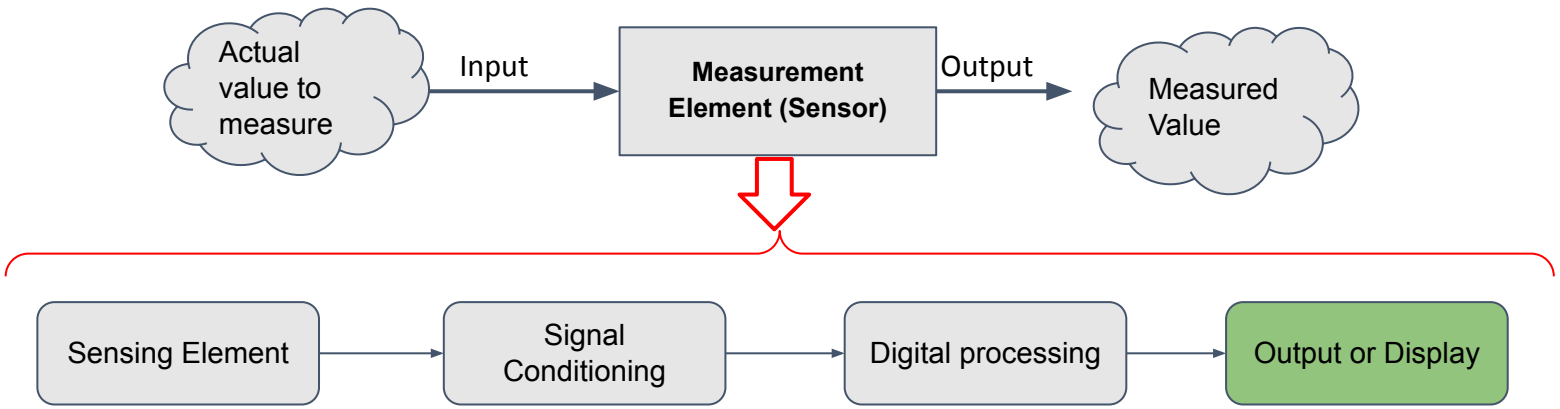
Instrumentation & Measurement

Winter 2024

Sensor Outputs

Amir Jafari, Ph.D., P.Eng.
Professor, Advanced Manufacturing
Faculty of Applied Sciences and Technology, Humber College

Sensor Components

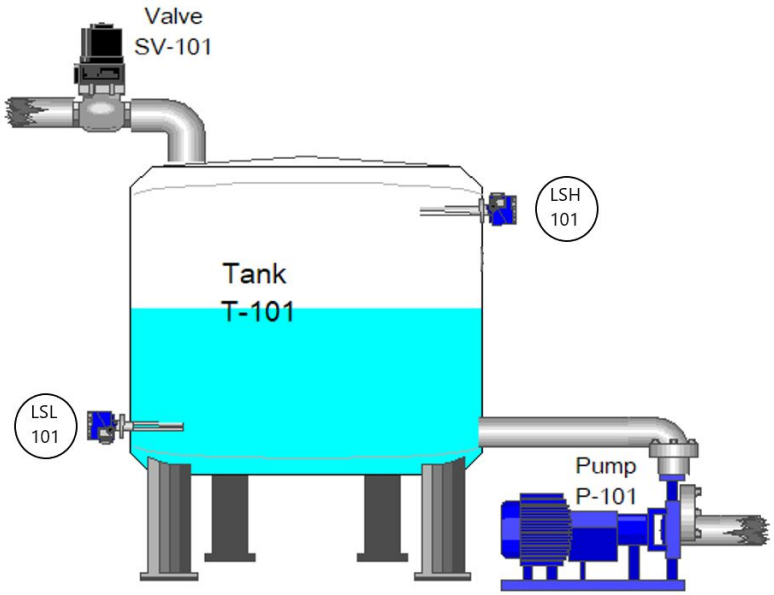


Types of Measurements

- **Point measurement**
- **Continuous measurement**

❖ Point measurement

- Point measurement shows that the measured quantity is at specific value or not. For example it is desired to check if the room temperature is 21 or not or to check if the level of a tank is at specific level or not.
- This type of measurement is commonly used for Monitoring or ON-Off control. For example to create an alarm for water level in front tank or turn on and off a final element like pump in front figure based on the water level.
- Front figure shows two level point measurements. One to detect tank is full and another to detect tank is empty. Both sensors can generate alarm and also the LSH-101 (Level Switch High) can be used to close the valve to avoid spill over and the LSL-101 (Level Switch Low) can be used to turn off the pump when the tank becomes empty to protect the pump from running dry and burning.



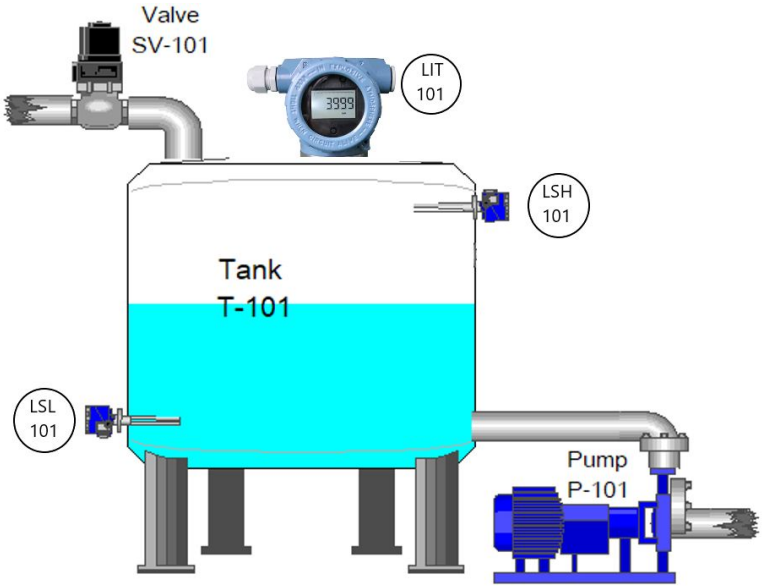
❖ Sensor Switch

- The sensors which provide the point of measurement are referred to as sensor switch like temperature switch, pressure switch, level switch and so on.

❖ Continuous measurement

- Continuous measurement is about the measured quantity value at every moment of time.
- For example a temperature sensor which shows the room temperature all the time.
- This type of measurement is used to indicate, control, record the measured quantity value.
- Front figure shows a level sensor at the top of the tank which can indicate the level of the tank at every moment and transfer this value to controller or computers. Therefore it is tagged as LIT-101 (Level Indicator Transmitter).

