Baumer Guideline for Analog Sensor Interfaces

Scope

This document describes the functionality of active analog sensor interfaces such as current and voltage signaling. It is intended to provide support for the selection of the most suitable analog sensor interface and its implementation. All information given must not be understood as a specification and Baumer does not assume any responsibility for the information provided.

Contents

1 General

Analog interfaces have been established on the market for a long time. Apart from its historical significance, no other type of interface has achieved such a high degree of interoperability (interchangeability between different manufacturers) to date, which is particularly advantageous for long-lived machines and systems when sensors have to be replaced. Despite the many more modern digital interfaces and buses, acceptance among users is still relatively high because there is a great deal of experience with them and diagnosis in the event of a fault can be carried out clearly with simple aids.

2 Current signaling

2.1 Functionality of current signaling

A current source impresses a current signal into the connected current loop. The magnitude of the current signal corresponds to the measuring signal via an appropriate scaling. Common current signalization ranges for the measuring information range 0 ... 100 % are 0 ... 20 mA and 4 ... 20 mA.

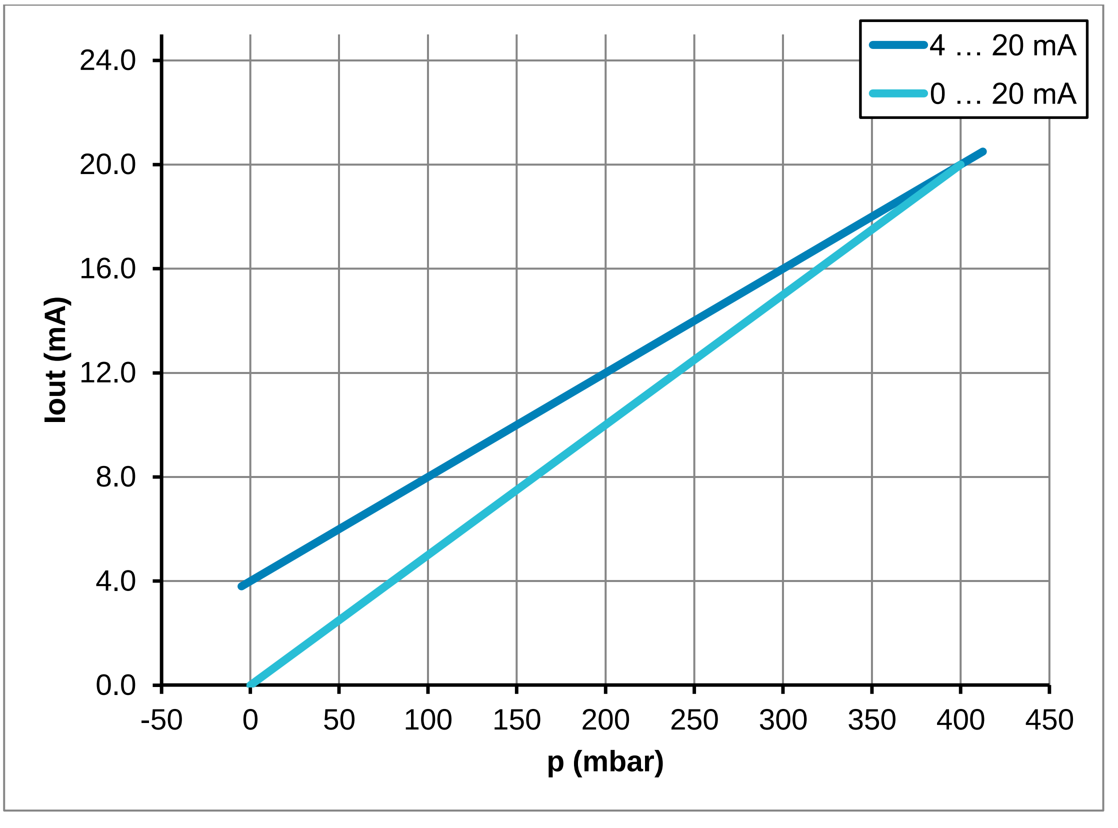

Figure 1: Measurement information and current signal by example of a 0 ... 400 mbar pressure sensor

2.2 Current signaling ranges

2.2.1 0 … 20 mA (Dead-Zero-Signal)

The measurement information "zero" means that no current signal is flowing. Therefore, a wire break or short-circuit of the connection lines cannot be detected clearly. In addition, there is no two-wire current loop, since with current signals close to zero there would be practically no power available to supply a sensor. This is why this type of signaling is hardly used in process automation today.

2.2.2 4 … 20 mA (Live-Zero-Signal)

The current signal for the measuring information "zero" is 4.0 mA. Thus a wire break or short-circuit can be reliably detected and sufficient power is still available with a two-wire current loop to supply the sensor. The current range limits of 4 mA and 20 mA for the measurement information and beyond this range for the failure information is the most commonly used standard today. NAMUR Recommendation NE 43 gives references for standardization of the signaling of failure information.

