



Analog signal transmission in the field of MCR technology

User manual

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1 Introduction

1.1 Motivation and target groups for this user manual

Interference-free transmission of signals plays a central role in the field of MCR technology (measurement, control, regulation). However, signal transmission is affected by increasingly electrical environments. This holds especially true for the weak signals emitted by the measuring sensors.

If the measuring signals are low voltages or electric currents that must be securely transmitted, carefully conditioned or evaluated, then there is an increase in the electromagnetic and high-frequency interference they are exposed to. This is due to the following reasons:

- The increasing number of electrically operated components in all performance classes, especially motors operated via frequency converters and other actuators
- The increasing miniaturization and packing density of device components
- The growing volume of wireless communication and control equipment
- The ever-increasing performance of digital systems working with higher transmission frequencies

Insufficient attention given to the above disturbance variables, incorrect adjustments, or any other lack of planning can all affect interference-free signal transmission.

As a precautionary measure, the control signals sent to the active components of technical systems are provided in an “electrically more robust” way. In general, however, they are subjected to the same disturbance variables, implementation and planning risks.

This user manual is an introduction to the technical and practical basics of analog data transmission that are essential for automation and process control engineering. In addition, this user manual points out the risks to functional safety and draws attention to frequent mistakes that are made during the planning or installation phase or found when troubleshooting the systems. This user manual is intended for all interested parties, in particular for trainees and technicians who want to become familiar with analog data transmission in the field of automation and process control engineering.

1.2 What type of signals are involved?

This user manual focuses on analog electrical voltage and current signals, collectively referred to as “analog signals”. If signals vary smoothly between a minimum and maximum value, they are referred to as “analog” or “continuous-valued” signals. The value range is very large and almost infinitely large regarding the measuring accuracy.

Analog signals, for example, are generated using a sensor that records states and state changes of physical variables and converts them into an electrical signal. Typically, the following variables are measured in system and process technology:

- Temperature
- Pressure
- Fill level
- Flow rate
- Vibration
- Deformation with regard to load measurement
- Humidity
- Gas concentration
- Electrophysical variables such as voltage, current, field strength, etc.

Electrical conductors are used to transmit analog signals from the signal source to the destination device. Using a sensor signal, various options are available for the destination device:

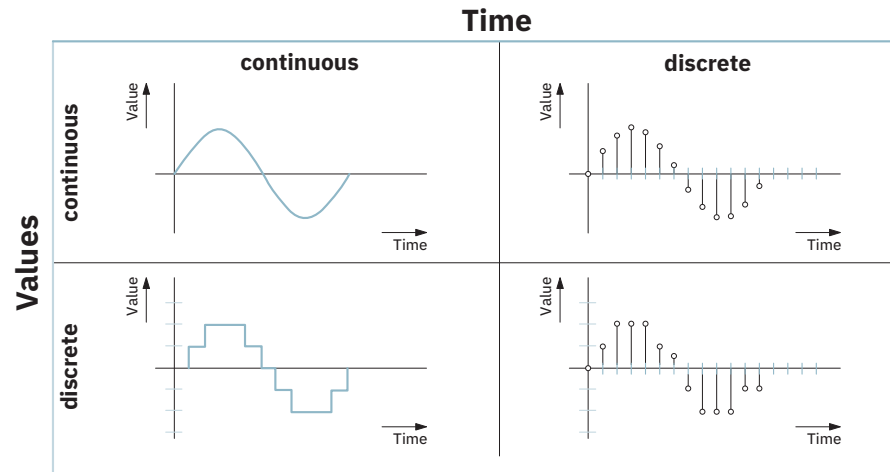
- A display device (e.g., fill level indicator in vehicles)
- A control system (e.g., for temperature control of a heating circuit)
- A signal converter (e.g., amplifier for a microphone signal)

A measuring transducer can be connected downstream of the sensor in order to convert the analog measuring signal into a so-called standard signal, thus enabling further signal processing via additional standardized, electrical modules. The measuring transducer may already be integrated in the sensor housing.

Compared to continuous-valued, analog signals, the situation is quite different when binary signals are considered. They can have only two possible values used to signalize the states “ON” and “OFF” or “1” and “0” respectively. Binary signals are often equated with “digital” signals. This is due to the fact that digital signals are usually binary coded. Signals that can take on a limited number of values in steps, and that are referred to as “discrete-valued” signals are to be classified between the analog and binary signals.

Continuous-valued (analog) and discrete-valued signals can be measured continuously by means of sampling and quantization, in this way becoming digital signals. The signal types described are shown in [Figure 1-1](#) for illustration purposes. In general, digital signals are binary coded and further processed in digital computer systems. It is also typical to reconvert digital signals into analog signals. The devices used for these conversion processes are referred to as A/D and D/A converters.

Figure 1-1 Analog and digital signal types



Conversions between “analog” and “digital” can be performed either by installing converters specially provided for this purpose or in a hidden way within processing components. The digitized signal type offers advantages with regard to transmission, storage, lossless copying and automatic correctability of signals. However, the conversion has some disadvantages:

- Device costs increase.
- Time response is too slow if there is any need for rapid reactions.
- There are system-related errors (e.g., the resolution may be insufficient for specific applications).

In the field of MCR technology, analog signals are often only evaluated binarily for a control system. This is the case, for example, when monitoring a temperature that should initiate countermeasures when exceeding a limit value. The currently measured temperature, for example, can only be used for comparison purposes to determine whether the temperature will exceed or fall below the limit value.

The transmission of analog signals in the area of telecommunications or the transmission of analog useful signals through modulation of a significantly higher-frequency carrier signal is outside the scope of this user manual.

2 Signal conditioning in MCR technology

2.1 Measuring signals

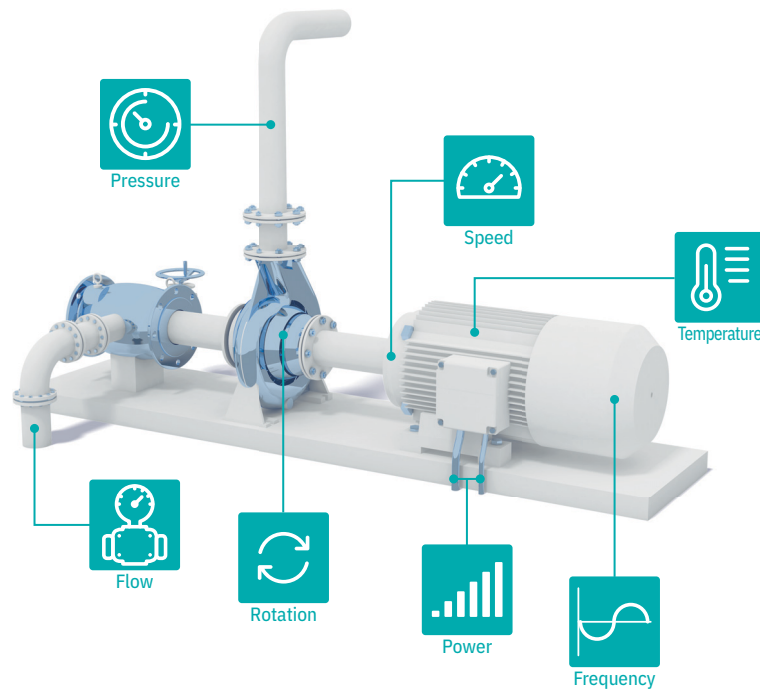
In the field of MCR technology, an analog measuring signal passes through the following stations:

1. A **sensor** reacts to a physical variable and converts it to an electrically evaluable signal. Either the sensor generates a voltage in the circuit or changes the circuit to which it is connected and that is supplied by a source of current or it changes the voltage drop along the electrical circuit fed with constant current. Sensors converting physical variables to electrical variables for measurement reasons are often referred to as **measuring transducers** or **transmitters**.

Sensors are typically used to measure the following physical variables (Figure 2-1):

- Temperature
- Pressure
- Substance concentrations
- Frequency (e.g., speed, flow rate)
- Electromagnetic and electrical properties (e.g., light, high-energy radiation, conductivity)

Figure 2-1 Examples of physical measured variables recorded by sensors



2. In general, the sensor is connected to an **interface module** used for signal conditioning. It is an electronic module which can have one or several of the following functions:
 - Electrical **amplification, filtering, and standardization** of the measuring signal
 - **Electrical isolation** of the measuring circuit from the device output circuit
 - **Electrical power supply** of the sensor, if required
 - The sensor and the interface module can be installed together in one housing. A device integrated in this way is sometimes referred to as **transmitter**.
3. The conditioned measuring signal is transmitted to a device or system which evaluates and further processes the measuring information. This can either be a display device or a control system with a very simple or highly complex structure. Depending on the characteristics, the following designations are commonly used for control systems:
 - **PLC** (Programmable Logic Controller)
 - **DDC** (Direct Digital Control)
 - **DCS** (Distributed Control System)In simple MCR systems, it is possible to combine interface modules and the control system in one device. The sensor may also be added, if required.
4. In industrial control systems, information is usually transmitted using communication bus systems. These systems enable a variety of information to be transmitted using only a limited number of electrical cable connections. An analog sensor signal needs to be conditioned for its transmission on a bus system. Conditioning takes place in an interface module and generally covers the following points:
 - **Digitization** of the analog signal
 - Signal integration into the bus access protocol (including addressing)
5. **Transmission** on the bus to the control system. In more extensive bus systems, several subsections can be used, if required. These are provided with repeater modules to compensate signal losses.