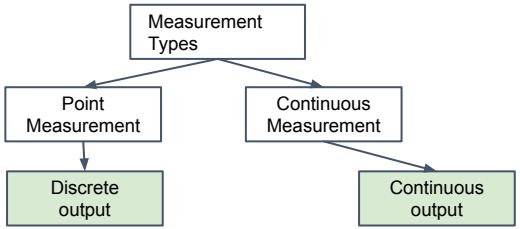
TIT - 102



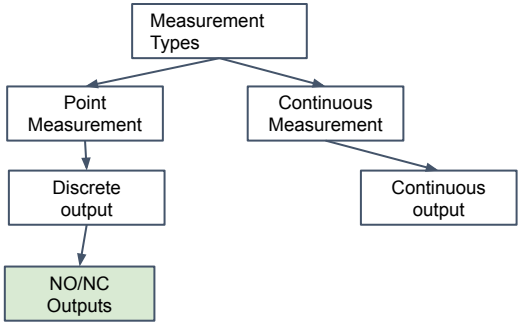
Sensor Output Types

Based on the sensor measurement types, the sensor output types are divided into two groups:

- Discrete outputs
- Continuous outputs



Discrete Outputs

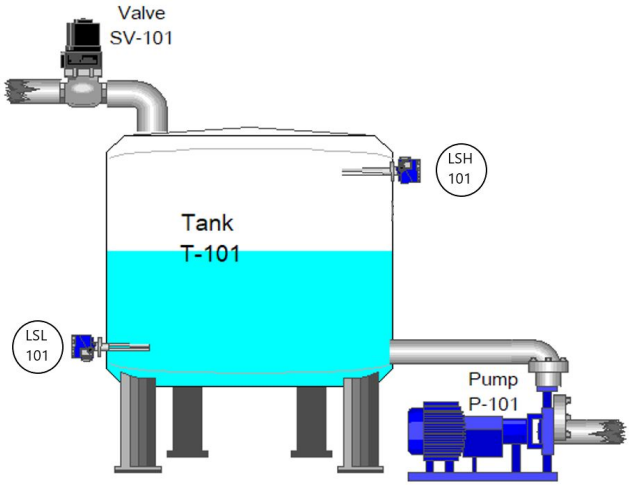


Discrete outputs have binary states like on-off switches. Either switches are closed or open.

Similar to switches they sensor switches have two types also.

- *Normally* Open output in short referred to as NO.
- *Normally* Closed output in short referred to as NC.

Normally in NO or NC referred to Normal condition for the sensor. Normal condition is when the sensor is not sensing the measured quantity.



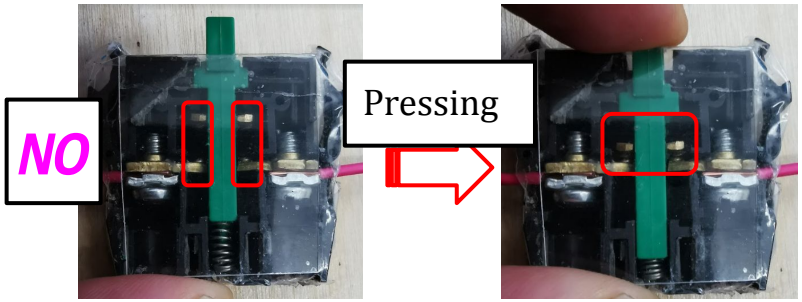
As example in front figure LSH is a level switch which is in its normal condition because it is not in contact with water and not sensing it. But LSL is in contact with water and sensing it.

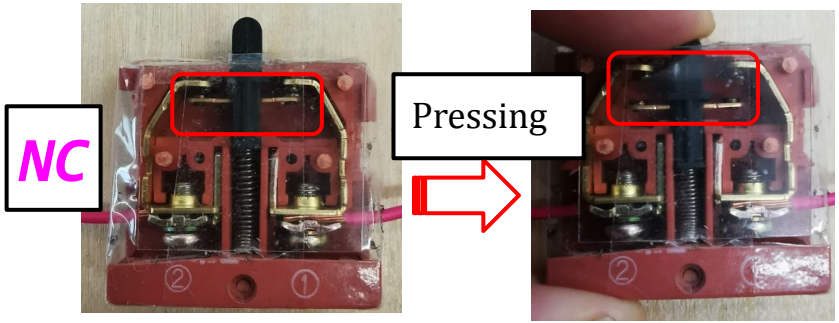
The information of NO or NC types for a sensor is provided by manufacturer in datasheets.

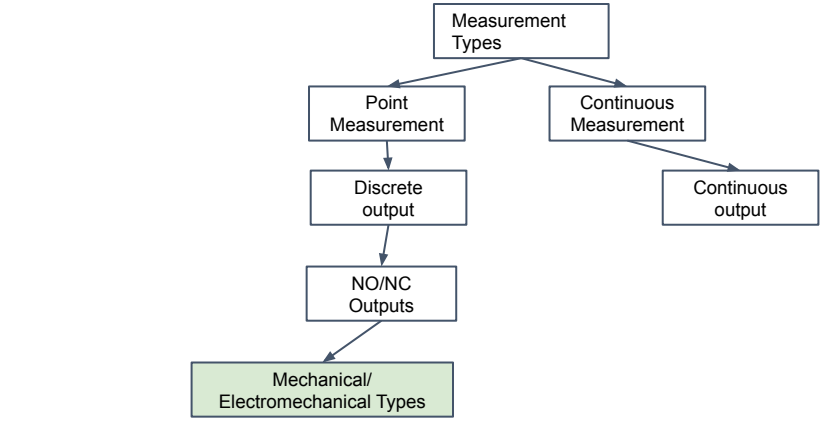
If the level switch types are given as NO, then at front condition the switch inside the LSH is open and sensor output is off and switch inside the LSL is closed and sensor output is on.

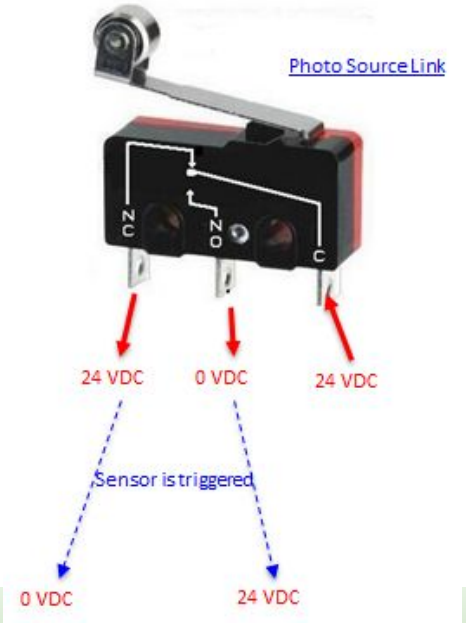
On contrary if the level switch types are given as NC, then at front condition LSH switch is closed and LSL is open which means sensor output is off.

Mechanical sensor switch Outputs







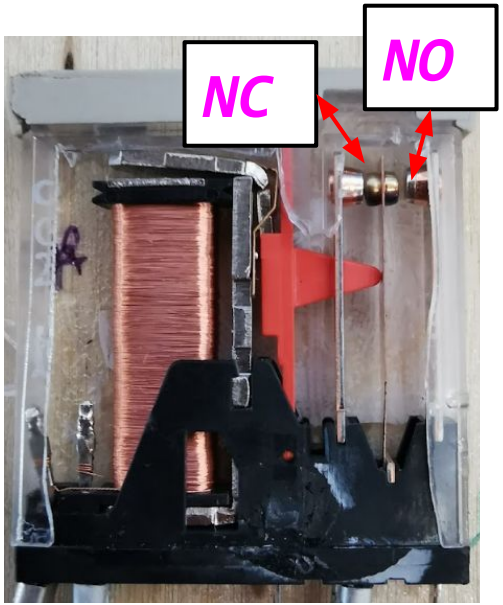


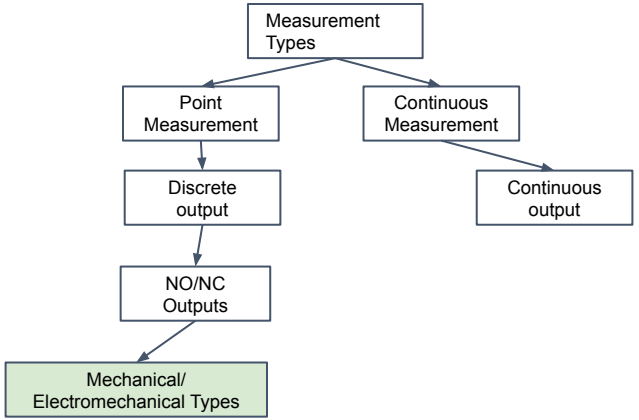
Example: This type of contact can be used to detect a door or window is open or closed

Electromechanical Sensors with Relay output

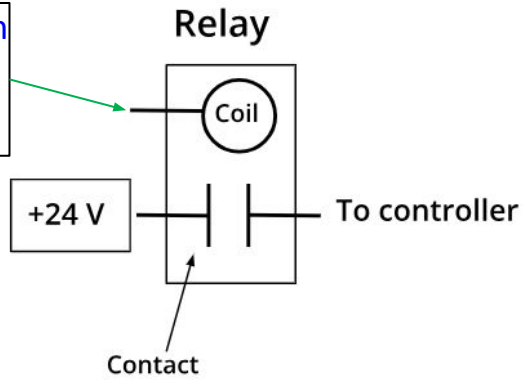
Play the video

https://www.youtube.com/watch?v=tbMX9USTyAI





The energy created from a condition change like temperature, pressure level and so on



NO or NC sensor?

