization or manipulation of the 4 to 20 mA signal to make a 'regular' actuator and valve combination behave with a different flow characteristic.

As aforementioned, the inherent flow characteristics that are illustrated in Figure 82 are not the same as the installed flow characteristics, unless there is a constant value of pressure drop across the valve. In a practical application, the pressure drop across an installed valve will change, based on a number of factors, including upstream pressure, downstream pressure, and the extent of valve opening. What we are able to determine about a valve by looking at the mA current that is sent to the I/P is where the valve actuator's position should be. For example, for a linear inherent flow characteristic valve, when the I/P receives a 12 mA signal, the actuator should put the valve at its 50% point (unless there are specially-characterized cams), which would be half-stroke for a sliding-stem valve or 45° for a quarter-turn (90°) valve. Does this mean that the flow through the valve will be 50% of the valve's maximum capacity? Not necessarily. The flow through the valve is dependent on the differential pressure across the half-open valve. The flow could be 50%, it could be higher, or it could be lower. For the same linear valve, the valve position will be 25% open for a current value of 8 mA and 75% open for a current value of 16 mA (see Figure 83).



Linear Valve Inherent Flow Characteristic
4 to 20 mA = 0 to 100% of Maximum C_v
Figure 83

The mA current reading values versus percentage of maximum C_v are shown on Figure 83 for a linear valve. Similarly, the corresponding current reading values versus percent of maximum C_v for a valve with a modified or approximately equal-percentage inherent flow characteristic are shown in Figure 84 (consult the valve catalog cut-sheet for the specific applicable curve).



Modified Equal Percentage Valve Inherent Flow Characteristic
4 to 20 mA = 0 to 100% of Maximum C_v
Figure 84

Notice the significantly different percent of maximum C_v results for the modified equal-percentage valve in Figure 84 when compared to the same current readings (8, 12, and 16 mA) for the linear valve in Figure 83. Notice also in Figure 84 that the valve is now fully closed at a 0% (4 mA) input to the I/P, as opposed to what is shown in Figure 82 for the "pure" equal-percentage inherent flow characteristic.

If you know the value of the 4 to 20 mA signal, you can determine the position, and therefore the opening, of the control valve, but you cannot determine the flow rate with only this information, since the flow rate depends on the process conditions. When a flow control loop (consisting of a flow transmitter, a controller, and a throttling control valve, as shown in Figure 81) is instructed to maintain a certain flow setpoint, the controller cannot look at the flow transmitter analog input value and determine the exact required analog output value to send to the control valve actuator to reach the flow setpoint. The flow controller will start off by calculating the proper analog output value, and then will continue to make adjustments to the analog output until the flow transmitter reads the correct flow.

Why is the flow measuring element usually located upstream of (before) the throttling flow control valve?

As is usually the case, if you ask three different people, you'll probably get three different answers. The most practical answer is: Valves almost always create turbulence in the fluid that is flowing through their tortuous internal paths and most flow measuring elements do not work as well when there is turbulent flow. Look at Figure 81. By putting the flow measuring element ahead of the valve (and maintaining required upstream and downstream straight-run piping lengths at the element), the 'noise' of the downstream control valve will not affect the flow measurement.

The main point of the above explanatory and somewhat repetitive discourse is that the value of the 4 to 20 mA signal from the analog output to the I/P of the control valve has no direct correlation to the flow going through the control valve. The two parameters are related, in that increasing the 4 to 20 mA signal to the I/P usually increases the flow through the valve, but it is not an exact relationship.

Before we leave this section, let's take one more look at the three different inherent flow characteristics above, namely, Quick-Opening, Linear, and Equal-Percentage. The first two, Quick-Opening and Linear, are easy to understand and are aptly named, but what does Equal-Percentage actually mean?

The term Equal-Percentage (often denoted as =%) means that if you increase the actuator position by a certain amount, such as 30%, you will get a certain ratio of increase in C_v. For example, consider a hypothetical valve for which the C_v is 2 at an actuator position of 25% and the C_v is 3.5 at an actuator position of 55% (a 30% change in actuator position) – the same ratio will apply if the actuator position is changed from 55% to 85% (a 30% change in actuator position). That being said, for a 30% change in actuator position, the ratio for this hypothetical valve is 3.5 / 2 = 1.75. Therefore, the same ratio would apply in going from the 55% to the 85% actuator position, such that the C_v at the 85% actuator position should be 3.5 * 1.75 = 6.125.