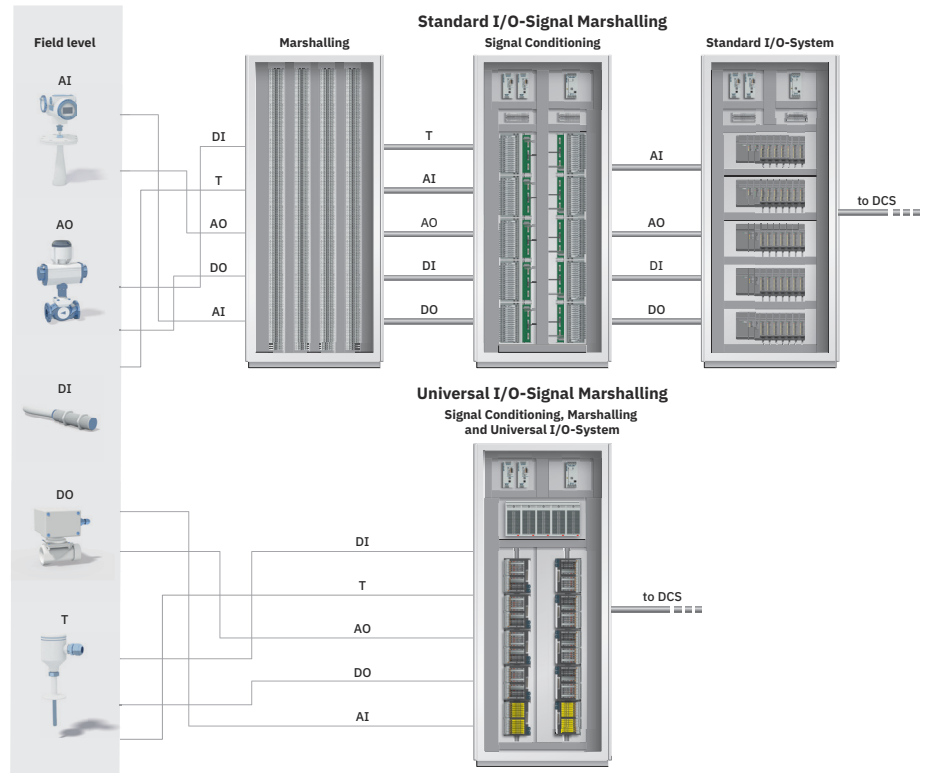
The electrosensory acquisition, conditioning, and evaluation of status data referring to the environment or an industrial system are considered to be the fundamental and core areas in the field of MCR technology.

However, the exact structure of the stations varies depending on the technology used, as do the costs and planning effort. These can be divided into standard I/O and universal I/O technology. This is compared in [Figure 2-2](#).

In standard I/O technology, a sensor with cables is connected directly to an interface module with a point-to-point connection. This module is also connected directly to a signal input on the control system. The control system must have as many input and output modules as there are signals used in the field.

The universal I/O technology differs from this in several respects. The sensor signals are connected to a collective terminal, the base element. The base element itself can now be assembled with any interface modules, so that any combination of signal types is still possible. A standardized cable can now be used to connect all signals to a single module of the control system. The interface modules on the base element can therefore be changed at any time without loosening a screw or changing the structure of the control system. At the same time, this means that only the number of signals needs to be known in the planning phase of a control system, which saves a considerable amount of time.

Figure 2-2 Analog signal from the sensor to the control unit in standard I/O and universal I/O technology



2.2 Control signals

Control systems evaluate information provided by the sensors and generate control signals in order to control actuators, producing effects either electromechanically or by other means. Actuators typically used in MCR systems are as follows:

- Relays
- Valves
- Electrically operated motors and further electrokinetic actuators
- Heating and cooling equipment

In both standard I/O and universal I/O technology, a control signal in the field of MCR technology passes through the following stations:

- Interface module for converting the control logic signal to the **access protocol** for the communication bus.
- **Transmission** on the bus to the actuator. If required, several subsections can be used when connected via repeater modules.
- Interface module for converting the bus signal to an analog or digital signal, enabling the addressed **actuator** to be accessed and operated. If necessary, this conversion may be carried out separately for the control logic and the electrical operation of the actuator. In the same way as with the modules used to condition measuring signals, the interface modules may have one or more functions in addition to the conversion function:
 - Amplification
 - Filtering
 - Standardization
 - Electrical isolation
 - Electrical supply

2.3 Standard signals


In the field of MCR technology, standard signals in accordance with DIN IEC 60381 are electrical signals with the following basic characteristics:

- Defined value range with the following electrical specifications:
 - Standard current signal** (DIN IEC 60381-1)
 - Standard voltage signal** (DIN IEC 60381-2)
- Basis for electrical components with simplified signal processing that are standardized and interchangeable regardless of the manufacturer.

Depending on the measuring task, analog sensor signals can be converted into one of the standard signals in an interface module. To avoid a distortion of the measurement results, the conversion result should be closely proportional to the measured input value.

If the lower limit value for the standard signal value range is set to 1/-10 V or 4 mA, it will then be possible to detect a break in the measurement circuit when the value 0 (V or mA) is detected by the evaluating component.

When setting the lower limit value of the value range to 0 (V or mA), the evaluating component is not able to differentiate whether the lowest value has been measured or a line break occurred when the value of these so-called “true zero signals” is 0.

 In almost all industrial applications, “life zero signals” are used where the zero point of the measurement is represented by 1/-10 V or 4 mA.

Transmitter

If the sensor and the interface module are located in the same housing, this unit is also referred to as a transmitter.

If a standard voltage signal is present, but a standard current signal is required, then standard voltage-to-current signal converters are available for this purpose. There are also standard current-to-voltage signal converters available for the reverse case.

Apart from the above-mentioned standard signals used in the field of MCR technology, unipolar and bipolar signals are used in the following areas:

- 50 mV ... 100 V
- 1 mA ... 100 mA

2.3.1 Standard voltage signals

The standard voltage signal is available in the following versions:

- 0 V ... 10 V
- 0 V ... 5 V
- 1 V ... 5 V (life zero)
- -10 V ... +10 V (life zero)

The standard voltage signal is mainly used in the field of building and factory automation. As the standard voltage signal is susceptible to electromagnetic interference and is influenced by voltage losses in long cables, it is rarely suitable for process automation, which places higher demands on accuracy.

Transmission errors of 0.1% (at 50 Ω line resistance and 10 kΩ input resistance of the evaluating unit) are typical for standard voltage signals.

2.3.2 Standard current signals

The standard current signal is available in two versions:

- 0 mA ... 20 mA
- 4 mA ... 20 mA (life zero)

The standard current signal of 0/4 mA ... 20 mA is less sensitive to electromagnetic interference than the standard voltage signal and largely immune to the disadvantages of long line paths between the signal source and the evaluating components. It fulfills the high accuracy requirements made on a wide range of applications in the field of process automation.

With regard to the standard current signal, a distinction must be made between the active current output (current source) and the passive current output (current sink).

Active current output (current source)

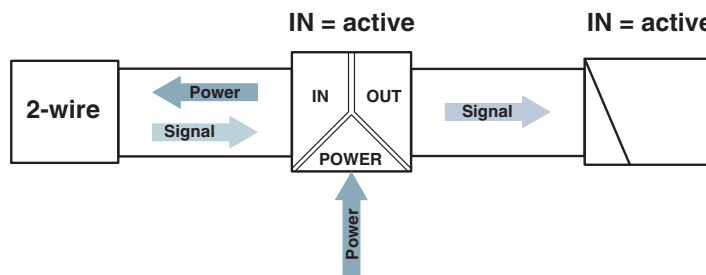
A sensor or signal converter with **active** current output delivers current proportional to the measured value. It has its own voltage source that can either be built in or connected as a separate supply, by means of additional cables from the evaluating component, if required. When using a sensor or signal converter with active current output, the maximum permissible ohmic load must be considered for its connection. It is specified in the device data sheets. The measuring signal will be distorted in the event of an overload.

An active current output can be used not only for the standardization of measuring signals, but also for the control of actuators. For example, the current source is able to control a valve that controls the flow rate proportionally to the delivered current strength between 0% and 100%.