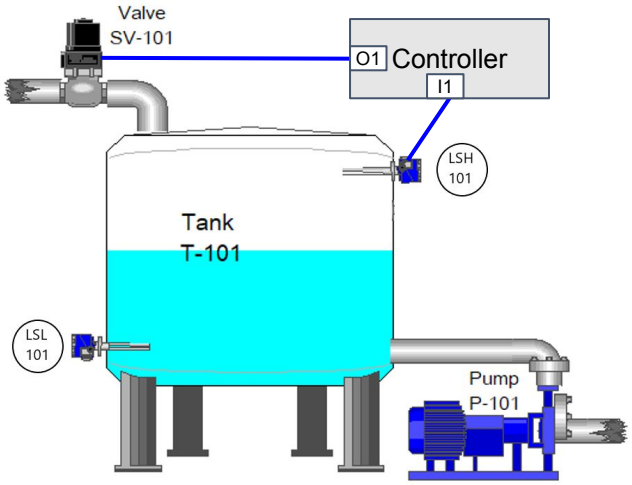
In front process the LSH-101 is used to close the valve when the tank is full. Question is which sensor is better to be selected, a sensor with NO or a sensor with NC?

Scenario 1 (NO sensor): Every time the sensor is in contact with the water, the sensor switch will be closed and controller will see the sensor output is on and then cut off the power from valve and valve will be closed.

If the connecting wire between sensor and controller is disconnected, misplaced, sensor is dysfunctional or etc. The water level will be detected by sensor but the controller would not know it to close the valve then the water will spill over.

Scenario 2(NC sensor): At front condition, LSH is in its normal condition and the sensor output will be on and the controller will receive power from the sensor. Every time the sensor is in contact with the water, it will go off and controller will see no power from sensor then the controller closes the valve accordingly.

Now if a failure in connection or in sensor happens before water goes high, the sensor will go off and the controller will not see power from the sensor then close the valve. The operator will see the tank is not full and valve is closed then realize something is not ok then sends for technician for troubleshooting. In this way the spillover will be avoided.



Regarding the front scenario the sensor with NC has advantage over NO sensor.

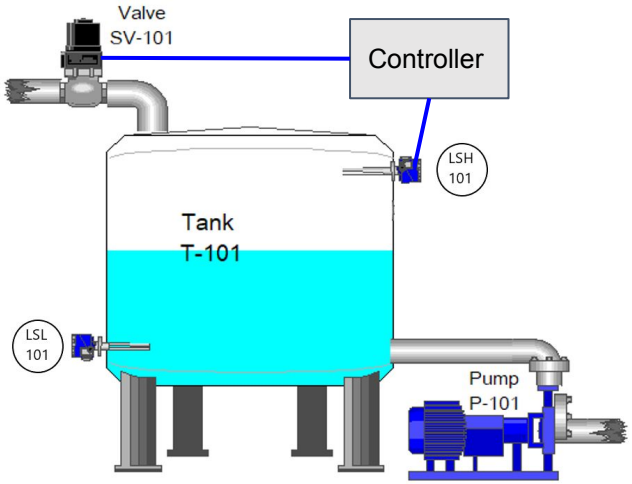
Process protection and human safety are factors in selecting the output type

NO or NC sensor?

Your turn:

In front whenever tank becomes empty the pump should be turned off. Running the pump empty will burn the pump.

For LSL which type of sensor would you select? NO or NC?

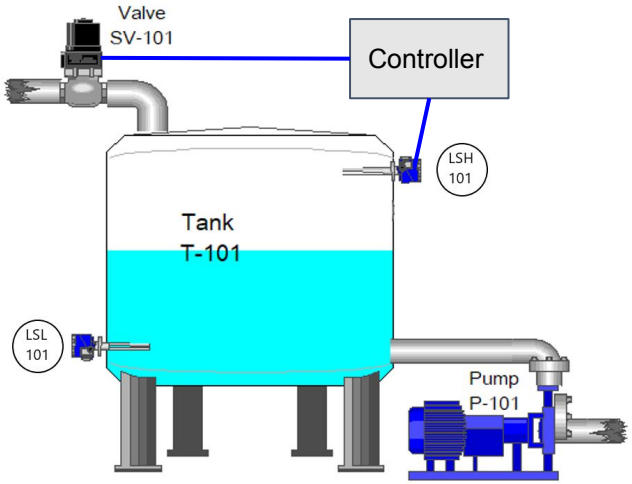


NO or NC sensor?

Your turn:

In front whenever tank becomes empty the pump should be turned off. Running the pump empty will burn the pump.

For LSL which type of sensor would you select? NO or NC?



Answer : NO

NO or NC?

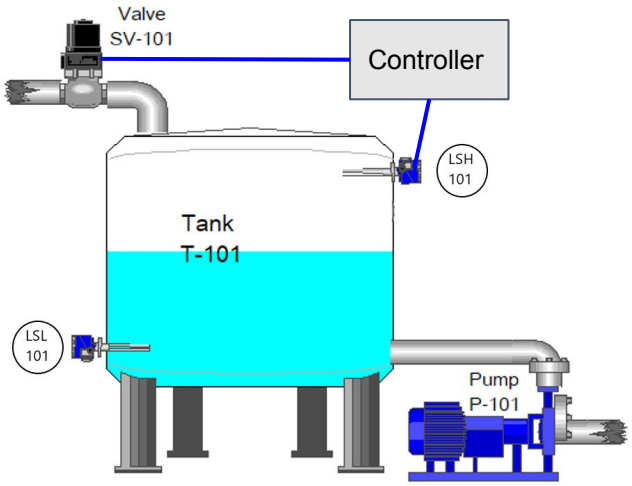
Question 1:

The valves SV-101 could have two types, NO and NC valve. “Normal” in NO or NC refers to status of valve when no power is applied to it. For example NO means that when no power is applied to the valve, valve will be open and NC means when no power applied valve will be closed.

Which type of valve will you select for the front application?

Question 2:

The pump has On and OFF push button. Which type of push button will you select for ON and OFF?



NO or NC?

Question 1:

The valves SV-101 could have two types, NO and NC valve. “Normal” in NO or NC refers to status of valve when no power is applied to it. For example NO means that when no power is applied to the valve, valve will be open and NC means when no power applied valve will be closed.