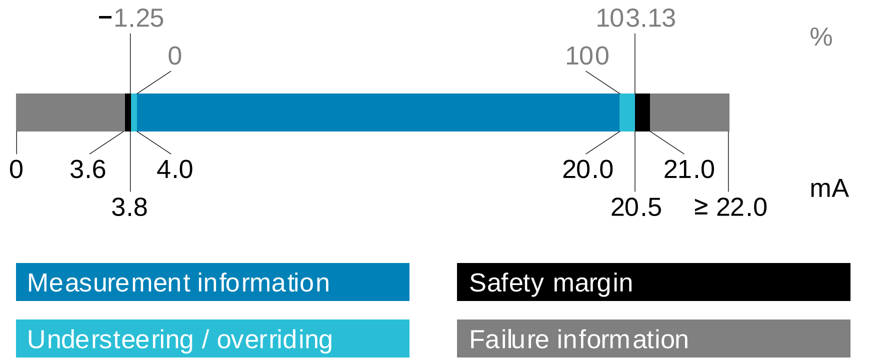

Figure 2: Definition of the failure information for the 4 ... 20 mA current signalization acc. to NE 43

Understeering and overriding indicate valid measurement information. A sensor can thus signal measured values beyond its nominal measuring range limits. For example, a pressure sensor with a measuring range of 0 ... 400 mbar can thus output -5.0 mbar to 412.5 mbar. In this case, a slight negative pressure (vacuum) can still be measured, which can be decisive for hydrostatic level measurements, for example. Configurable sensors usually allow the setting of understeer or override limits.

Figure 3: Current signaling range by example of a 400 mbar pressure sensor

The respective safety margin is used to clearly differentiate between measurement information and failure information. No current signal should be output in these ranges. The assignment of current values for the failure information is defined or adjustable device-specifically. The NAMUR Recommendation prescribes at least one current value for this. For power-critical devices, this can only be selected in the range ≥ 21 mA. The failure information with 0 mA is understandably reserved for wire breaks, as it’s a short-circuit to GND (0 V). A short-circuit against the positive supply voltage generates an overflow error.

Other failure information may include

- Measurement information invalid or not (no longer) available
- Sensor element defective (e.g. with Pt100 sensor break or short-circuit)
- Self-test not successful
- Sensor element worn, e.g. due to corrosion
- Sensor dry (e.g. continuous level sensor not immersed)
- Supply voltage too low

2.3 Types of current signaling

2.3.1 Two-wire current loop

In the two-wire current loop, the sensor is a passive current sink. For this purpose, the analog input of the control device must provide a supply voltage.

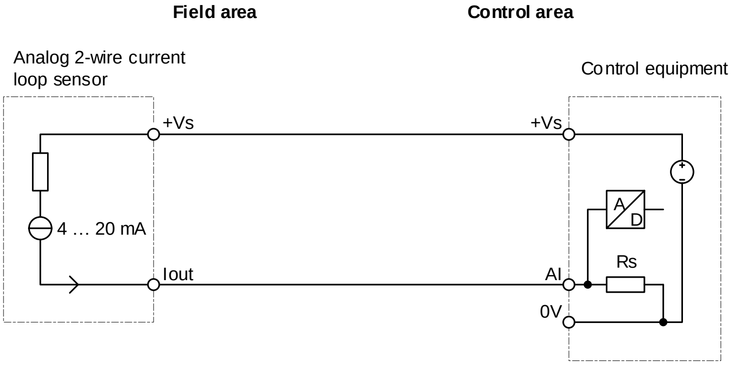

Figure 4: Signaling with two-wire current loop

The sensor has only two connections to the supply voltage. The drawn supply current is proportional to the measurement signal. The sensor always regulates its electrical resistance so that the setpoint value of the current signal always flows, regardless of the magnitude of the supply voltage provided or its source resistance. As a rule, the smallest current signal is 3.6 mA (for error signaling), which presents a great challenge for power management. Assuming a minimum supply voltage of 10 V for the sensor, only 35 mW supply power is available for the sensor.

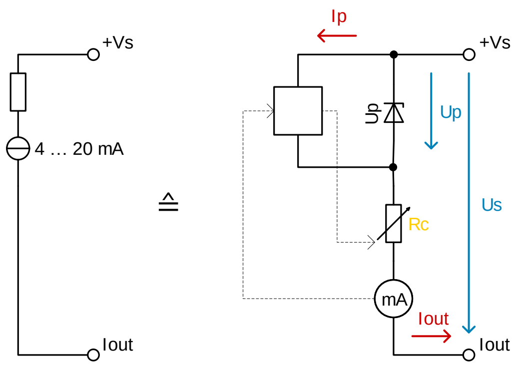

Figure 5: Schematic diagram of a two-wire current loop sensor

The sensor draws a certain supply power from the supply voltage Up and the supply current Ip in a bypass of the current loop. It continuously measures the flowing current signal Iout and adjusts the virtual resistance Rc so that it always corresponds to the desired measurement information. In this way, fluctuations in the supply voltage +Vs, in the supply current Ip and other resistances such as shunts or displays in the current loop are compensated. This causes the terminal voltage Us to change accordingly.

The sensor can determine its own minimum supply voltage requirement Up and thus obtain sufficient power even with small current signals. This is at the expense of the maximum possible external shunt resistance Rs, since there is less voltage reserve in the current loop, especially with the max. current signal (e.g. 23 mA). Most sensors maintain a constant supply voltage requirement Up over the current signal range, e.g. with a Zener diode. More complex sensors increase their supply voltage requirement Up with decreasing current signal Iout. This enables them to supply themselves with constant power over the entire current signal range. A minimum supply voltage dropping from 18 V to 9 V for the current signal range of 3.5 - 23 mA is practical, for example; at least a supply power of 18 V × 3.5 mA = 63 mW is then available. With the largest current signal of 23 mA, the supply voltage requirement Up is correspondingly low at 9 V, so that there is no longer such a large limitation for the max. shunt resistance Rs as there would be at 18 V. The corresponding characteristic curves or calculation formulas can be found in the data sheet of the respective sensor (see also section 2.5).