Take a look at Table 2, which illustrates a different hypothetical equal-percentage valve with some examples of different changes in actuator position, such as 30% in the example we've just discussed, plus 5%, 10%, 15%, and 20%. Remember from above that the formula for an equal-percentage inherent flow characteristic is (with % being a value from 0.0 to 1.0):

(% of maximum C_v) = $R^{[(\% \text{ Actuator Movement})-1]}$ {R = Rangeability = 50 in this example}

Table 2

Actuator Position 0 to 1.0	R=	% of Max. C_v	5% Change: Ratio of New / Previous C_v	10% Change: Ratio of New / Previous C_v	15% Change: Ratio of New / Previous C_v	20% Change: Ratio of New / Previous C_v	30% Change: Ratio of New / Previous C_v
0	50	2.00	N.A.	N.A.	N.A.	N.A.	N.A.
0.05	50	2.43	1.2160				
0.1	50	2.96	1.2160	1.4788			
0.15	50	3.60	1.2160		1.7982		
0.2	50	4.37	1.2160	1.4788		2.1867	
0.25	50	5.32	1.2160				
0.3	50	6.47	1.2160	1.4788	1.7982		3.2336
0.35	50	7.86	1.2160				
0.4	50	9.56	1.2160	1.4788		2.1867	
0.45	50	11.63	1.2160		1.7982		
0.5	50	14.14	1.2160	1.4788			
0.55	50	17.20	1.2160				
0.6	50	20.91	1.2160	1.4788	1.7982	2.1867	3.2336
0.65	50	25.43	1.2160				
0.7	50	30.92	1.2160	1.4788			
0.75	50	37.61	1.2160		1.7982		
0.8	50	45.73	1.2160	1.4788		2.1867	
0.85	50	55.61	1.2160				
0.9	50	67.62	1.2160	1.4788	1.7982		3.2336
0.95	50	82.23	1.2160				
1	50	100.00	1.2160	1.4788		2.1867	

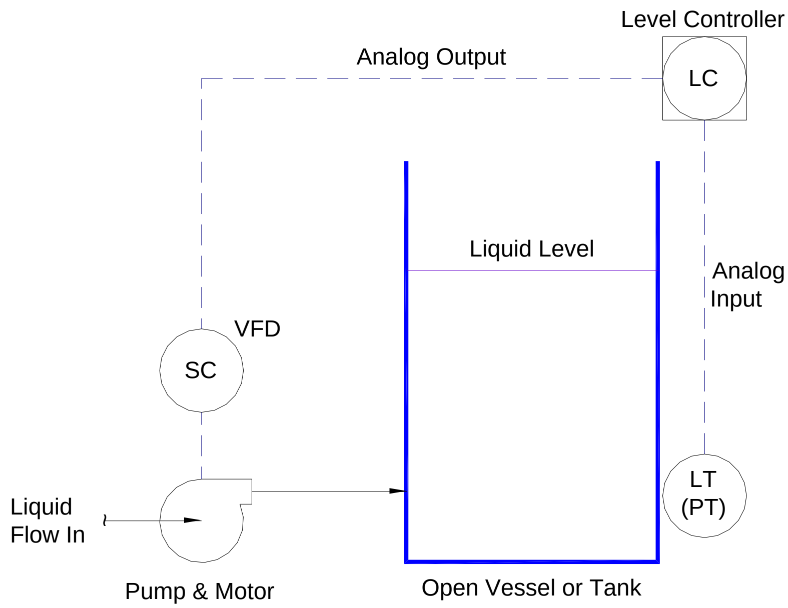
In Table 2, notice in the 15% Change column that for every 15% change in actuator position (such as from 0 to 15% or from 45% to 60%), the ratio of the new C_v to the previous C_v is always 1.7982. The formula used above to create Table 2 is a true, mathematically-pure equal-percentage inherent flow characteristic, so the valve doesn't close completely at the 0% actuator position (see 0% Actuator Position row in Table 2, in which the valve is open 2% of max C_v). As discussed previously, equal-percentage valves are actually supplied with modified or approximate equal-percentage inherent flow characteristics such that they typically close completely at the 0% actuator position.