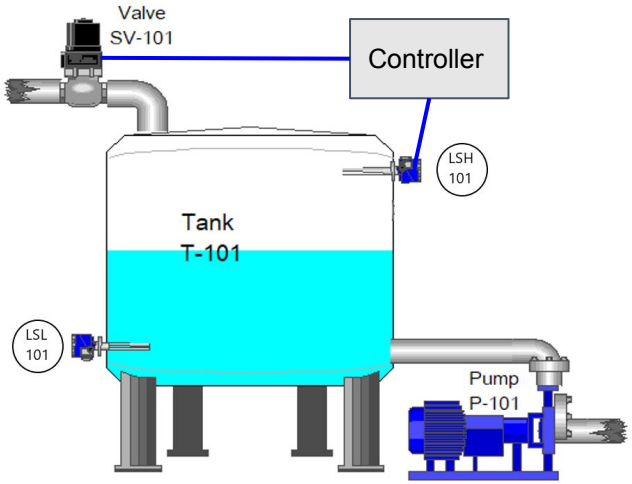
Which type of valve will you select for the front application?

Answer : NC

Question 2:

The pump has On and OFF push button. Which type of push button will you select for ON and OFF?

Answer : NO for ON and NC for Off

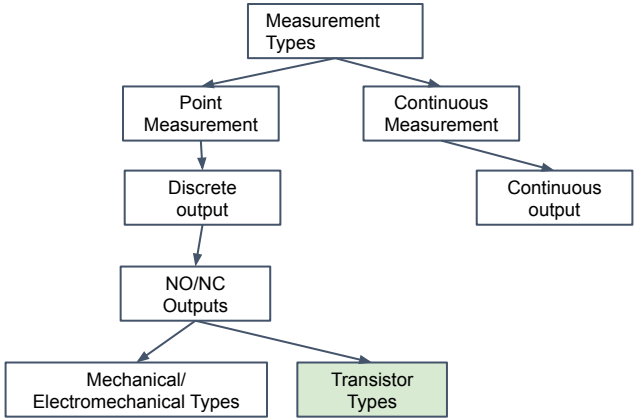


Sensors with Transistor Output

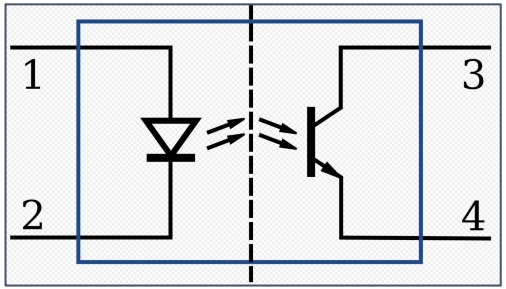
- Transistor is a semiconductor device.
- Can be configured and be used as switch.
- Does not have mechanical part

Properties:

- It can be turned on and off many times contrary to relay which has mechanical part
- Prone to short circuit and can be burned.
- Opening and closing time faster than relay



The electrical energy created from a condition change like temperature, pressure level and so on → Transistor



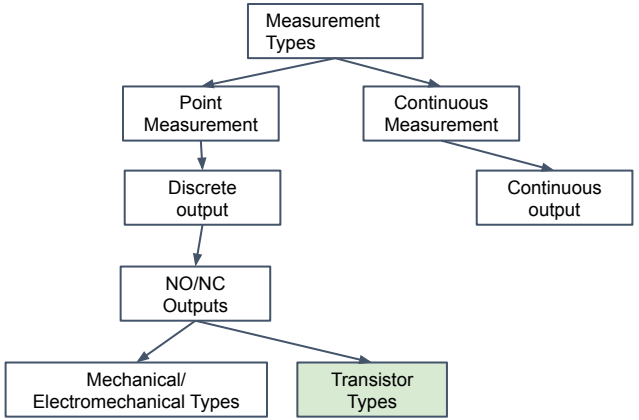
Optocoupler

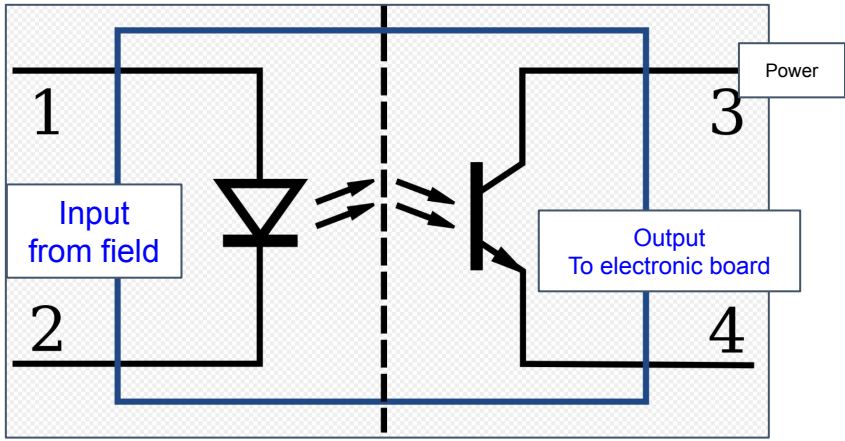
Optocoupler is a transistor base device. Which has two sides, input and output. The input side is made of LED and the output side is made of a light detector for example a phototransistor. This transistor on output works as light operated switch. When a power is applied to input side the LED will turn on. The light will activates the the transistor on output side and act as switch.

As the figure shows two sides are not connected by wire to each other therefore they are electrically isolated from each other.

Optocoupler can isolate the electronic circuit from field. If there is high voltage or short circuit on the field side it will not affect entire electronic circuit.

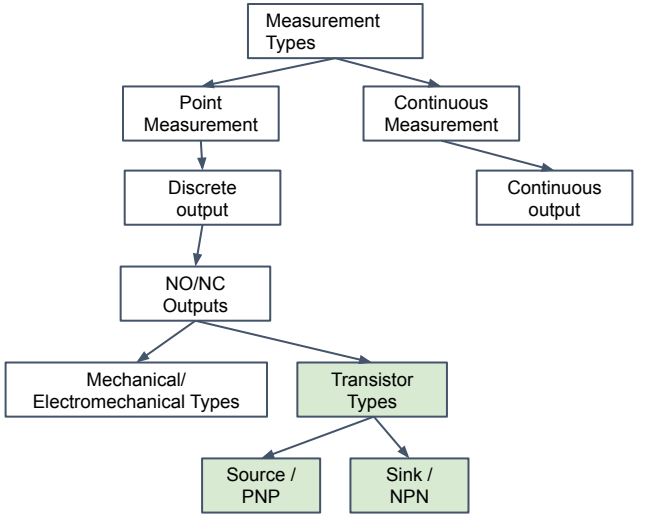
Optocoupler are being used as output of sensors , input or output of the PLCs and controllers in general.