Hazardous areas

The two-wire current loop has its greatest significance in hazardous areas with the concept of intrinsic safety. When the circuit is earthed, only a single-channel barrier is required. The shunt resistance Rs must be in the positive supply line, which requires a special analog input.

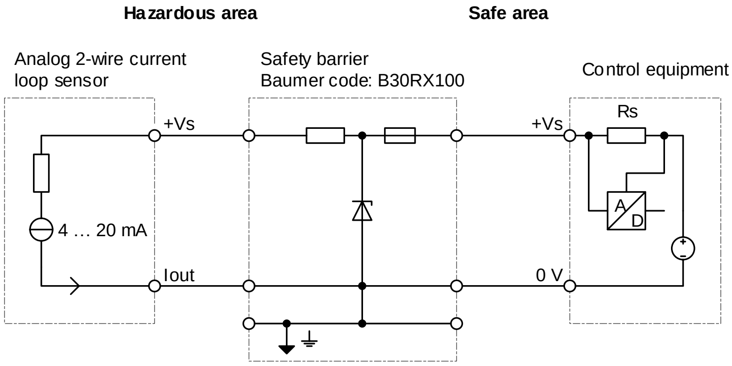

Figure 6: Intrinsically safe, grounded field circuit with single-channel barrier

A dual-channel barrier is required for a non-grounded circuit. The shunt resistor can then have 0 V reference as usual.

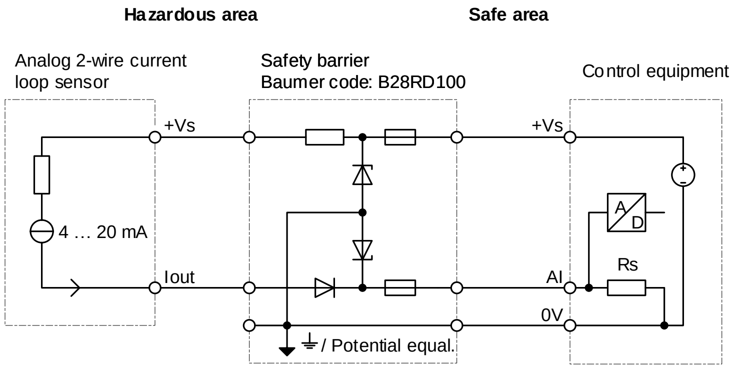

Figure 7: Intrinsically safe, ungrounded field circuit with dual-channel barrier

There are also active isolators available, which include galvanic isolation. They work like a classic isolation amplifier but with additional voltage and current limitation to provide an intrinsically safe field circuit for the hazardous area.

2.3.2 Three-wire current output

Depending on the connection type of the supply voltage, a distinction is made between passive and active circuit. For the sensor itself there are no differences.

2.3.2.1 Passive Circuit

With the passive circuit the signaling is the same as with the two-wire current loop. However, the sensor can output an additional current to the GND connection for its supply requirements. This makes power management much easier to implement. If the active voltage source of the analog input in the control device is used for supply, it must be able to provide the entire current requirement of the sensor, i.e. possibly considerably more than 20 mA.

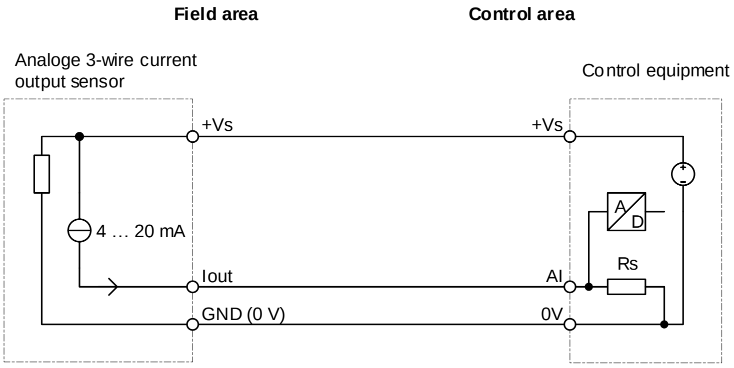

Figure 8: Passive circuit with three-wire current output

2.3.2.2 Active Circuit

The power supply can also be provided by a separate power supply unit, i.e. the supply and evaluation unit are separate, possibly even over a greater distance. This concept is advantageous if a separate supply network is available. The so-called externally supplied sensor is then in an active circuit, although it is the same sensor as in the passive circuit according to section 0.

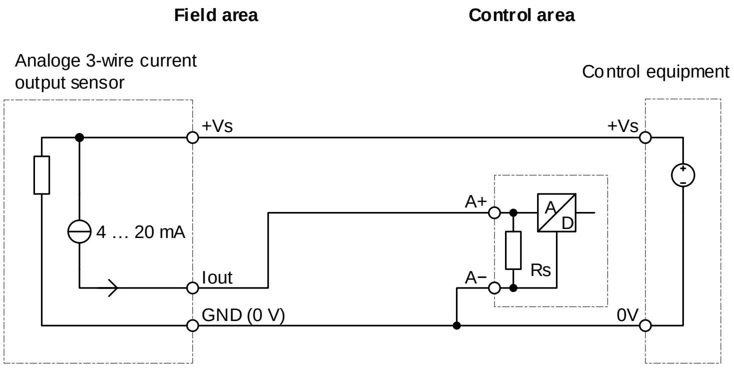

Figure 9: Active circuit with three-wire current output

2.3.2.3 Four-wire current output with electrical isolation

With certain sensors the current output is available galvanically isolated. The processing unit can thus have a different potential reference for power supply. As a rule, however, this concept does not replace the requirement for a mandatory galvanic separation between field and control area.