Passive current output (current sink)

A sensor or signal converter with a **passive** current output changes its internal resistance proportionally to the measured value and therefore the current in the conductor loop of the measuring circuit. The sensor or signal converter is supplied by the evaluating component via the two measuring lines and requires a part of the supply voltage for its functioning. When using a passive current output, the maximum permissible voltage value needs to be considered. It is specified in the device data sheets. If the voltage is too high, the measuring signal may be distorted and the device destroyed.

Figure 2-3 Interface module with sensor supply and standard signal output



- The sensor is supplied by an interface module and provides a measuring signal.
- The interface module converts the measuring signal into a standard signal (standard voltage or current signal).
- The standard signal is fed to a component for evaluation.

3 Signal conditioners

Interface modules can have these functions in signal conditioning:

- Signal amplification
- Standardization
- Filtering
- Electrical isolation
- Electrical supply of connected components
- Line monitoring

The electronic components used for these tasks are collectively referred to as signal conditioners and can have different individual functions as well as combinations of the above functions. Manufacturers therefore offer a wide range of highly specialized as well as universally applicable signal conditioners.

Depending on the input signal types, signal conditioners can be divided into the following groups:

- Signal conditioners for binary signals (switching amplifiers with relay or contactor function, frequency converters for acquisition of speed and direction of rotation)
- Signal conditioners for proportional analog signals (sensor supply devices, measuring transducers with standard signal output, limit sensors)

In the following, the basic properties of signal conditioners are explained by means of wiring examples.

3.1 Signal amplification

Signal amplification is always required if a signal is too weak and its acquisition by the evaluation unit will only be distorted or attenuated.

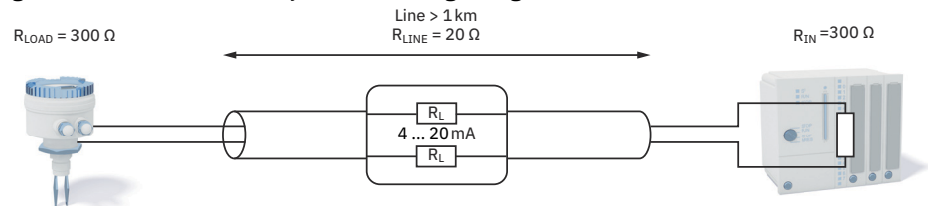
This may be due to the following factors, either individually or in combination:

- Long line paths, high line resistances
- High input resistance of the evaluation unit or high total resistance of several signal loads connected in series
- Signals of voltage-generating sensors or transmitters with weak output power due to their construction type

In electrotechnical parlance, the following clear diagnostics is made with regard to these incorrect adjustments: Either the signal generator or the signal is not able to drive the connected, excessive load. The maximum permissible load for a signal output is indicated as resistance value in the data sheets for electrical MCR components.

Problem

Figure 3-1 Incorrect adjustment owing to high line and terminal resistances

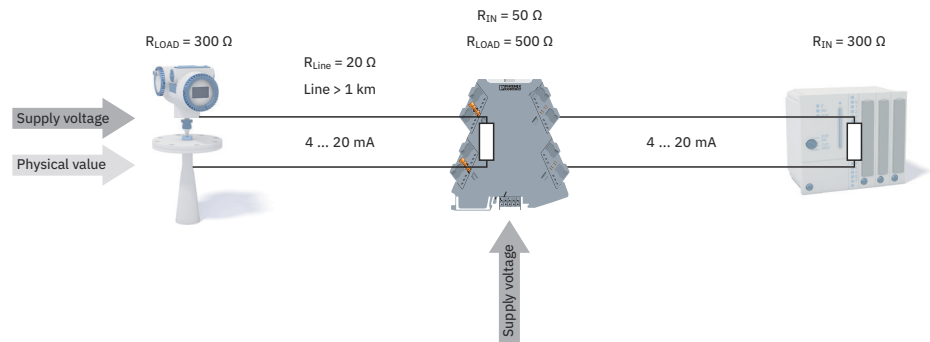


- Sum of the resistances of the measuring signal lines and the evaluation unit input:
 $20 \Omega + 300 \Omega = 320 \Omega$

i The load connected to the measuring sensor is 320Ω and thus exceeds its maximum permissible load of 300Ω . The measuring sensor is not able to drive this load, leading to a distorted measuring signal.

Solution

Figure 3-2 Signal amplification to correct the error in the adjustment



- Adding an amplifier for analog signals to the connecting cables for the measuring signal.
- Sum of resistances of the measuring signal lines and the amplifier input:
 $20\ \Omega + 50\ \Omega = 70\ \Omega$



The load connected to the measuring sensor is $70\ \Omega$ and thus lower than the maximum permissible load of $300\ \Omega$. Furthermore, the input resistance of the evaluation unit of $300\ \Omega$ does not overload the amplifier output, as it is intended to drive a load of up to $500\ \Omega$. The measuring signal will not be distorted.

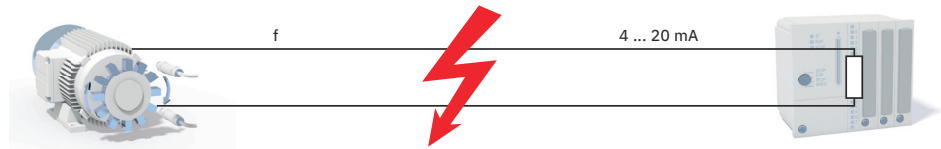
3.2 Conversion to a standard signal

A standard signal converter is required in applications in which a sensor converts a physical value into an electrical signal. This electrical signal can be in the form of a current or voltage outside the standard or a frequency.

The standard signal converter can record different electrical input signals and convert them into a standard current or voltage signal. For this purpose, you must specify a minimum and maximum expected input value. In addition, some devices enter various error states in the event of limit value overrange or underrange. This could be implemented as follows:

- Exceeding and falling below the output value range (e.g., 3 mA and 21 mA)
- Opening/closing a relay or transistor output

Figure 3-3 No direct connection option due to different signal types



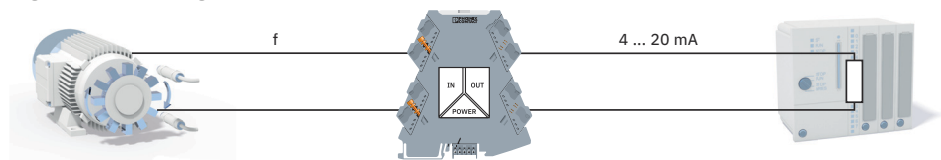
Problem

In the circuit example in [Figure 3-3](#), a speed sensor is installed that converts the mechanical rotational frequency of the rotating body into an electrical variable. In the example application, an inductive sensor with a PNP output was installed. With each rotation, the sensor is triggered once or several times and switches the output, so that the electrical switching frequency is directly dependent on the mechanical rotational frequency. Please note that both the maximum switching frequency of the sensor and the maximum input frequency of the standard signal converter must not be exceeded.

Solution

In order to monitor the speed with a remote control system, a standard signal converter is required that converts the frequency signal into a 4 mA ... 20 mA signal and can bridge the line path, see [Figure 3-4](#).

Figure 3-4 Signal conversion for compatibility on both sides

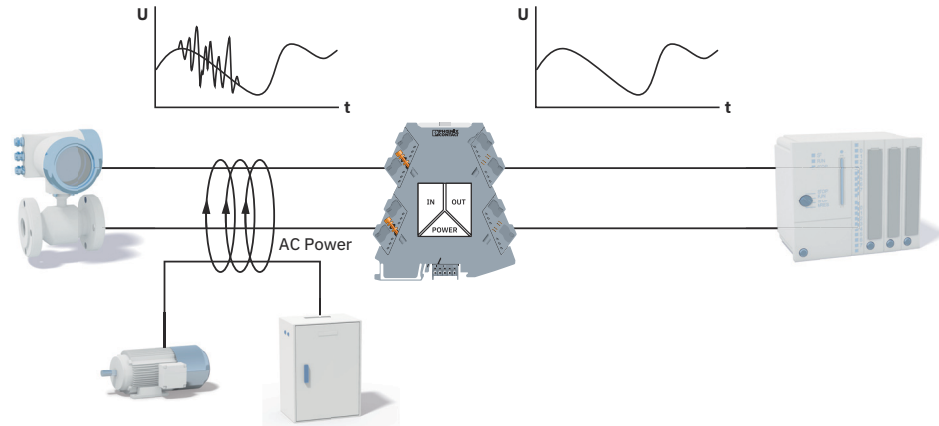


The standard signal converter, in this particular case a frequency measuring transducer, is configured so that the minimum and maximum input frequency corresponds to the output values 4 mA and 20 mA.

3.3 Filtering

Signal conditioners with filtering function are able to detect and suppress interference voltages within a wide frequency spectrum. To avoid interference resulting from the above-mentioned causes, the voltage signal should be converted into a current signal.