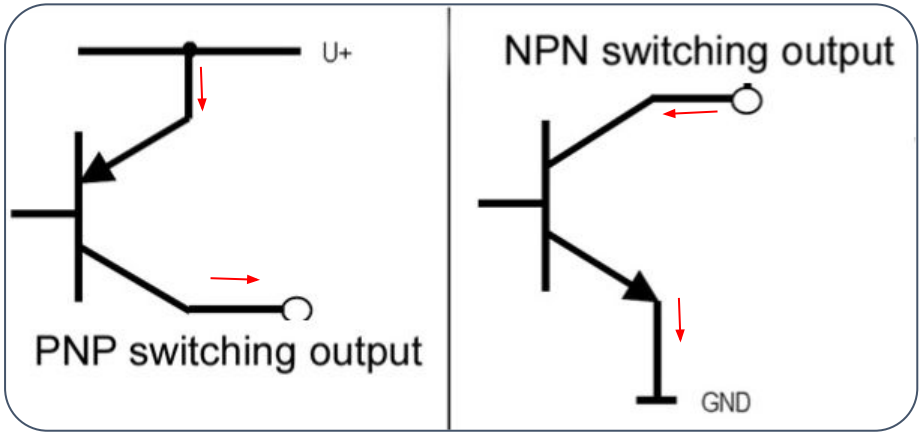




Transistor Output - Sink and Source

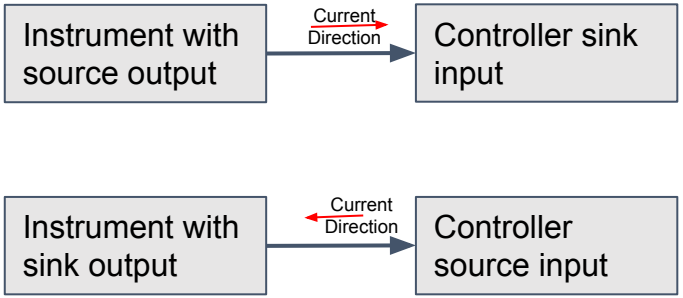
- There are two types of transistor output PNP and NPN. Figure front shows two typical wiring for the sensors with transistor outputs. The red arrow shows the electrical current direction.
- For an instrument with PNP output, the electric current flows out of device and when the output is on there will be voltage on the output. **The PNP output known as Source output also.**
- An instrument with NPN output will drain the current into instrument and present no voltage. **The NPN output known as Sink output.**



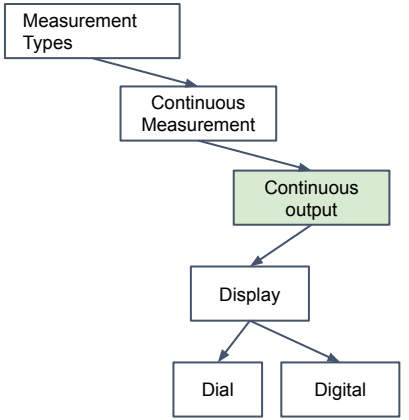


Sink and Source Connection

- If we want to connect two devices to each other and one of them is source, the other one has to be sink or vice versa.
- For example if a sensor should be connected to controller which has sink input, the sensor output type has to be selected as Source. The sensor send current out and the controller will drain it.
- If two sink or two source are connected to each other connectivity will be dysfunctional.
- Sensor output types or general wiring drawing can be found on the data sheet of the instrument.

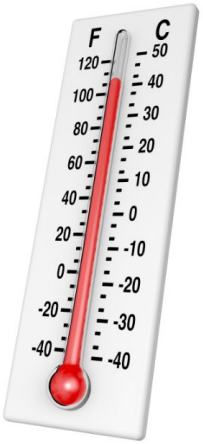


Continuous Outputs Display

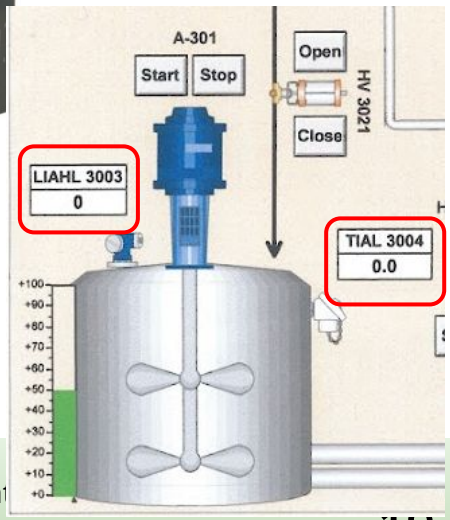


- Continuous Outputs presentation
  - Displays
    - Mechanical
    - Digitized Display
- In P&ID drawing are tagged with “I” which stands for Indicator like TI, PI or in below figure LIAHL-3003 (Level Indicator Alarm High Low)

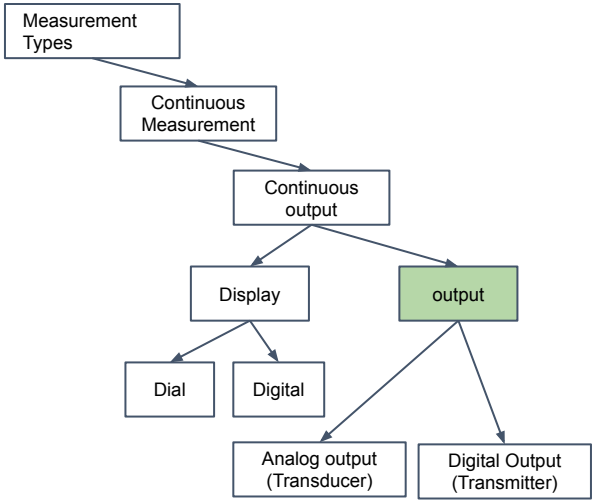
Mechanical Display



Digital Display



Continuous Outputs - Transducers



- Some sensors do not come with indicators. They convert the measured quantity to the electrical or mechanical form of energy as output signal.
- These signals can be used to display values or being used in the controller for the process control or monitoring.
- Pneumatic outputs common examples:
  - 0-15 psi , 3-15 Psi
- Electrical Outputs common examples:
  - 4-20 mA, 0-20 mA
  - 0-5 , 0-10 , 2-10 V
- These types of electrical outputs known as analog output and they change in relation with measured quantity. For example the sensor in the front figure generates 4-20 mA for 0-500 psi.
- These types of sensors are commonly known as Transducers and in P&ID symbols they are represented with "T" in second letter. Example PT-101 (Pressure Transducer -101)
- Transducers do not have digital device processing device like microcontroller in them.

Voltage Vs Current Output

In industrial environment the power cables for equipments like motors create an alternative magnetic field around them.

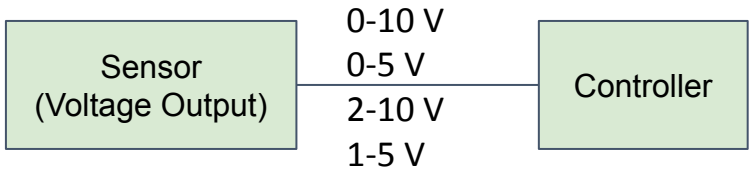
These varying magnetic field can induce voltage on the conductors including the wires which connects the sensor to the controller. The induced voltages are considered as noises which change the sensor voltage output received by controller.

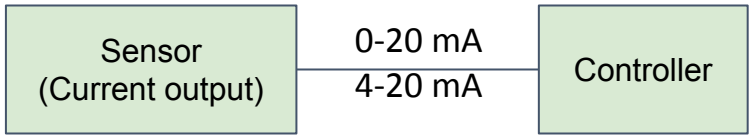
The sensors with current outputs are more immune to noises and preferred to instruments with voltage output.

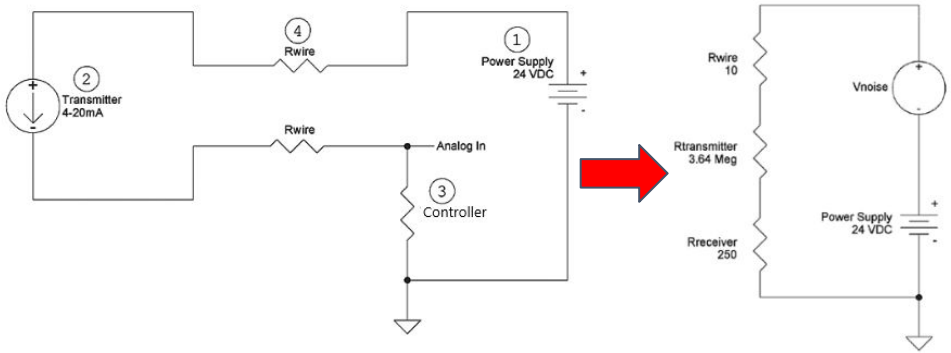
In front figure Number 2 is the transmitter which has large internal resistance. The induced voltage on wires divided by this resistance make it a very small current, therefore the controller receives almost the same 4-20 mA sent by transmitter.