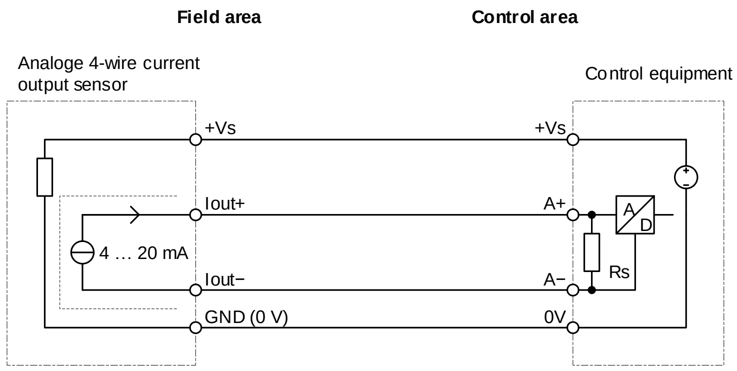

Figure 10: Signaling with galvanically isolated four-wire current output

With the four-wire current output, the current source is active, i.e. the analog input of the control device does not have to provide an active voltage supply. It should also be noted that the supply current of the sensor can be significantly higher than 20 mA (e.g. 150 mA), which may not be provided by the sensor supply of an analog input.
An alternative version exists for devices with mains connection. The supply voltage +Vs is obtained via an integrated power supply unit.

2.4 Current loop display unit

Each of the current signaling types shown above contains a current signal circuit. A current loop display unit can be integrated into this circuit at any position, which usually generates its supply voltage from the signal current. The additional voltage loss in the current loop must be taken into consideration when checking the maximum load. The current loop display unit must not be connected to a reference potential such as earth or GND (0 V). Otherwise the control unit will receive no signal or a distorted signal.

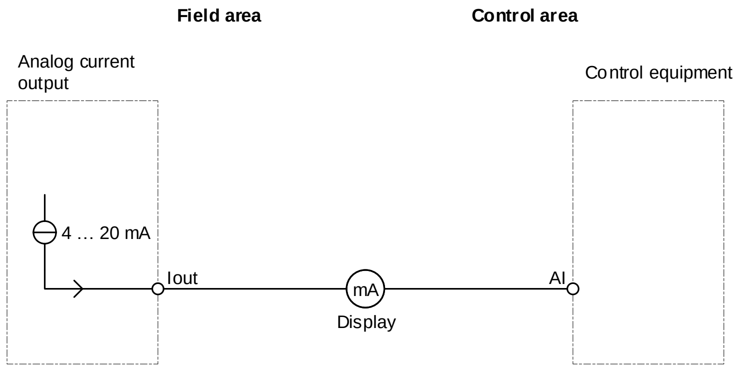

Figure 11: Current loop display unit in a current signal

2.5 Checking the burden

The aim of the check is to determine whether the sensor still receives sufficient supply voltage in the worst case. This can be done manually using the voltage method or by comparing the burden specifications.

2.5.1 Voltage method for passive current output

- Refer to the sensor data sheet for the minimum supply voltage (e.g. 8 V) and the maximum current signal of the current output (e.g. 23 mA).

- From the analog input, the values for the min. available supply voltage (e.g. 19.2 V) and the size of the shunt resistance Rs (e.g. 125 Ω) must be known.
- The cable resistance Rc is calculated from the cable length and the data sheet information per wire multiplied by a factor of two (for outgoing and return conductors). In the example we assume 25 Ω, this corresponds to a length of 500 m with a cable cross section of 0.34 mm2.
- If there are other devices, such as a display, in the current loop, its maximum voltage drop is of interest (e.g. 6.5 V).

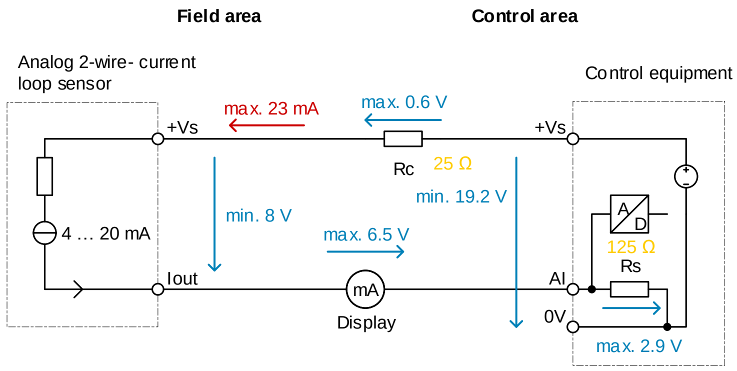

Figure 12: Voltage conditions at a passive current output

First the voltage drop at the shunt resistor Rs and cable resistance Rc is calculated:

23 mA × 125 Ω = 2.9 V

23 mA × 25 Ω = 0.6 V

Then all consumer voltages are subtracted from the supply voltage +Vs:

19.2 V – 0.6 V – 8 V – 6.5 V – 2.9 V = 1.2 V

The result is the voltage reserve to supply the sensor. If this is positive, the check is confirmed. If the result is negative, the sensor no longer receives the minimum required supply voltage, especially at max. signal current. In this case, either the parameters must be adjusted, e.g. the minimum supply voltage from the control unit must be increased, the shunt resistance Rs must be reduced, the cable cross section must be increased or the display must be omitted. If possible, the display can also be operated in a mode with reduced brightness of the backlight, which reduces its voltage drop.