Figure 3-5 Signal filtering



Problem

Interference voltages may occur in cables used for measured-value transmission:

- Owing to electromagnetic induction caused by currents in electrical cables which are installed in nearby locations (see [Figure 3-5](#))
- Owing to the impact of high-frequency signals caused by electrical devices in the industrial environment, e.g., frequency converters

Solution

If voltage signals are affected, interference is particularly strong. Depending on the cables used, signal transmission can be protected against such interference to a certain extent:

- Twisted pairs reduce interference through voltages induced in the line.



The conductive sheaths of shielded cables reflect and absorb the electrical fields to which the cables are exposed.

3.4 Electrical isolation


There are different reasons to electrically isolate the circuit in which the sensor or transmitter is installed from the circuit in which the evaluation unit is installed:

- To interrupt and avoid compensating currents between potential differences
- To avoid electromagnetic interference in measuring technology, data transmission, and electro-acoustic systems
- To increase safety and protect electrical devices and systems from hazardous voltages and voltage pulses

Depending on the application, the electrical isolation - also referred to as galvanic decoupling or separation - can be achieved in different ways:

- Inductively by means of transformers (for alternating voltages and pulses)
- Capacitively by means of capacitors (for high-frequency signals)
- Optically by means of optocouplers or fiber optic paths (for all types of information)
- Mechanically by means of relays and pneumatic elements (for transmission of electromechanical/pneumatic switching states and pulses)

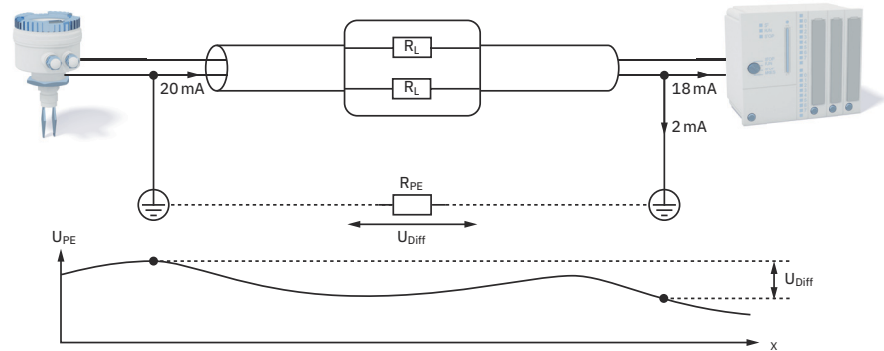
Each one of these methods has its advantages and disadvantages. Optocouplers, for example, have a high dielectric strength. However, they do not allow power to be transmitted and are subjected to undesired aging processes. Conventional transformers allow for power transmission, but they are large and expensive. Microcoils embedded in the semiconductor material of integrated circuits (“coreless transformers”) do not have this disadvantage but usually suffer the loss of the power transmission function. Digital signal transmitters are an exception here.

 An electrically isolated signal connection is referred to as a floating connection because there are no compensating currents flowing between potential differences.

In plant and process technology, the electrical isolation of field circuits from system control circuits has gained acceptance. In this context, “field” is the technical term that summarizes all sensors, transmitters, and actuators within the controlled system. In addition, circuits are often electrically isolated within the field.

Problem

Figure 3-6 Ground current loop

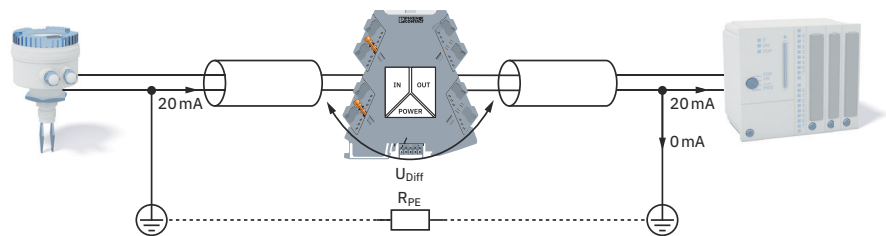


In the example shown, there is the problem of a so-called ground current loop. This is caused by the fact that electrical loads have discharge currents or the N conductor in the terminal box is connected to PE. As a result, a voltage is present at the respective grounding point. This occurs to varying degrees at each grounding point, depending on the loads, so that a voltage is present between the grounding points. As buildings are usually grounded via a central grounding point, this voltage cannot be measured in a building. However, if field devices are operated at a different ground potential, sometimes far away from the evaluation unit, a current can be driven by the voltage difference. This changes the analog value recorded by the evaluation unit, resulting in a non-qualifiable error. The diagram shows an example of a possible voltage curve over the distance to the field device.

Solution

To counteract this behavior, the two devices are electrically isolated from each other. This means that no more current can be driven through the measuring lines and the measurement result remains unchanged.

Figure 3-7 Electrical isolation to break ground current loops

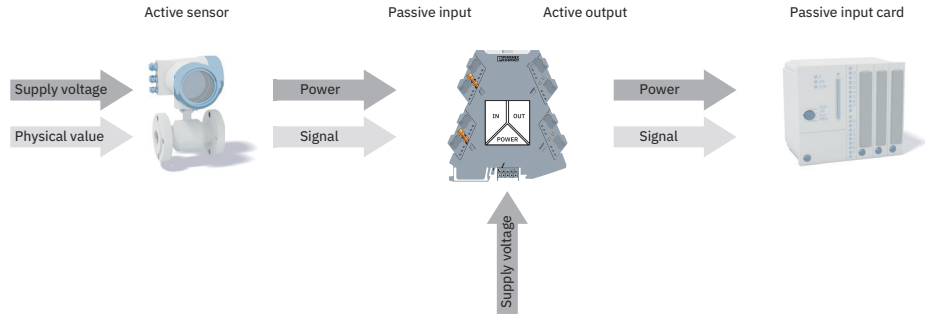


3.5 Electrical supply and isolation of signal paths

Depending on whether the connected sensor or transmitter has its own power supply or is supplied via sensor signal lines, there is a difference made between a passive and active input at the input terminals of a signal conditioner or evaluation unit.

Passive input

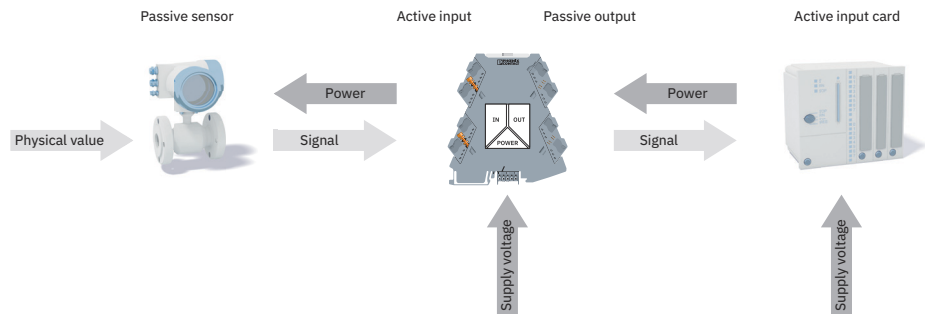
Figure 3-8 Examples of a passive signal input



- The only function of the signal input is to receive the signal. In the example, the signal conditioner and the evaluation unit have passive inputs.
- The active sensor or transmitter (with four connections) supplies the passive input of the signal conditioner.
- The active output of the signal conditioner supplies the passive input of the evaluation unit.

Active input

Figure 3-9 Example of an active signal input



The signal input has two functions:

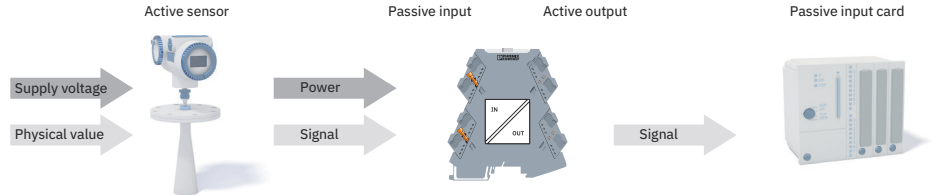
1. Signal receipt
 2. Power supply of the signal generator
- In the example, the signal conditioner has an active input. It supplies the 2 or 3-wire sensor or transmitter.
 - Components with an electric power source can be supplied by separate power supplies or via the signal lines.