Anyhow in presence of such noises the below practice are helpful to reduce the induced noises:

- **using a shielded cable for instruments and grounding the shield**
- **Using cables with twisted wires**
- **not laying instruments cable besides power cables**







Biased (Non-zero) Output Vs Zero Output

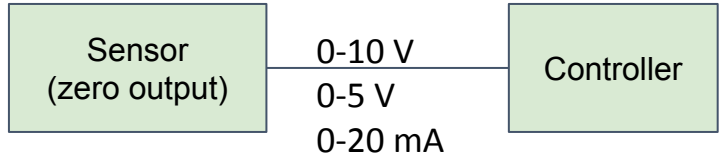
If a sensor generates a non-zero value at the minimum of the measurement range, it can be referred to as biased output (Non-zero output). For example, a sensor measuring 0-100 psi and provides 4-20 mA or 2-10 V or 1-5 V. This sensor output is 4 mA or 2 V or 1 V at 0 psi pressure.

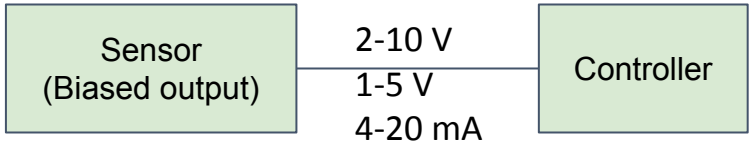
If a sensor generates a zero value at the minimum of the measurement range, it is referred to as zero output (non-biased output). For example, a sensor measuring 0-100 psi and provides 0-20 mA or 0-10 V or 0-5 V. This sensor outputs 0 mA or 0 V or 0 V at 0 psi pressure.

Which one?

For a zero output sensor, If the connecting wire between sensor and controller is disconnected, misplaced, loose or the sensor is dysfunctional or powered off, the controller will not see anything from sensor and it would not be able to realize this is due to the minimum input or for example disconnection.

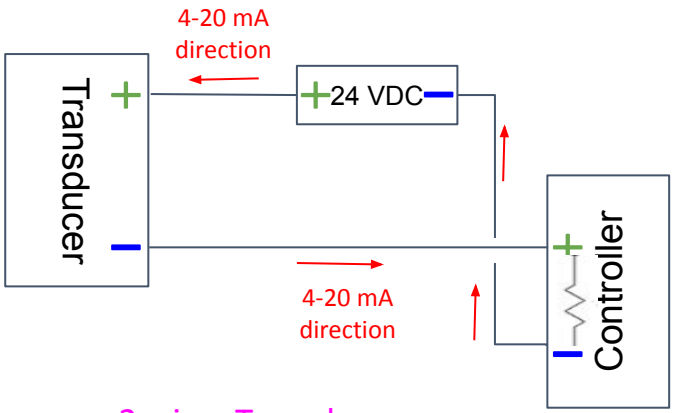
In case a sensor with Biased output is used the minimum measurement and disconnection can be differentiated in the controller and provide proper alarm for troubleshooting.



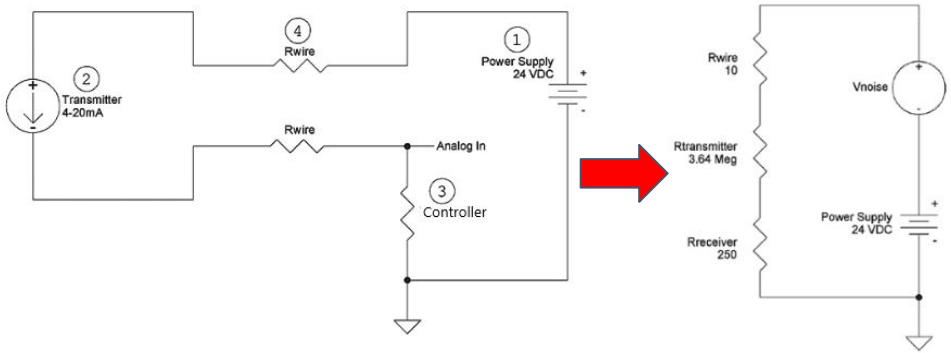


4-20 mA Output Properties

- It can be done by two wire instead of 3 or more wires.
- It can travel longer distance compare to voltage output. The voltage output can drop due to the wire resistance in the long distance wiring.
- It is less sensitive to noises.
- Because of 4 mA output, the wire disconnection or sensor failure can be detected.

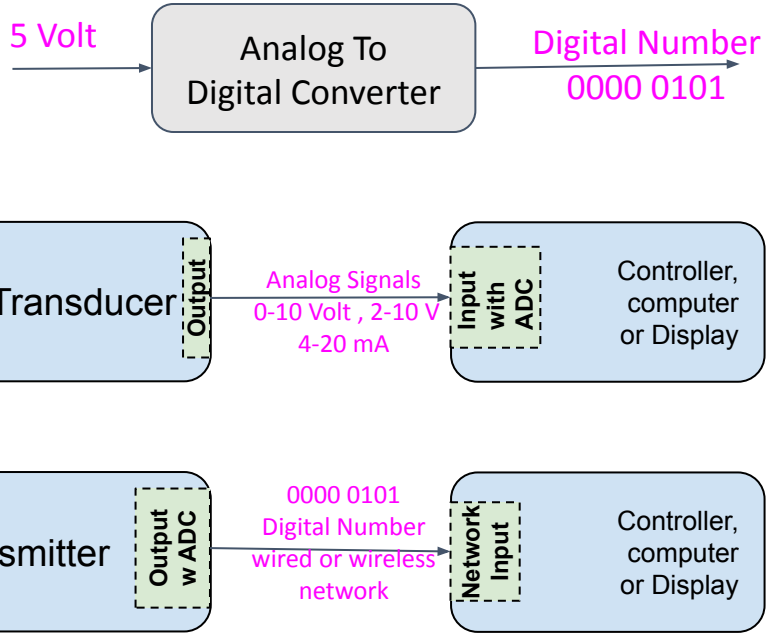


2 wires Transducer



Continuous Outputs - Transmitters

- To use the electrical signal in digital controller or display their value on digital display, the analog signal like 4-20 mA should be converted to digital number. Therefore the computers or controller are equipped with a Analog to digital converter known as ADC.
- Some sensors have the ADC inside them and convert the analog signal to digital format inside themselves therefore their output will be in format of digital number like 23.5 ℃ in binary format.
- To transfer the digital number to controller or remote display, a communication network are used.
- These type of sensors which come with digital converter and microcontroller in them are commonly known as Transmitters.
- The transmitters in P&ID symbols are represented with “T” in second letter also. Example PT-101 (Pressure Transmitter -101)