2.5.2 Voltage method with active current output

- The data sheet of the sensor contains the specifications for the max. output voltage (e.g. 16 V) and the max. current signal of the current output (e.g. 22 mA).
- From the analog input, the value for the size of the shunt resistance Rs (e.g. 125 Ω) must be known.
- The cable resistance Rc is calculated from the cable length and the data sheet specification per wire times factor two (for outgoing and return conductor). In the example we assume again 25 Ω.
- If there are other devices, such as a display, in the current loop, its maximum voltage drop is of interest (e.g. 6.5 V).

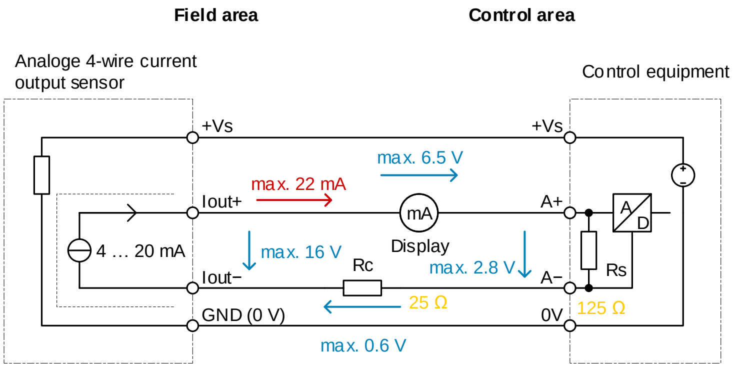

Figure 13: Voltage conditions at an active current output

First the voltage drop at the shunt resistor Rs and cable resistance Rc is calculated:

22 mA × 125 Ω = 2.8 V

22 mA × 25 Ω = 0.6 V

Then all consumer voltages are subtracted from the maximum output voltage:

16 V – 6.5 V – 2.8 V – 0.6 V = 6.1 V

The result is the voltage reserve to drive the current loop. If this is positive, the check is confirmed. If the result is negative, the current output can no longer drive the maximum current signal. In this case either the shunt resistance Rs must be reduced or the display must be omitted. If possible, the display can also be operated in a mode with reduced brightness of the backlight, which reduces its voltage drop.

2.5.3 Burden method (only for two-wire current loop)

In the current loop, each device or component can be characterized by the so-called "burden". This is the effective ohmic resistance in the current loop. For constant resistances, such as shunts, the resistance is independent of the signal current. However, since, for example, the current sink of a sensor must change its resistance with the current signal, the burden is always specified for a signal current of 20 mA.

- The specification for the minimum supply voltage (e.g. 8 V) is taken from the sensor data sheet.
- The value of the max. connectable load must be known from the input card of the control device, e.g. 650 Ω.
- The cable resistance Rc is calculated from the cable length and the data sheet specification per wire multiplied by a factor of two (for outgoing and return conductor). In the example we assume again 25 Ω.
- If there are other devices, such as a display, in the current loop, its maximum voltage drop is of interest (e.g. 6.5 V).

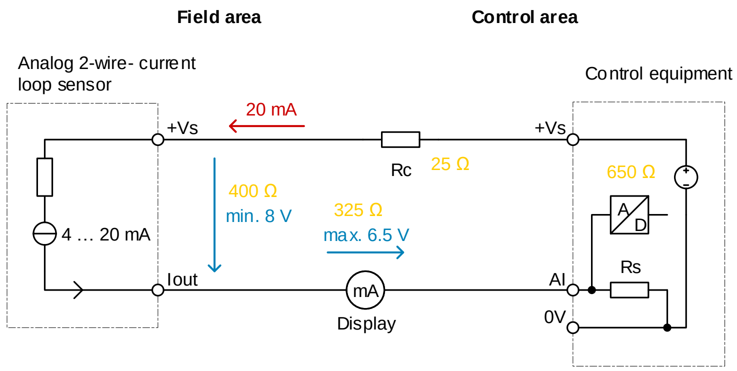

Figure 14: Resistance conditions at a passive current output (burden method)

The burden of the sensor is:

8 V ÷ 20 mA = 400 Ω

The load of the display is calculated:

6,5 V ÷ 20 mA = 325 Ω

The burden of the cable resistance is the calculated value of Rc = 25 Ω.

The sum of the load from the connected devices sensor and display is therefore:

25 Ω + 400 Ω + 325 Ω = 750 Ω

This is greater than the maximum load that can be connected from the specifications on the entry card with 650 Ω. This means that the function is not guaranteed, at least for larger current signals. As an alternative we are looking for the optional setting for a reduced brightness of the display and find 4.5 V for this in its data sheet. The alternative load of the display is then calculated:

4,5 V ÷ 20 mA = 225 Ω

The alternative sum is thus:

25 Ω + 400 Ω + 225 Ω = 650 Ω

The result is equal to the maximum allowed load of 650 Ω which means that safe operation is exactly what is needed now.

The specifications of the max. connectable load in the data sheet of the manufacturer of the input card take into account the worst case, i.e. the min. possible operating voltage and thus the min. possible supply voltage available for the sensor. If the lower tolerance limit of the minimum operating voltage is not used, the function can still be guaranteed. If necessary, this can be checked with the voltage method procedure.