Table 3-1 Supply paths for signal isolators: advantages and disadvantages

Power supply	Advantages	Disadvantages
Separate	– Electrical isolation of the supply circuit from the signal circuits	– Extra expense in material and costs
Via signal lines	– Material and cost savings	– Not possible for all applications – Increased risk of interference

Passive Isolation (input loop-powered)

Figure 3-10 Example 1 of passive isolation (input loop-powered)



Signal conditioner supply via its signal input through transmitter (input loop-powered)

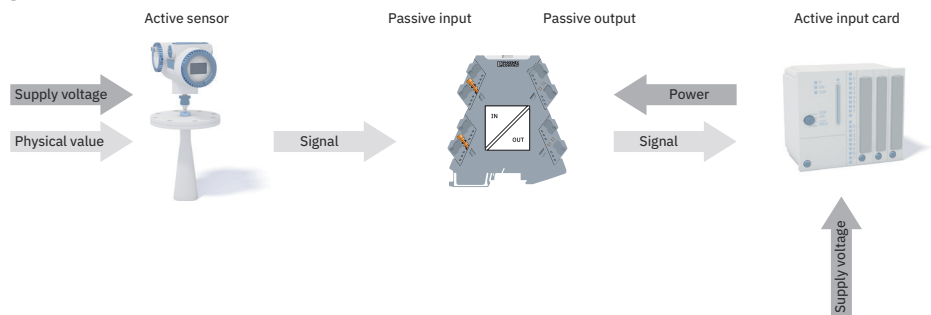
- The signal paths between the active sensor or transmitter with four connections and the signal conditioner are not isolated from the transmitter supply.



The sensor or transmitter must drive the entire load from the signal conditioner and evaluation unit input.

Passive isolation (output loop-powered)

Figure 3-11 Example 2 of passive isolation (output loop-powered)



Signal conditioner supply via the signal output through the evaluation unit (output loop-powered)

- The signal path between the sensor or transmitter and signal conditioner is isolated from the transmitter supply.
- The signal path between the signal conditioner and evaluation unit is not isolated from the evaluation unit supply.



Only suitable for the 4 mA ... 20 mA output signal.

3.6 Line monitoring

With regard to connecting a switch to an evaluation unit, Figure 4-1 on page 29 shows how, using two resistors, a simple monitoring function for line interruptions and short circuits can be implemented for a 2-wire line.

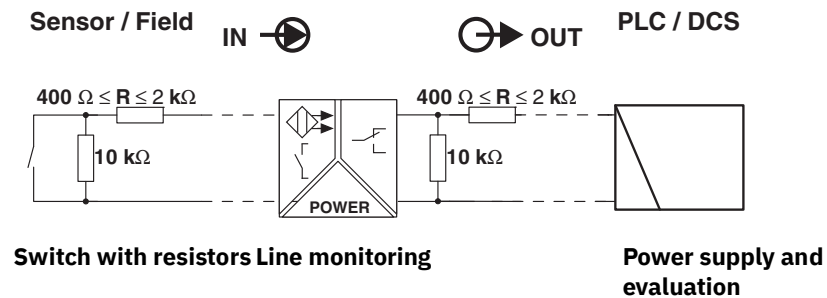
This monitoring function is specified in greater detail in the NE 21 Recommendation provided by the User Association of Automation Technology in Process Industries.

Special isolation switch amplifiers are available for line monitoring which do not have any other monitoring functions.

Line monitoring is integrated in many signal conditioners and measuring transducers as an additional function. Errors will be indicated here at separate terminal blocks and displayed on the modules via LEDs.

The following figure shows schematically how line monitoring can be used for the total signal transmission path from the sensor to the evaluation unit.

Figure 3-12 Line monitoring



3.7 Additional functions of signal conditioners

Apart from the basic functions of signal conditioners, a wide range of additional functions is available for interface modules within the field of MCR technology. The modules may be single-channel, multi-channel, duplicating, or, together with other functions, be integrated in one housing:

- Switching amplifier with relay function for high loads
- Configurable limit sensors, comparators
- Special measuring transducers for temperature sensors
- Amplifiers for the connection of strain gauges
- Frequency-analog measuring transducers, analog-frequency measuring transducers
- Configurable converters for converting measuring values (e.g., in the event of an irregularly shaped tank, to linearize fill level values which are not proportional to the filling quantity)
- HART-transparent interface modules (see Section [“HART®” on page 42](#))
- Signal conditioners and measuring transducers with bus and network connection (see Section [“Digital fieldbuses” on page 57](#))
- With functional safety (SIL/PL) (see Section [“Basics of functional safety” on page 69](#))
- For use in potentially explosive areas (see Section [“Basics of explosion protection” on page 77](#))

3.8 Analog and digital signal inputs and outputs

The function and application of an interface module determine how its inputs and outputs are to be “wired” which means what other electrical components can be usefully connected. Interface modules are therefore mainly categorized by their value ranges for inputs and outputs. In addition, they can be categorized by information regarding the power supply, further electrophysical properties, design, and dimensions.

Basically, they can be classified by indicating whether their signal inputs and outputs are used to process analog or digital signals. See [“What type of signals are involved?” on page 8](#) for analog and digital signal differentiation.

In automation and process control engineering, signal conditioners and measuring transducers with the functions described in this section are primarily used:

Table 3-2 Interface modules with analog and digital signal inputs (IN) and outputs (OUT)

IN	OUT	Type	Examples
Analog	Analog	Signal conditioner	<ul style="list-style-type: none"> – Universal signal conditioner – Evaluation unit input isolator (for electrical isolation of signal generators in the field from the control system) – Repeater power supply (with power supply for the signal generator) – Signal duplicator – Output isolator (for electrical isolation of actuators in the field from the control system); with or without HART transparency <p>Output can be configured proportionally to the input or with a different characteristic.</p>
		Temperature measuring transducer	For RTD and TC signals, see “Temperature measurement” on page 31
Analog	Digital	Limit and threshold adjuster	For analog signals from potentiometers, temperature sensors, etc.; several outputs possible; with relay or transistor output, several outputs possible
Digital	Digital	Signal conditioner	<ul style="list-style-type: none"> – For switching contacts – NAMUR signal conditioner for proximity sensors (capacitive/magneto-inductive, inductive, optical); see “Proximity sensors according to NAMUR standard” on page 40 – Digital solenoid drivers <p>With relay or transistor output, several outputs possible</p>
Digital	Analog	Frequency measuring transducer	D/A converter with an analog output that is proportional to the frequency or configurable with a different characteristic



Application examples for the four types can be found in Section 5 on page 47.

4 Basic theoretical principles

4.1 Event acquisition, pulse and frequency measurement

Switches or buttons are used to acquire and record events that occur rarely, occasionally, or in a slow sequence. In machine building, for example, microswitches are used to determine positions or directions of motion. These are operated mechanically via switching nubs on moving machine parts. If any contact should be avoided, electromagnetic encoders can fulfill the same function (Hall sensors, slot-type initiators, etc.).

Non-contact methods are mainly used for the acquisition of fast pulse sequences (e.g., to determine the flow volume via an impeller or to measure the motor speed). Each rotation will be acquired electromagnetically by a pulse encoder.

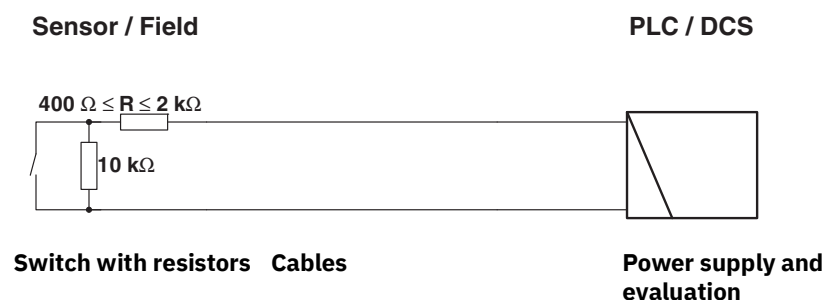
Switches, buttons, and pulse encoders that are connected to a circuit provide a binary signal. If required, this signal can be further adapted with a suitable module and evaluated by the display or control unit. Depending on the application, the signal can be used in different ways:

- Triggering an action
- Measuring the event duration
- Counting the events
- Measuring the frequency

Converter modules are available for frequency display or frequency evaluation in any other way, which convert the frequency to a proportional current signal.

To monitor the correct measuring function, the “Switched on” and “Switched off” states should be distinguishable from a short circuit or line interruption being present in the measuring circuit. For this purpose, resistors are added to the measuring circuit, as shown in [Figure 4-1](#).

Figure 4-1 Switch connection with resistors added to the circuit for line monitoring



- | | |
|---------------------------------|---|
| 400 Ω ... 2 k Ω : | Resistance for maximum current when the switch is closed (short-circuit current is higher) |
| 10 k Ω : | Resistance for the closed-circuit current when the switch is opened (in case of line break the current is equal to 0) |

Analog signal transmission in the field of MCR technology

Dimensioning of the resistors needs to be adapted to the measuring circuit in a way that the evaluation unit is able to reliably differentiate between the four states:

- Short circuit
- Switch closed
- Switch opened
- Line interrupted

Many interface modules offer the option of error detection and forwarding to the control system, so that a defective sensor or an error in the supply line only requires a short troubleshooting process. However, there are also many sensors and switching contacts available on the market that do not offer the option of remote error detection. Retrofit solutions can be purchased to ensure that a system works safely and stably. The resistors required to differentiate between short circuits and line breaks are attached directly to the sensor or switching contact.