To put Table 2 in terms of the 4 to 20 mA signal, if the signal current is increased by 20% of the span (such as from 7.2 mA to 10.4 mA), the actuator position will increase by 20% and the new C_v (at 10.4 mA) will be 2.1867 times the previous C_v (at 7.2 mA). The same would be true if the signal current is increased by another 20% of the span (from 10.4 mA to 13.6 mA). How much will the flow through the valve change based on the change in the Cv? Again, that cannot be determined without knowing how much the differential pressure across the valve changed. The flow transmitter will tell us how much the flow has changed.

Variable Speed Drive:

Another common device that receives an analog output signal is the analog input of a variable speed drive (VSD), also known as an adjustable speed drive (ASD). One type of VSD is a variable frequency drive or VFD (also called an inverter, by some), and we'll be using that terminology for the remainder of this discussion.

As was seen earlier in Figure 26, the control system receives an analog input and manipulates the analog output until the measured parameter (level, in this case) is where it needs to be. If the control loop in Figure 26 were to be represented on a P&ID, it would be similar to the simplified version shown in Figure 85.



Level Control Using
Variable Frequency Drive
Figure 85

As was the case for the flow control loop, the level controller (LC) receives the analog input value (level), calculates the appropriate analog output value (motor speed), and sends the 4 to 20 mA analog output signal to the VFD (speed controller SC).

Just as the modulating valve had a positioner to control the exact position of the valve's actuator, the motor connected to a VFD could have an optional speed sensor (tachometer) to control the exact speed of the motor. In common, everyday cases, however, this level of precise speed control is not required.

As mentioned previously, many VFDs are furnished with loop control functions such that it is possible, in simple applications, to skip the DCS or PLC, bring the analog input directly to the VFD, and allow the built-in loop controller in the VFD to determine the required speed of the motor. This scenario was shown earlier in Figure 25.

As was seen in Figure 25 and Figure 26, the analog input at the VFD usually acts just like a DCS or PLC analog input. It uses a resistor (typically 250 ohms) to convert the 4 to 20 mA current signal to a 1 to 5 VDC signal. The VFD converts this voltage signal to a digital value that it then uses to calculate the appropriate frequency to output to the motor.

When a mA signal is sent to the AI of the VFD, the motor doesn't immediately start rotating at the requested speed. Most VFDs are intentionally programmed by the user or installer to have a soft-start and soft-stop, such that the motor will gradually increase in speed when it is started and gradually coast to a stop when it is stopped, depending on the application.

Many motors have built-in internal fans that cool the motor as it rotates. These fans need to rotate at a certain minimum speed in order to provide effective cooling. Consequently, the motor needs to turn at a certain minimum speed, or it will overheat. Because of this, the 4 to 20 mA signal usually does not represent a 0 to 60 hZ output to the motor, but has some non-zero Hertz value for the low end. A typical rule of thumb is 20% of the 60 Hz as the minimum frequency for non-inverter-duty motors, but the VFD programmer should always check the specs on the particular motor. Whether the load on the motor is variable-torque or constant-torque also affects this evaluation.

In Closing:

In this document, we have discussed how analog input, and analog output loops are affected by total loop resistance and by the devices (transmitters, I/Ps, analog inputs, etc.) connected to those loops. We have also discussed how various types of transmitters use transducers and conversion circuitry to convert the measured parameters of pressure and temperature to produce a 4 to 20 mA signal and also derive other parameters, such as level or flow. We have discussed how a 4 to 20 mA output signal controls a valve actuator's position, but not necessarily the flow through that valve.