2.6 HART

HART stands for «Highway Addressable Remote Transducer». HART is a digital data protocol which is superimposed on the current signal. For bit coding, AC voltage or AC current signals are modulated with two different frequencies (frequency shift keying), namely 1200 Hz for logic "1" and 2200 Hz for logic "0". The rectifying component of the modulated signal is zero, so it does not disturb the evaluation for analog current signaling as a rule. To enable modulation, the total resistance of the current loop must be at least 250 Ω. The bit rate of the bidirectional possible data transmission is 1200 bit/s.

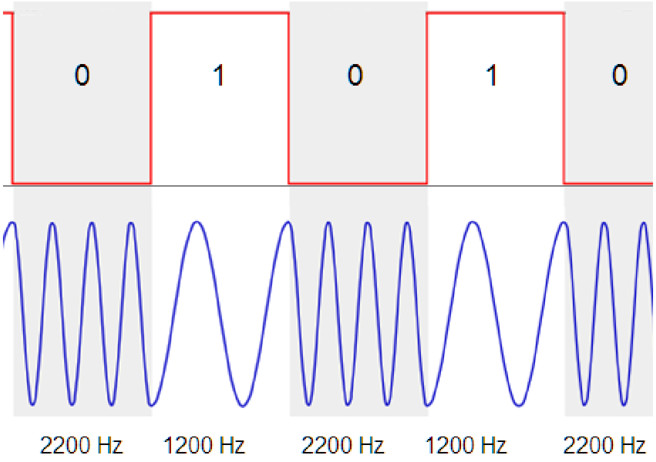

Figure 15: Modulation of the HART signaling by frequency shift keying

In addition to the additional digital and thus undistorted information of the primary sensor measured value, secondary additional information such as further measured values or diagnostic data can be transmitted. It is also possible to exchange measured values between devices. In addition to display instruments, a conductivity meter, for example, can also receive the measured temperature value for temperature compensation from an external temperature sensor. Many devices also offer a parameter setting option. Mandatory universal and recommended standard commands are defined. The device description ("DD") can also be used to make device-specific commands known to the communication device.
In addition to HART-capable communication modules for controllers, there are also handhelds for field use. These so-called primary and secondary masters can be connected simultaneously and control the respective data traffic.
Compared to purely analog current signaling with rise times in the millisecond range, the update rate of the HART protocol is relatively slow, about two messages per second. It can be interesting to obtain faster process information, such as process pressures, from the current signaling and to transmit secondary information, such as temperature or diagnostic data, simultaneously via the HART protocol. A possibly shorter cycle time compared to purely analog current signaling must be taken into account by filtering out the modulated HART signaling.
The cabling does not have to be changed when retrofitting HART-capable devices. This can offer interesting perspectives when retrofitting or upgrading.
If analog current signaling is omitted, several sensors can even be connected in parallel to a two-wire line (multidrop technology). The update rate for measured values is then reduced accordingly.
The maximum cable length for a point-to-point connection can be in the range of 1000 m, depending on the type of cable used. The cable resistance together with the capacitance are the determining parameters (RC value).
HART provides cost-effective digital communication in hazardous areas, even over the distances required there.

3 Voltage signaling

3.1 How the voltage signaling works

A variable voltage source provides the voltage signal. The voltage corresponds to the measuring signal via a corresponding scaling. Usual voltage signaling ranges for the measurement information range 0 ... 100 % are defined between 0 V and 10 V, but there are also bipolar ranges between -10 V and +10 V.