Continuous Outputs - Transmitters

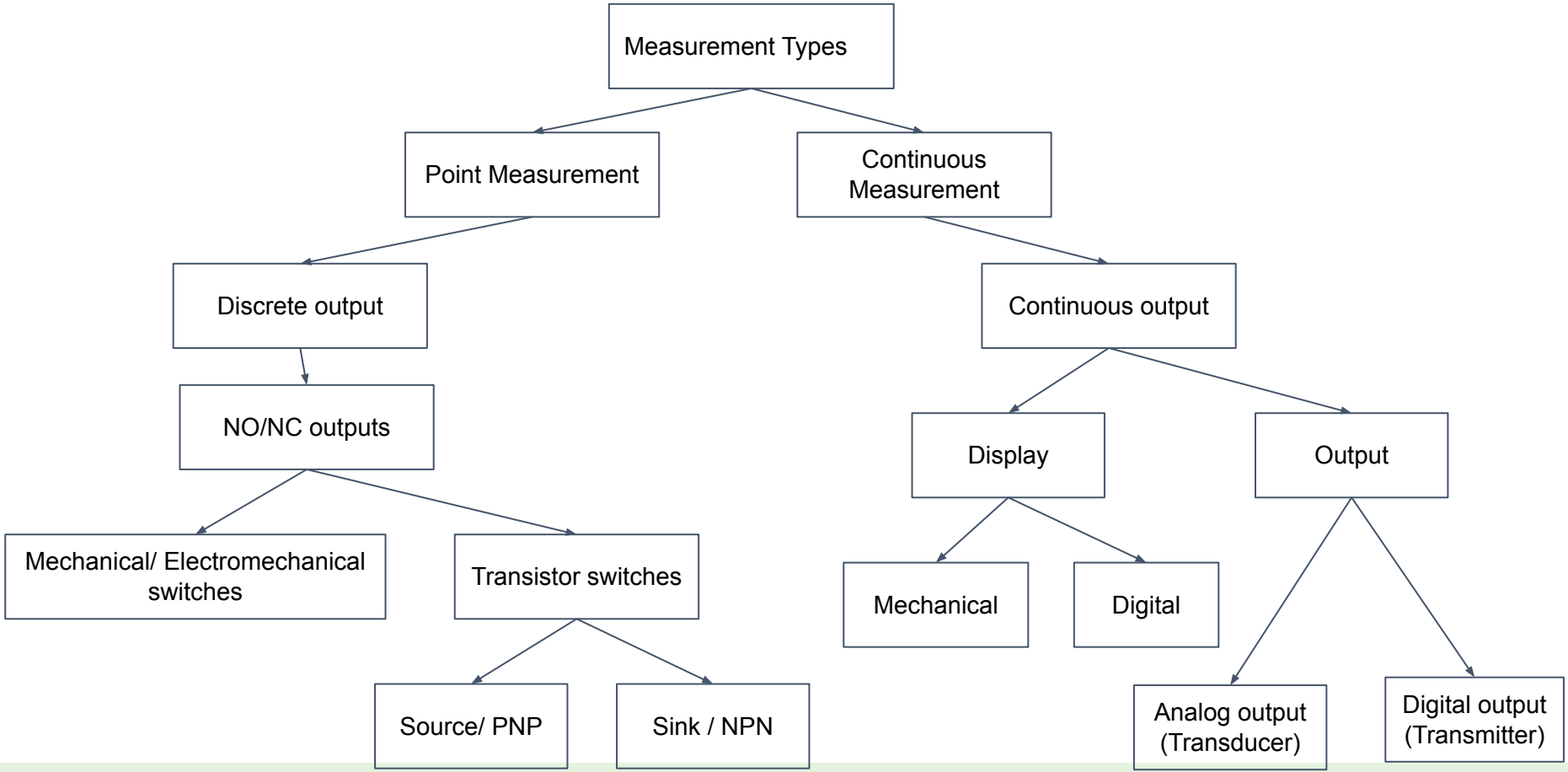
- Transmitter Communication Network examples:
  - Data Highway +
  - CanBus
  - Profibus
  - Modbus plus
  - Advanced protocol such as Ethernet/IP , Modbus TCP , Profinet, EtherCAT
  - IO-Link
- The Transmitters can send their value either through wired network or wireless network.

Attention: Transmitter or Transducer is not a firm standard name for these two types of sensors. They might be used alternatively. Some might refer to a transducer as transmitter or another way around. Some use these two terms (the same in this course) to differentiate between sensors with digital capability and sensors with analog outputs.

Transmitter Properties

- Reducing load on the controller processor by:
  - Converting analog to Digital in sensor head unit
  - Including the diagnostic data from the sensor for the controler
- Including fault tolerant methods and providing more reliable outputs
- Transferring data over communication network make it less prone to noises.
- Providing programmability (Buttons on sensor head) provides more adaptability and more options for adjustment
- The digital processing could make the sensor response time larger (slower sensor)
- They are more expensive compare to the transducers as their counterpart

Sensor Outputs

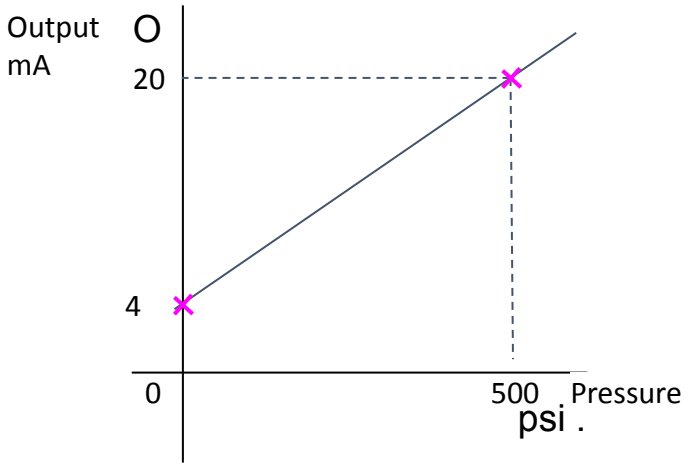


Conversion: measurement Range ↔ Output Range

In front figure you see a pressure transducer. As label shows the measurement range is 0-500 psi and output range is 4-20 mA. The relation between output and input is presented on front chart. Since graph is an straight line, these type of sensors are known as linear sensors

Question 1 - Let's assume this transducer is installed on one pipe to measure the pressure. We measure the output current by amperemeter and it shows 16 mA. What pressure is sensed by the sensor?

Question 2 - In another case, there is doubt that the pressure transducer is working properly. Therefore the pressure of the tank is measured with other accurate and reliable sensor and we know the pressure inside the pipe is 100 psi. We measure the the output current, what should we expect to read if the transducer is working properly?

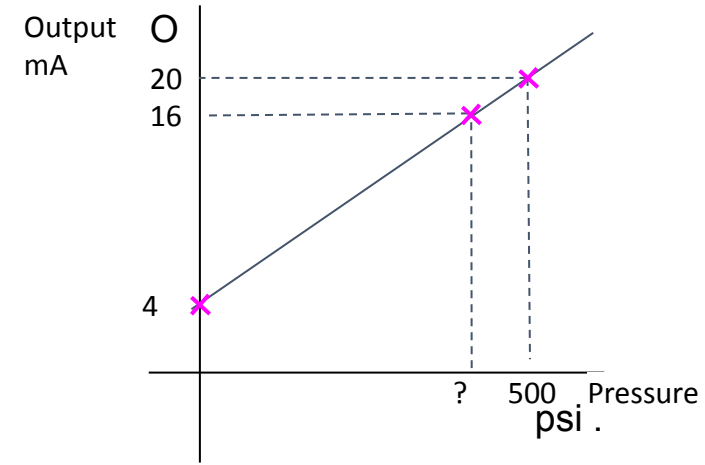


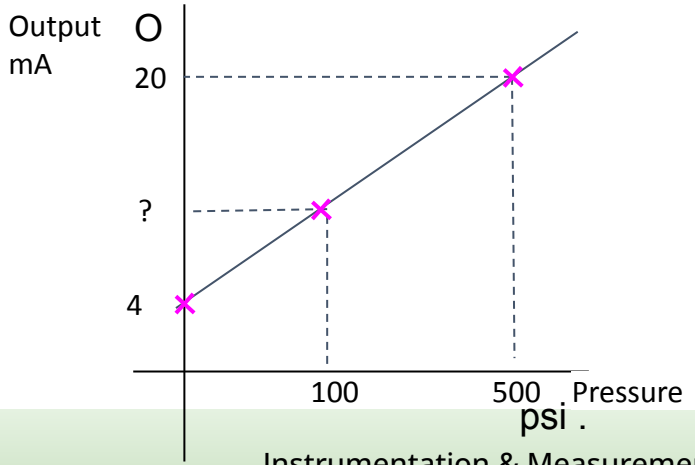
Conversion: measurement Range ↔ Output Range

In front figure you see a pressure transducer. As label shows the measurement range is 0-500 psi and output range is 4-20 mA. The relation between output and input is presented on front chart. Since graph is an straight line, these type of sensors are known as linear sensors

Question 1 - Let's assume this transducer is installed on one pipe to measure the pressure. We measure the output current by amperemeter and it shows 16 mA. What pressure is sensed by the sensor?