Abbreviations:

A – Amps, a measure of current (used in mA)
AC – Alternating Current
AI – Analog Input
AO – Analog Output
ASD – Adjustable Speed Drive (another term for VSD)
C_v – The liquid flow coefficient of a particular valve at a certain actuator position. A valve with a C_v of 1 will pass 1 GPM of a liquid with a specific gravity of 1 at a differential pressure of 1 PSID across the valve.
COM – Common or Return terminal on a DC power supply
DC – Direct Current
DCS – Distributed Control System

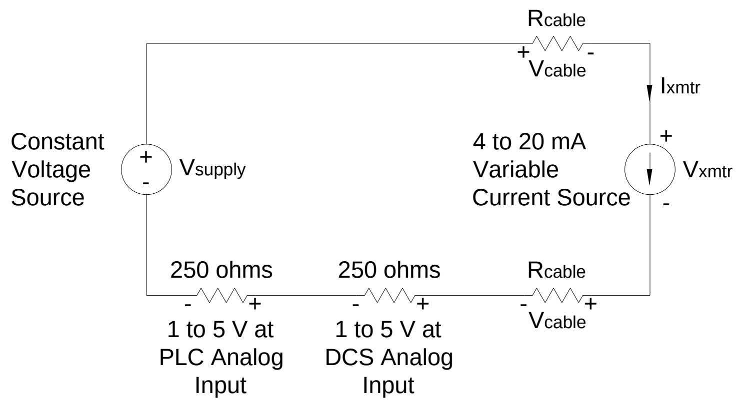
DP – Differential Pressure
FC – Flow Controller
FT – Flow Transmitter (such as DP, coriolis, or ultrasonic)
GPM – Gallons per Minute
HART – Highway Addressable Remote Transducer
I – Current (amps)
I/P – Current to Pressure (Current to Pneumatic) signal converter or transducer, typically 4 to 20 mA input / 3 to 15 PSIG output
LC – Level Controller
LT – Level Transmitter (such as DP, radar, or ultrasonic)
mA – milliamps (1 / 1,000 of an amp)
mADC – milliamps DC (synonymous with mA in this document)
MV – Measured Variable (also known as PV – Process Variable)
P&ID – Process and Instrumentation Diagram (sometimes called Piping and Instrumentation Diagram)
PDIT – Pressure (Differential) Indicating Transmitter
PDT – Pressure (Differential) Transmitter
PID – Proportional, Integral, and Derivative control algorithm for analog control systems
PIT – Pressure Indicating Transmitter (Absolute or Gage)
PLC – Programmable Logic Controller
PSI – Pounds per Square Inch (usually assumed to be Gage or Differential)
PSIA – Pounds per Square Inch Absolute
PSID – Pounds per Square Inch Differential
PSIG – Pounds per Square Inch Gage
PSIS – Pounds per Square Inch Sealed
PSIV – Pounds per Square Inch Vacuum
PT – Pressure Transmitter (Absolute or Gage)
PV – Process Variable (the value of the parameter that is being measured, such as 23 PSIG)
R – Rangeability of Control Valve = Maximum Controllable C_v / Minimum Controllable C_v
R – Resistance
RTD – Resistance Temperature Device
SC – Speed Controller (such as a VFD)
S.G. – Specific Gravity
STP – Shielded Twisted Pair
TE – Temperature Element (such as thermocouple or RTD)
TT – Temperature Transmitter
V – Volts
VAC – Volts AC
VDC – Volts DC
VFD – Variable Frequency Drive (a type of VSD)
VSD – Variable Speed Drive (another term for ASD)
w.c. – Water Column (a measure of pressure, usually expressed as inches of water column)
XMTR – Transmitter

The author wishes to thank Roger Poole for his time and invaluable input on this project.

Additional information is presented in the Appendix in the pages that follow.

Voltage-Drop Calculations around a Current Loop:

Beginning with Example 1 earlier in this document, it was stated that the total of the voltage drops around a loop must be equal to the driving voltage, which is either V_{supply} for two-wire analog input loop (Figure 12) or V_{AO} for an internally-powered analog output loop (Figure 5). The concept of all of the voltages in a loop adding up to zero is called Kirchoff's Voltage Law. It is generally assumed that electrical current flows from plus (+) to minus (-) [although the electrons actually flow the opposite direction] and this is important for differentiating between the voltage sources and voltage drops in a loop. For direct-current loops, as the current flows through voltage sources, such as a battery or loop power supply, the upstream terminal is labeled (-) and the downstream terminal is labeled (+). See Figure A-1, wherein the current (I_{xmtr}) is flowing in a clockwise direction. The opposite sign convention is used for a load, such as a resistor or transmitter, in that a (+) is assigned to the upstream terminal and a (-) is assigned to the downstream terminal. See Figure A-1, in which the source (V_{supply}) has the opposite sign convention as the load (V_{xmtr}) and the voltage drops at the resistance loads.