4.2 Temperature measurement

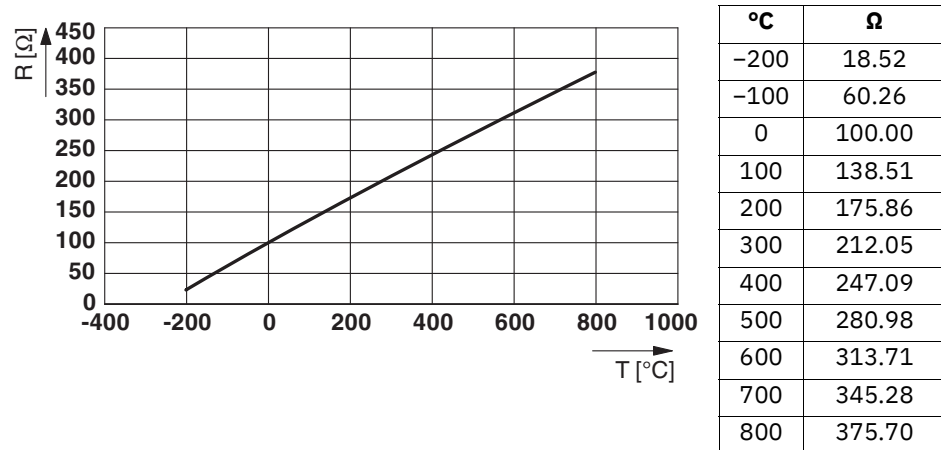
Temperature measurement methods using resistance thermometers and thermocouples have become well established in industrial applications.

4.2.1 Resistance thermometers

A resistance thermometer, also known as an RTD (Resistance Temperature Detector), can be seen as a normal resistor. Its only distinguishing feature is that the resistance value is strongly temperature-dependent. The aim is to keep the relationship between resistance value and temperature as linear as possible.

Pt 100 characteristic curve

Table 4-1 Pt 100 characteristic curve (IEC 751)



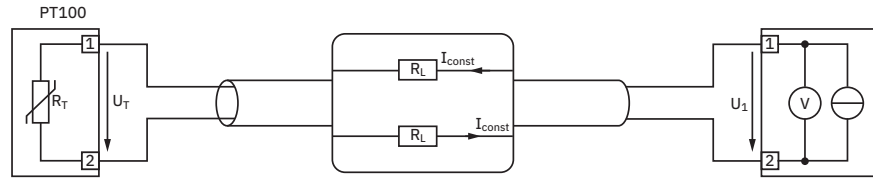
To measure the resistance, the sensors are supplied with a direct current. The direct current must be as low as possible and is usually in the range of approx. 1 mA. Higher currents lead to disruptive self-heating of the resistance thermometer, which leads to a falsified measurement result. In order to determine a resistance, the current through the resistor and the voltage applied to it must be known. The current is specified by the device, so only the voltage across the resistor has to be measured. Depending on the required accuracy and the ambient conditions, there are three different options.

2-wire connection

2-wire connection is suitable for less accurate measurements. The evaluation unit measures the resistance of the line together with the shunt.

To increase the accuracy of the system, the resistance value of the lines can be determined and set as an offset in many evaluation units. Resistance changes that occur due to temperature fluctuations in the supply line, for example, cannot be taken into account when measuring. Therefore, 3 or 4-wire connection of the resistance thermometer should be used for longer line lengths from approx. 10 m and for more precise measurements.

Figure 4-2 Resistance thermometer with 2-wire connection



$$U_T = U_1 - (2 I_{const} R_L)$$

$$R_T = U_T / I_{const}$$

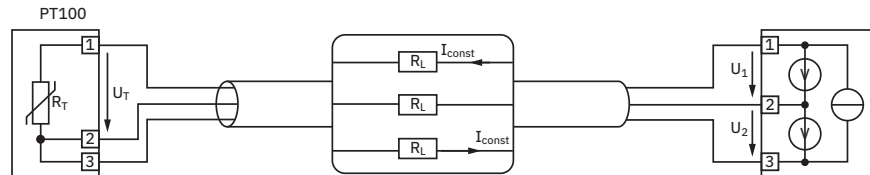
- U_1 : Total voltage drop determined with voltage measuring device
- U_T : Voltage drop at shunt
- R_T : Shunt resistance
- R_L : Line resistance between voltage measuring device and shunt
- I_{const} : Constant current source (with electronically controlled current output)

i For a 1 mm² copper conductor, the resistance is approx. 0.17 Ω per 10 m. For a resistance thermometer of type Pt 100, 0.385 Ω equals an approx. 1 °K change in temperature

3-wire connection

3-wire connection is suitable for lines of more than 10 m between the sensor and measuring transducer. An additional third line is used here to connect the shunt to the evaluation unit. According to the wiring shown in Figure 4-3, the measuring current will not pass through this line. This makes it possible to measure and consider the resistance and its temperature-dependent change on one of the lines through which current is flowing.

Figure 4-3 Resistance thermometer with 3-wire connection



$$U_1 = I_{\text{const}} R_T + I_{\text{const}} R_L$$

$$U_2 = I_{\text{const}} R_L$$

$$U_T = U_1 - U_2$$

$$R_T = U_T / I_{\text{const}}$$

U_1 : Voltage drop at R_T and R_L determined with voltage measuring device 1

U_2 : Voltage drop at R_L determined with voltage measuring device 2

U_T : Voltage drop at shunt

R_T : Shunt resistance

R_L : Line resistance between voltage measuring device and shunt (must be the same for the two lines through which current is flowing)

I_{const} : Constant current source (with electronically controlled current output)

i In this case, however, the resistances of the two lines through which current is flowing must be the same. This is generally the case when using a 3-wire line. Accordingly, the 3-wire connection method is most frequently used.

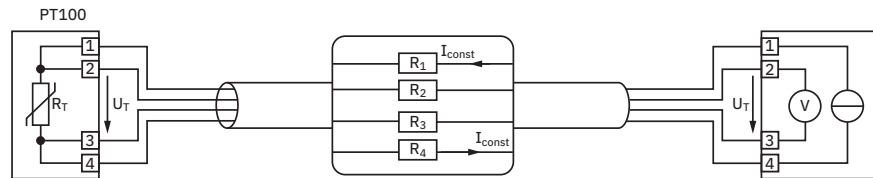
i In addition to the wiring shown in Figure 4-3, there is also a variant of 3-wire connection with two current sources. This has the advantage that the voltage only needs to be measured once.

4-wire connection

4-wire connection is suitable for lines of more than 10 m between the sensor and measuring transducer. When using 4-wire connection, two measuring lines are connected to the sensor, without any measuring current flowing through them. This has the advantage that the sizes of all resistors no longer play a role.

Figure 4-4 Resistance thermometer with 4-wire connection

$R_T = U_T / I_{const}$



- U_1 : Voltage drop at R_T determined with a voltage measuring device
- U_T : Voltage drop at shunt
- R_T : Shunt resistance
- $R_1 \dots 4$: Line resistances between voltage measuring device and shunt (may be different for all lines: $R_1 \neq R_2 \neq R_3 \neq R_4$)
- I_{const} : Constant current source (with electronically controlled current output)

The most accurate measurements with resistance thermometers are possible using 4-wire connection.

i To provide a good CMV¹ suppression of the measuring transducer, it is useful if R_2 and R_3 are identical.

¹ Common Mode Voltage

4.2.2 Thermocouples

Thermocouples (TC) consist of two conductors made of different metals connected to each other on one side. As the temperature rises, the electrons in the conductor move faster. If a conductor has a different temperature at two points, a potential difference arises due to the electrons in the conductor being excited to different degrees by the temperature.

If we now extend the circuit to include a return conductor made of the same metal, the potential difference in both conductors is equal in magnitude but reversed in sign. This cancels out the voltages completely. In a thermocouple, the supply and return conductors are therefore made of two different metals that have different thermoelectric properties.

If the sensor tip at the contact point has a different temperature than the connection point, a voltage, the thermoelectric voltage, can be measured due to the different potentials.

However, the thermoelectric voltage itself is only very small and is in the range of a few $10 \mu\text{V}$ per $^{\circ}\text{C}$. In order to increase the voltage and achieve a correspondingly greater accuracy, several thermocouples can be connected in series, a so-called thermopile. The voltage of the thermopile is greater by the factor of the number of thermocouples.