Question 2 - In another case, there is doubt that the pressure transducer is working properly. Therefore the pressure of the tank is measured with other accurate and reliable sensor and we know the pressure inside the pipe is 100 psi. We measure the the output current, what should we expect to read if the transducer is working properly?





Conversion: measurement Range ↔ Output Range

Solution:

To find the corresponding values we should find the line equation which is in general informat of

$$O = a \times I + b$$

- When line equation is found then we can put pressure value in it and calculate the output current or vise versa.
- b is the bias value or the value of output when the input is minimum

$$O = a \times I + b$$

$$a = \frac{\Delta O}{\Delta I} = \frac{20mA - 4mA}{500\,psi - 0\,psi} = 0.032\,\frac{mA}{psi}$$

$$4\,mA = 0.032 \times 0 + b \Rightarrow b = 4\,mA$$

$$O = 0.032 \times I + 4\,mA$$

Question 1:

$$O = 0.032 \times 100 + 4 = 7.2\,mA$$

Question 2:

$$16 = 0.032 \times I + 4 \Rightarrow I = 375\,psi$$

Zero Drift & Sensitivity Drift

The sensors (Transducer or transmitters) are set up to specific input and output range and they are matched to each other. For example if a sensor is designed to have 0-100 ℃ input range and 4-20 mA output range, this sensor convert the temperatures from 0 to 100 to 4 -20 mA respectively.

Sometimes, for example after long time use of sensor and wear out or environmental condition change or etc the sensor input and output might not match. For example above sensor might deliver 18 mA at 100 ℃ instead of 20 mA or deliver 5 mA at 0 ℃ instead of 4 mA. In this case the sensors known to be out of Calibration.

The mismatch between input and output can appear in two ways known as zero drift or sensitivity drift. (sensitivity is defined as slope of line)

If the sensor is out of calibration then the mapping between input and output should be adjusted. This process is called Calibration.

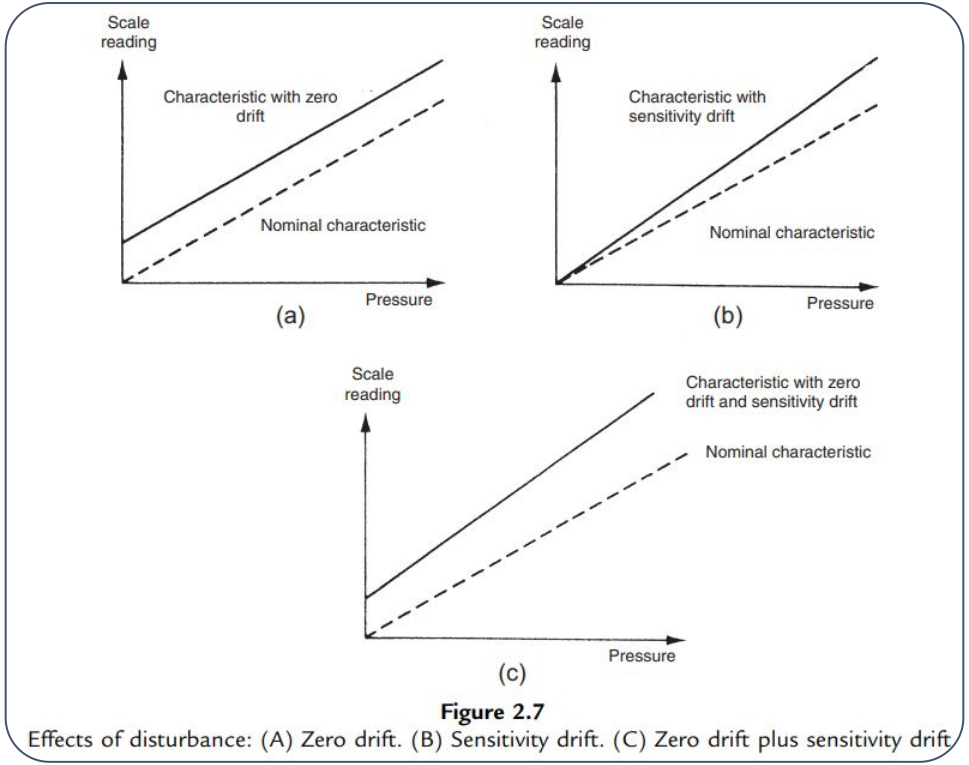


Figure 2.7
Effects of disturbance: (A) Zero drift. (B) Sensitivity drift. (C) Zero drift plus sensitivity drift

Calibration : Adjusting Input/Output Ranges

To calibrate, the sensors usually come with two knobs, Zero & Span.

The Zero is used to match the minimum of the input range to the minimum of the output.

For example a temperature sensor which suppose to measure 0-100 ℃ and provide 4-20 mA. When put the sensor in 0 ℃ iced water instead of getting 4 mA the sensor provides 5 mA. This is a zero drift, to make the output 4 mA we can turn the zero knob until output becomes 4 mA.

The span is used to adjust the maximums. For example the above temperature sensor can be put in a 100 ℃ boiling water then by turning the span knob make the output 20 mA.

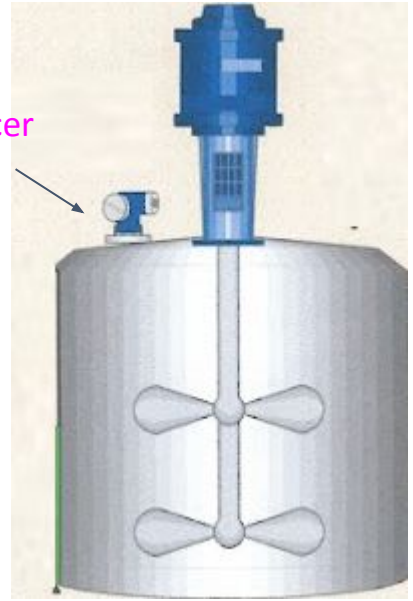
End

Homework 1

There is a level transducer measuring level of a tank. The measurement range is 0.3 to 1.8 meter and the output range is 2-10 volt. The transducer is linear sensor like previous example.

Question 1 - If the sensor output voltage is 5 volt what is the level of the tank in meter?

Question 2 - If the level of the tank is 1 meter what would be the the sensor output voltage value?



Homework 2

In front P&ID TT-301 is a temperature transducer. Let's assume the measurement range of the transducer is -50 to 150 ℃ and its output range is 0 - 20 mA

Question 1 - If the sensor output current is 8 mA. what would be the tank temperature in ℃ ?

Question 2 - If the temperature is 120 ℃ what would be the the sensor output current?

Based on data sheet the transducer is linear sensor