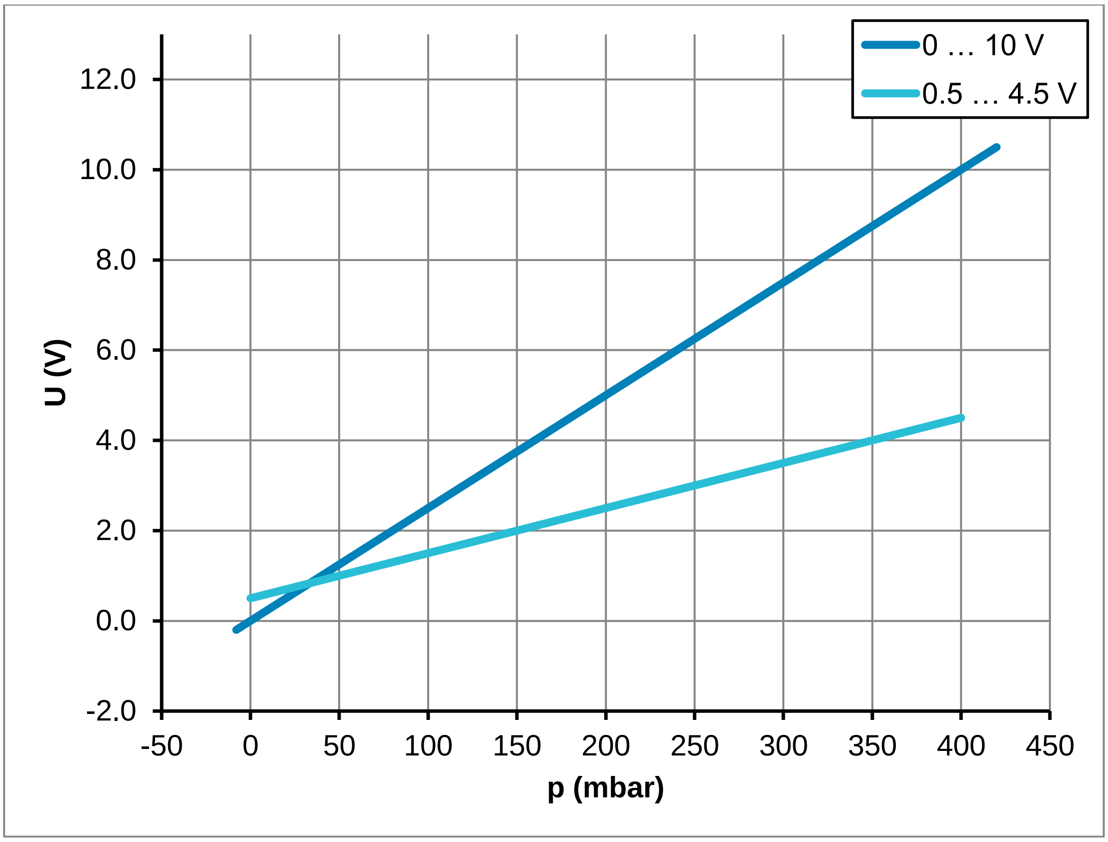

Figure 16: Measurement information and voltage signal by example of a 0 ... 400 mbar pressure sensor

3.2 Voltage signaling ranges

In practice, there are numerous voltage signaling ranges that have historically arisen for various reasons. These also include bipolar ranges (e.g. -10 V ... 10 V). In the following, only a selection of the most common ranges will be explained. The information can also be applied to other ranges accordingly.

3.2.1 0 … 5 V and 0 … 10 V (Dead-Zero-Signal)

The measurement information "zero" means a voltage signal of 0 V. Therefore, a wire break or short-circuit of the connecting cables cannot be clearly detected. However, the scaling is very simple. The signal can be directly applied to a voltage indicator with an appropriate scale (e.g. 0 ... 100 %).

3.2.2 1 … 5 V and 2 … 10 V (Live-Zero-Signal)

The voltage signal for the measurement information "zero" is 1 V or 2 V. This allows a wire break or short-circuit to be reliably detected. The scaling is less suitable for direct connection to a voltage indicator, but analog input cards of control devices offer the selection of this signaling range directly.

3.2.3 0,5 … 4,5 V

This signaling range is mainly used in OEM applications, e.g. for sensor elements. In most cases, the reference is "ratiometric". It is assumed that the specified signaling range applies with a nominal supply voltage of 5 V. If the supply voltage deviates within certain limits from 5 V, the signaling range is changed in the same ratio. This means that the signaling range is always 10 ... 90 % of the supply voltage. This eliminates the need to use a calibrated reference voltage on both sides, which reduces costs and significantly increases long-term and temperature stability. If digital-to-analog and analog-to-digital converters are used, their reference voltages on both sides can be easily derived from the supply voltage.

3.3 Types of voltage signaling

Voltage signaling usually requires three wires, the reference potential, the supply voltage and voltage signaling.

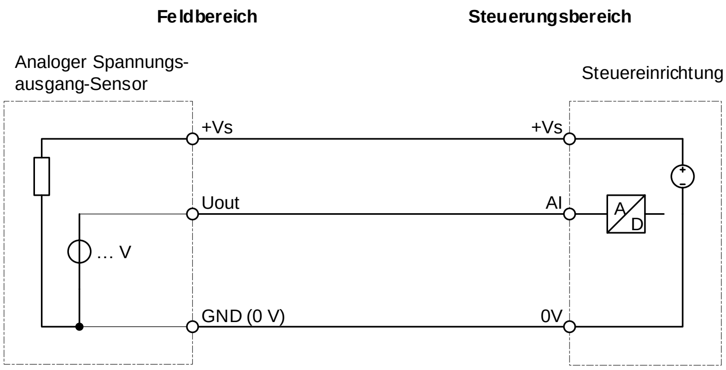

Figure 17: Signaling with voltage output

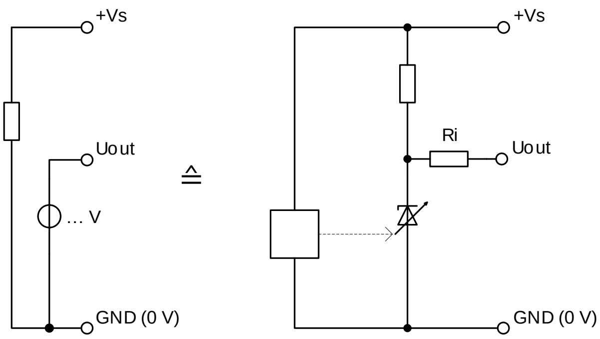

Figure 18: Schematic representation of voltage signaling

The specification of the sensor contains information about the max. load rating of the signal output to maintain the specified accuracy. If the load is too high, the internal resistance Ri of the signal source can cause distortion.

The ratiometric voltage signal is obtained with a virtual potentiometer (Rc). This is usually implemented in circuitry with a digital-to-analog converter (DAC), whose reference voltage is derived directly from the supply voltage (see also Section 3.2.3).