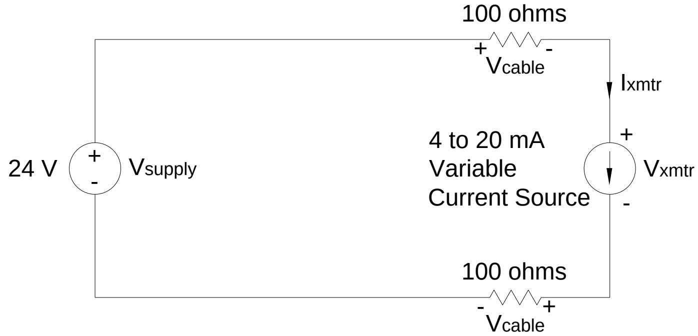


Voltage Drops in an Analog Input Loop
Figure A-1

Figure A-2 shows a loop power supply and a two-wire 4 to 20 mA transmitter with no cable resistance. This example represents the scenario wherein the transmitter is hooked up to a power supply on the technician's test bench.

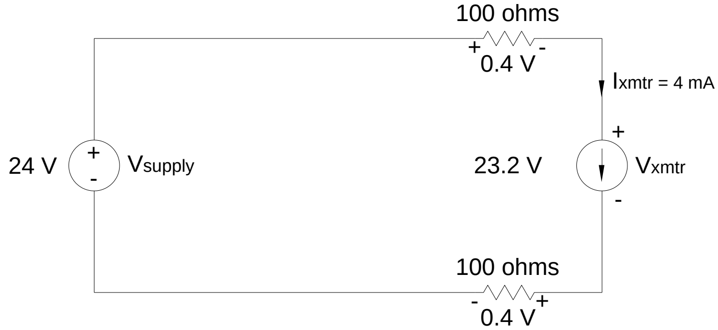
Voltage Drop in an Analog Input Loop
Figure A-2

When you travel around the loop in the same direction as the current (clockwise), the voltage increases as you go from a (-) to a (+) and it decreases as you go from a (+) to a (-). For example, if we start our journey around the loop at the lower left-hand corner of Figure A-2 (we start counting at 0 volts, no matter where we start), we add 24 V as we go from (-) to (+) through the loop power supply (V_{supply}), then we subtract voltage drops across loads as we go from (+) to (-) [V_{xmtr}]. Since the transmitter is the only other device in the loop in Figure A-2, it has to drop all of the 24 V from the source across its terminals, regardless of the value of the 4 to 20 mA current. If the transmitter is putting out 4 mA, the voltage drop across the transmitter will be 24 V. If the transmitter is putting out 20 mA, the voltage drop across the transmitter will still be 24 V, since it is the only voltage drop in this loop. One could say that the equivalent resistance of the transmitter is 24 V / 4 mA = 6,000 ohms at 4 mA and 24 V / 20 mA = 1,200 ohms at 20 mA, since resistance is equal to voltage divided by current. The equivalent resistance of the transmitter changes to whatever it needs to be for the current through the transmitter to be the proper value. Likewise, the voltage drop across the transmitter changes to whatever it needs to be for the current through the transmitter to be the proper value, as will be seen in Figures A-4, A-5, and A-6 later.



Voltage Drops in an Analog Input Loop
Figure A-3

We have added some cable resistance in Figure A-3, so the voltage drop will be shared by the transmitter and the cables. As a result of the cable resistance, the voltage drop across the transmitter will change for different current outputs, since more or less voltage will be dropped across the cable resistance, based on the loop current of 4 to 20 mA. Figure A-4 shows the case for a loop current of 4 mA. The voltage drop across each 100-ohm resistor is 4 mA * 100 ohms = 0.4 V.