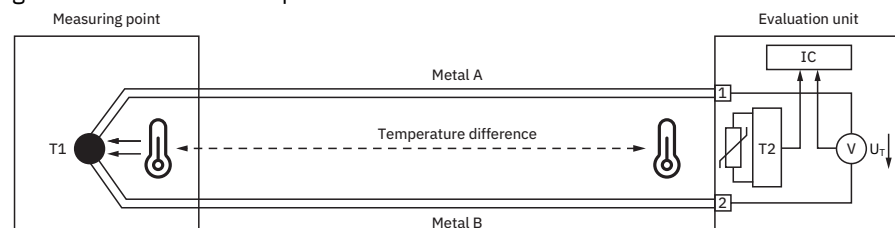
Cold junction compensation

As the thermoelectric voltage depends on the temperature difference between the measuring point and the evaluation unit, it is not possible to determine an absolute temperature. In order to calculate this absolute temperature, the temperature at the evaluation unit is required. Many devices offer cold junction compensation for this purpose. These measure the ambient temperature, e.g., with a Pt 100 or Pt 1000 installed in the device.

If such a function is not available, the temperature of the evaluation unit is specified by reference measurement. With a reference measurement, however, it should be noted that the temperature deviates by the difference from the actual ambient temperature. To make matters worse, the thermoelectric voltage curve is not linear with respect to temperature, so a different cold junction compensation temperature can lead to a significantly greater measurement inaccuracy.

For the highest possible accuracy, a temperature sensor that is thermally coupled to the connection points of the thermocouple for cold junction compensation should be used.

Figure 4-5 Thermocouple connection



T_1 : Temperature at the measurement point

T_2 : Temperature at the connection point

U_T : Voltage generated between the measurement point and the connection point. Indicates the absolute temperature T_1 at the measurement point by considering the connection point temperature T_2

4.2.3 Summary tables

The advantages and disadvantages of the temperature measurement methods are summarized below and the different types, including their characteristic curves, are shown.

Table 4-2 Widely used temperature measurement methods

Features	Sensor type	
	Resistance thermometer, RTD	Thermocouple, TC
Measured quantity	Resistance (measured via voltage drop, depends on the absolute temperature)	Temperature difference (generates a voltage)
Temperature range	Relatively limited in the upper value: -200°C ... +850°C	-250°C ... +3000°C
Accuracy	Very good	Good
Response times	Long	Short
Cold junction	Not required	Required (Reference measurement/cold junction compensation)
Sensor material	Platinum, copper, or nickel	Pairs of different metals
Robustness	Good	Very good
Resistance to vibration	Very sensitive (non-encapsulated)	Very robust
Long-term stability	Very good	Satisfactory
Self-heating	Needs to be considered	None
Surface temperature measurement	Limited suitability	Suitable
Sensor dimensions/ measurement point	Relatively large/shunt length	Very small sensors can be produced, punctiform
Characteristic	Widely linear	Non-linear
Electrical signal strength	Low (approx. 0.4 mV per degree K at 1 mA measuring current, Pt 100)	Very low (some µV per degree temperature difference)
Measuring current supply	Required	Not required
Connecting cables	Copper instrumentation cable	Thermal material or compensating line (less expensive)
Price	Relatively expensive	Rather inexpensive (except for Pt alloys)

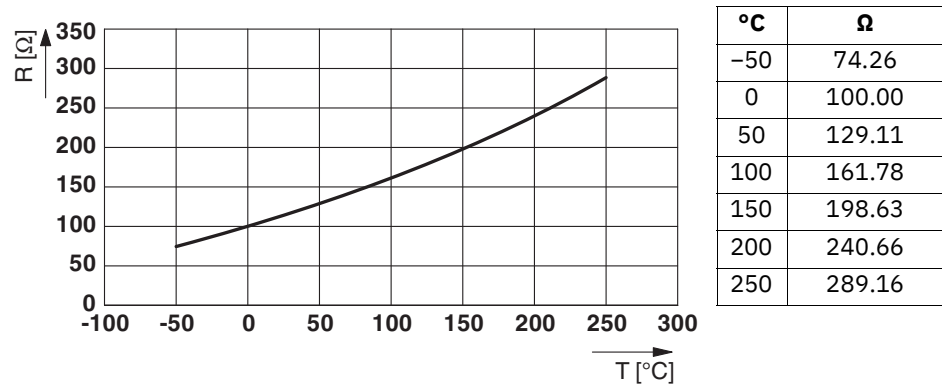
Table 4-3 Resistance thermometer types

Type	Standardization	Temperature range [°C]
Pt 100	IEC 751/GOST 6651 $\alpha = 0.00385$	-200 ... +850
Pt 200	IEC 751/GOST 6651 $\alpha = 0.00385$	-200 ... +850
Pt 500	IEC 751/GOST 6651 $\alpha = 0.00385$	-200 ... +850
Pt 1000	IEC 751/GOST 6651 $\alpha = 0.00385$	-200 ... +850
Pt 100	GOST 6651 $\alpha = 0.00391$	-200 ... +850
Pt 100	GOST 6651 $\alpha = 0.00391$	-200 ... +850
Pt 100	JIS C1604-1997	-200 ... +850
Pt 1000	JIS C1604-1997	-200 ... +850
Ni 100	DIN 43760	-60 ... +250
Ni 1000	DIN 43760	-60 ... +250
Cu 50	GOST 6651 $\alpha = 0.00428$	-180 ... +200
Cu 100	GOST 6651 $\alpha = 0.00428$	-180 ... +200
Cu 53	GOST 6651 $\alpha = 0.00426$	-50 ... +180

The following tables provide examples of, in addition to “Pt 100 characteristic curve (IEC 751)” on page 31, the characteristic curves for commonly used resistance thermometers. The X-axis represents the temperature in °C, the Y-axis the resistance in Ω .

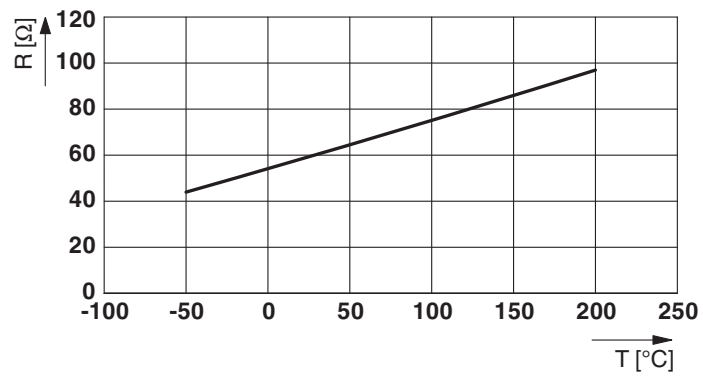
Ni 100 characteristic curve

Table 4-4 Ni 100 characteristic curve (DIN 43760)



Cu 53 characteristic curve





Table 4-5 Cu 53 characteristic curve (GOST 6651 $\alpha = 0.00426$)



°C	Ω
-50	41.71
0	53.00
50	64.29
100	75.58

Thermocouple types

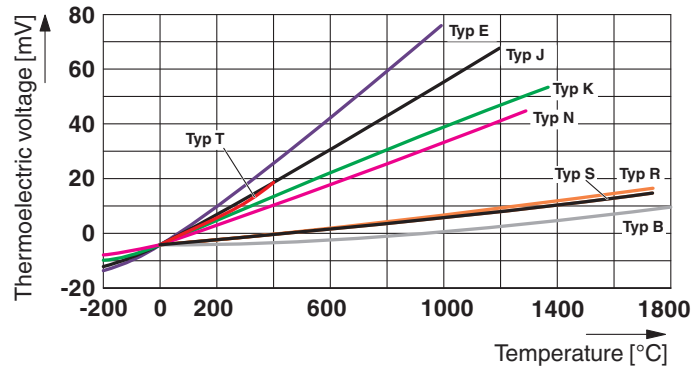
Table 4-6 Thermocouple types

Type	Standardization	Temperature range [°C]	IEC ¹ color code
B	IEC 60584	+500 ... +1820	Not defined
E	IEC 60584	-230 ... +1000	
J	IEC 60584	-210 ... +1200	
K	IEC 60584	-250 ... +1372	
N	IEC 60584	-200 ... +1300	
R	IEC 60584	-50 ... +1768	
S	IEC 60584	-50 ... +1768	Not defined
T	IEC 60584	-200 ... +400	
L	DIN 43760	-200 ... +900	-
U	DIN 43760	-200 ... +600	-
A-1	GOST 8.585	0 ... +2500	-
A-2	GOST 8.585	0 ... +1800	-
A-3	GOST 8.585	0 ... +1800	-
M	GOST 8.585	-200 ... +100	-
L	GOST 8.585	-200 ... +800	-

¹ International Electrotechnical Commission

Characteristic curves of thermocouples

Figure 4-6 Characteristic curves of thermocouples



4.3 Proximity sensors according to NAMUR¹ standard

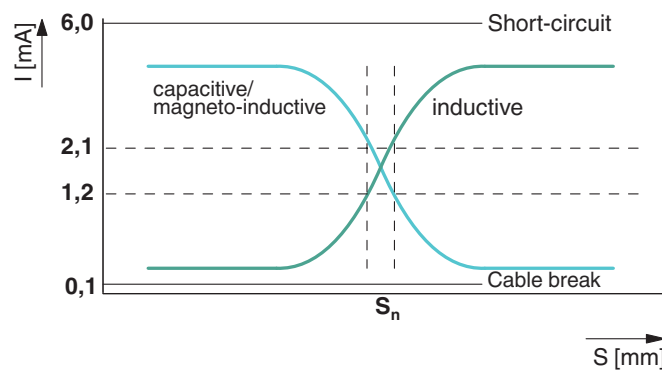
NAMUR sensors

NAMUR sensors are proximity sensors that are widely used in the fields of process technology and machine building. Depending on the different application purposes, they are available as optoelectronic, magneto-inductive, capacitive, and inductive sensors.