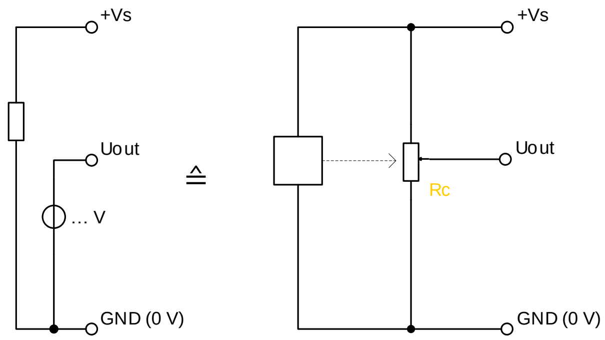

Figure 19: Schematic representation of voltage signaling with ratiometric output

3.4 Voltage signaling display unit

The voltage signaling allows several display units to be placed anywhere as long as the load remains within the specified range. However, the supply of the display unit is usually not obtained from the voltage signal but must be provided separately. Compared to the current loop display unit, the voltage signal display unit may have a potential reference, but ground loops must not occur.

4 Selection of the most suitable analog sensor interface

4.1 Immunity to interference and electromagnetic compatibility (EMC)

4.1.1 Leakage currents

The voltage signaling is insensitive to leakage currents, as can occur, for example, with cables that have become damp or insulation faults. In current signaling, any leakage current directly affects a fault because of the current divider that is created. This can happen unnoticed for a long time.

4.1.2 Capacitive interference coupling

Capacitive interference coupling, which can occur, for example, with closely parallel installed cables, primarily causes interference currents. These are harmful to current signaling. However, capacitive interference can easily be avoided with shielded cables. It is recommended to connect the shield only on one side of the evaluation unit, i.e. usually the control unit.
As long as the internal resistance of the signal source is sufficiently low impedance (approx. < 50 Ω), the capacitive interference currents can be compensated. Shielded cables can then be omitted. If a more distant wire break occurs, the cable may act as an antenna and trap capacitive interference currents that generate interference voltages at the relatively large input resistance of the analog input. This can lead to the wire break not being reliably detected because the voltage reading is not 0 V. A shielded cable is then also recommended as a remedy here.

4.1.3 Inductive interference coupling

Current signaling, on the other hand, is robust against inductive interference, even with unshielded cables, since interference currents can be compensated by the signal output.

4.2 Cabling

The cost of cables increases with the number of wires. For very long cables, the two-wire current loop can offer considerable cost advantages. With short cables, especially when pre-assembled cables with M12 connectors are used, the savings potential is usually not significant.

For reasons of interference immunity, the outgoing and return conductors of the two-wire current loop should always be next to each other, i.e. run in the same cable, even if it would theoretically be possible to lay a loop to different devices with a single-wire cable.

4.3 Signal distribution

If the measurement signal is to be tapped simultaneously at several points, e.g. for a display and a digital recorder, a current signal can be looped through the corresponding devices. Disadvantageous are the limited load and possible potential problems if a device is grounded at one connection. Differential inputs or isolating amplifiers can remedy this situation, but require a corresponding additional effort.
A voltage signal can be easily connected in parallel to several devices as long as the maximum load is not exceeded. This is often found in HVAC technology, e.g. when two flaps have to be moved against each other.

4.4 Service and trouble shooting

In order to be able to check the signal during current signaling with a measuring instrument, the line must be opened at one point and the measuring instrument looped in. In addition to the increased effort, this also requires an interruption of the function. With voltage signaling, on the other hand, the voltage signal can be measured at any accessible point without affecting the running process.

4.5 Energy consumption

The signal current in current signaling is always converted into heat at the end. When using a large number of sensors, this can be an argument for voltage signaling, especially in systems that are fed from solar cells or for which an uninterruptible power supply (UPS) is desired.
In principle, two-wire current loop sensors are designed to save energy. These can have an advantage over current-hungry three- or four-wire sensors.

4.6 Hazardous areas (EX)

The concept for intrinsic safety is much easier to implement with the 2-wire current signal. A single-channel Zener barrier or a dual-channel barrier with return channel can be used. To supply a sensor with voltage output, a dual-channel barrier with a resistor also in the return line is required. Since both channels usually contain the same values for the two resistors, the short-circuit currents must be added together because of the connection to a single device. This leads to the necessary selection of a barrier type with a higher resistance value, which reduces the maximum possible supply current.

4.7 Conclusion

Current signaling is the most widely used because it is robust against inductive interference, which cannot be eliminated easily even with shielded cables. The higher susceptibility to interference of capacitive interference couplings, on the other hand, can easily be reduced by using a cable shield on one side. When properly installed with shielded cable (only one side connected), the current signaling is therefore advantageous with regard to interference immunity.
In a humid environment, where leakage currents are to be expected in the long term, voltage signaling is the better choice. This is all the more so if, for example, remote installations are involved in the environmental sector, where the energy is generated by solar cells, for example.
The question of cabling, service and troubleshooting must be answered depending on the circumstances.

Item	Current signal (2-wire)	Voltage signal
Leakage current (poor cable insulation)	–	+
Capacitive interference (from parallel cables)	–	+
Inductive interference (from high power cables)	+	–
Cable shield connection	one side	both sides
Ground reference (earth potential)	floating	grounded
Cable cost (for long lines)	+	–
Signal distribution (e.g. multiple actors)	–	+
Service and trouble shooting	–	+
Energy consumption	–	+
Hazardous areas (EX)	+	–
Popularity (availability for interoperability)	+++	–
Market share	90 %	10 %

Figure 20: Comparison between current signal and voltage signal

5 Appendix

5.1 List of figures

5.2 Documentation history

Version	Date	Reviewed by	Amendment / Supplement / Description
V1.00	28.04.2020	fep	Translation from German