Voltage Drops in an Analog Input Loop at 4 mA
Figure A-4

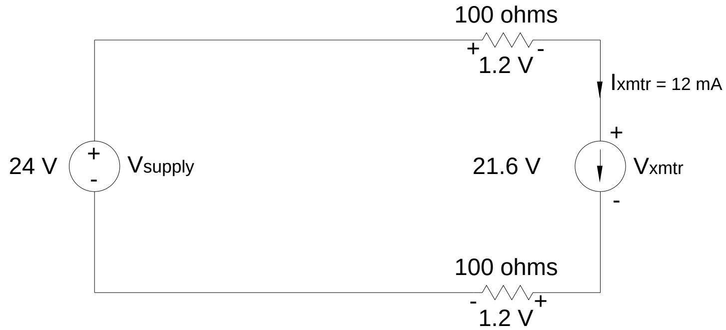
As we travel around the loop in Figure A-4 in the direction of the current (clockwise, in this example), we add voltage as we go from (-) to (+) and we subtract voltage as we go from (+) to (-). Let's start in the upper left-hand corner this time, with our imaginary voltage counter at zero volts. As we go clockwise, we go from (+) to (-) at the 100-ohm resistor, so we subtract 0.4 V. Then, we subtract V_{xmtr}, which is presently unknown. Then we subtract another 0.4 V for the second 100-ohm resistor. Finally, we add 24 V for the loop power supply and we return to our starting point. Our voltage counter at the end of our journey reads:

$– 0.4 – V_{xmtr} – 0.4 + 24 = 0$, since the sum of all of the voltages is zero, which can be rearranged as:

$V_{xmtr} = 24 – 0.4 – 0.4$, so

$V_{xmtr} = 23.2$

Let's try the same thing at a loop current of 12 mA, as illustrated in Figure A-5.



Voltage Drops in an Analog Input Loop at 12 mA
Figure A-5

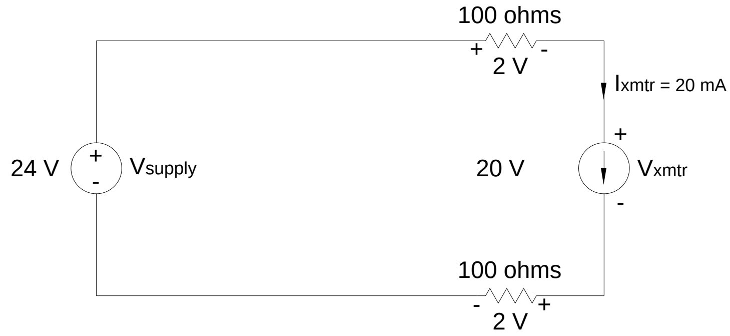
It doesn't matter where we start, so let's start at the upper right-hand corner this time with our imaginary voltage counter set to zero volts. First, we subtract the value of V_{xmtr}, which is unknown at this time. Then we subtract 1.2 V for the first 100-ohm resistor at the bottom of the drawing, we add 24 V for the loop power supply, and we subtract another 1.2 V for the second 100-ohm resistor, bringing us back to our starting point at the upper right-hand corner of the loop. Our voltage counter reads:

$– V_{xmtr} – 1.2 + 24 – 1.2 = 0$, which can be rearranged as

$V_{xmtr} = 24 – 1.2 – 1.2$

$V_{xmtr} = 21.6$

Let's try one more example of the same loop, but this time at a loop current of 20 mA, as illustrated in Figure A-6.



Voltage Drops in an Analog Input Loop at 20 mA
Figure A-6

Again, it doesn't matter where we start our journey to utilize Kirchoff's Voltage Law, so let's start at the bottom right-hand corner, with our imaginary voltage counter set to zero. We first pass through the 100-ohm resistor at the bottom of the drawing and subtract 2 V as we go from (+) to (-). We then add 24 V for the loop power supply as we go through it from (-) to (+). We then subtract 2 V and subtract V_{xmtr} to bring us back to our starting point at the bottom right-hand corner of the drawing. Our voltage counter reads:

$–2 + 24 – 2 – V_{xmtr} = 0$, which can be rearranged as

$V_{xmtr} = 24 – 2 – 2$

$V_{xmtr} = 20$

To re-state the basic concept of Kirchoff's Voltage Law: The sum of the voltages in a loop equals zero. That brings us to the end of this Appendix.