Sensors complying with the NAMUR standard have standardized electrical properties and measuring characteristics (IEC 60947-5-6: Control circuit devices and switching elements - DC interface for proximity sensors and switching amplifiers). They can therefore be used interchangeably regardless of their manufacturer. NAMUR sensors are short-circuit-proof. Short circuits and line breaks can be detected by the evaluating unit. There is no separate power supply required for the NAMUR sensor; it is supplied via the measuring circuit.

Figure 4-7 shows the measurement behavior of two NAMUR sensor types. Their essential properties are explained in the following.

Figure 4-7 NAMUR sensor characteristic (without optoelectronic variant)



$I_{[mA]}$: Sensor output current measured in mA

$S_{[mm]}$: Distance between object and sensor in mm

S_n : Distance between the two switching points that correspond to the associated current values and to which the switching behavior of the evaluating unit should be adapted.

Using capacitive and magneto-inductive sensor variants, the measured sensor output current will decrease when the object moves away from the sensor. In comparison, the output current will increase when using inductive sensor variants.

Hysteresis

The dashed lines are used to indicate the switching points to which the evaluating unit should be set. The lines are drawn in pairs to indicate the offset (hysteresis) that needs to be taken into account for the setting of the two switching points. This enables chatter to be avoided between switching on and off, when only one switching point is set and both the object and sensor will move in proximity of this switching point.

¹ The acronym "NAMUR" is based on the former German association name "Normenarbeitsgemeinschaft für Mess- und Regeltechnik in der chemischen Industrie" (standards working group for measurement and control engineering in the chemical industry). The acronym was kept.

Example

When using a capacitive sensor, the evaluation unit should use a measured current of 1.2 mA as the off signal when the object moves away from the sensor. If the object approaches the sensor again, the switching on process, however, should only take place at a measured current of 2.1 mA.

If the evaluating unit measures a sensor output current of 6 mA or higher, there will be a short circuit in the sensor or between the two connecting cables.

If the evaluating unit measures a sensor output current of 0.1 mA or lower, the sensor circuit or the connecting cables are interrupted.

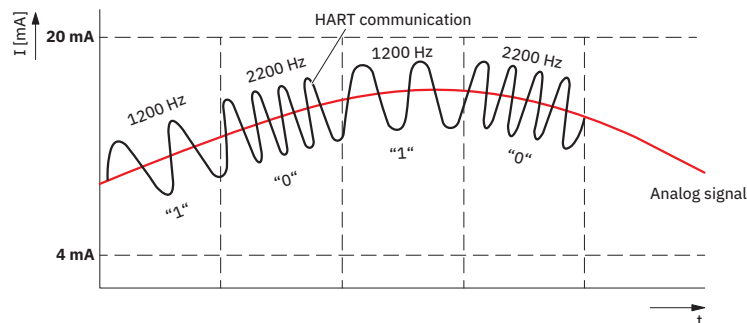


4.4 HART®

HART (Highway Addressable Remote Transducer) is an open fieldbus standard, whose technology is supported by the HART Communication Foundation (HCF), an independent non-profit organization.

The HART protocol is mainly characterized by the fact that, as opposed to other digital fieldbus systems, it is used in addition to conventional analog standard signals. Consequently, it does not replace point-to-point wiring, but enables the integration of intelligent field devices.

Figure 4-8 HART modulation of an analog standard current signal



Basics

Using the FSK (Frequency Shift Keying) method, a higher-frequency oscillation with an amplitude of ± 0.5 mA is modulated to the low-frequency 4 mA ... 20 mA standard signal, to simultaneously transmit digital and analog information (see Figure 4-8). In this process, a digital 1 is signaled and detected as a frequency of 1.2 kHz, and a digital 0 is signaled and detected as a frequency of 2.2 kHz.

In a flow meter, for example, it would thus be possible to transmit information about the current status of the device in addition to the 4 mA ... 20 mA proportional analog value of the flow rate, and to transmit new configuration data to the device.

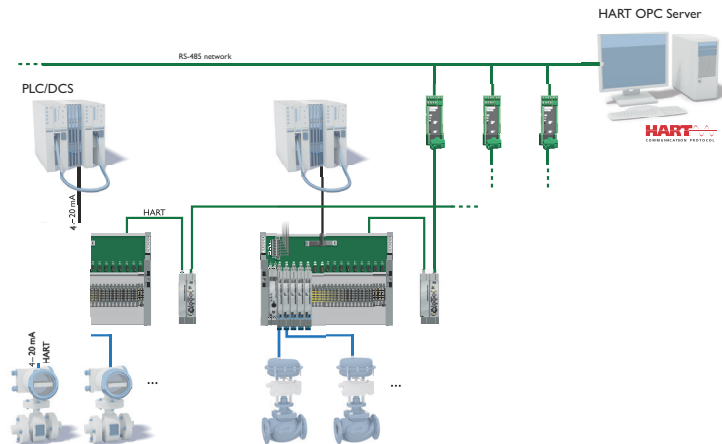
Characteristics

Essential properties of the HART standard are the following:

- Tried and tested, easy to install, to maintain, and to use
- Open de-facto standard freely available to any manufacturer or user; manufacturer-specific adjustments and extensions
- Retention of the cabling used for communication via the 4 mA ... 20 mA standard signal, which is prevalent throughout the industries
- HART allows for bidirectional digital communication between multiple HART field devices in addition to the continuing transmission of the analog standard current signal.
- The field devices used must be equipped with HART microprocessor technology, which is why they are often called "SMART" devices.
- Standardized in CPF9 (Communication Profile Family in accordance with IEC 61784)
- According to relevant equipment approvals: use of "intrinsically safe" circuits with limited current flow and protection against incendive sparks (suitable for potentially explosive areas, Ex zones 0 and 1)
- Optional use of two operating panels: the engineering panel in the control unit, and a secondary, usually mobile operating panel (laptop or control unit in the form of a handheld terminal)
- Optional looping-in of HART displays, for on-site diagnostics

Topology

Figure 4-9 HART topology



Field of application

Usually, HART signals are used when implementing the following communication functions:

- Extension of existing systems with HART components, and transmission of information about status, diagnostics, configuration, and control.
- Subsequent or temporary installation of field devices, e.g., transportable interoperable devices for implementing measurements and configurations.

i For the HART communication to work between the HART components, it must not be blocked by signal isolators or other interface modules.

Therefore, different interface modules are available for HART communication:

- Interface modules that let HART signals pass through unmodified (HART-transparent modules)
- Interface modules that block HART signals, for instance in order to disconnect certain parts of a system from HART communication because it might cause malfunctions there.
- Interface modules that can be adjusted either to forward or to block HART signals.

Advantages

All in all, arguments in favor of using HART technology are the following:

- Easy construction of a robust digital communication network, thanks to the use of existing 4 mA ... 20 mA wiring
- Efficient field device configuration and status diagnostics with online access
- Increased system availability with the preventive detection of deviations and errors
- Error-free bidirectional data exchange with HART-transparent signal conditioners – electrically isolated, even for intrinsically safe circuits
- Long distances covered and inexpensive retrofitting of system parts – with WirelessHART devices

4.4.1 HART multiplexer

HART multiplexers allow HART information to be integrated into engineering and management systems which are operated separately from evaluation and control unit(s).

The connections between HART field devices and the controller are brought together on a HART multiplexer connection board. There, the HART information is electrically isolated and either transmitted to the multiplexer, or received by it.

The multiplexer stores the process variables, configuration data, and diagnostic data of all connected HART-compatible field devices, communicating with the engineering and management system via one single connection.

Advantages


Arguments in favor of using HART multiplexers are the following:

- Bundling of many HART channels on a single line (usually 32 channels per multiplexer)
- Bundling of many HART multiplexers on a single controller interface (usually 128 multiplexers on one PC interface)
- Minimal space requirements, especially important for retrofitting in control cabinets with little space left for additional components
- Simple additional usage of information so far unused, and of functions of HART-compatible field devices

WirelessHART

4.4.2 WirelessHART

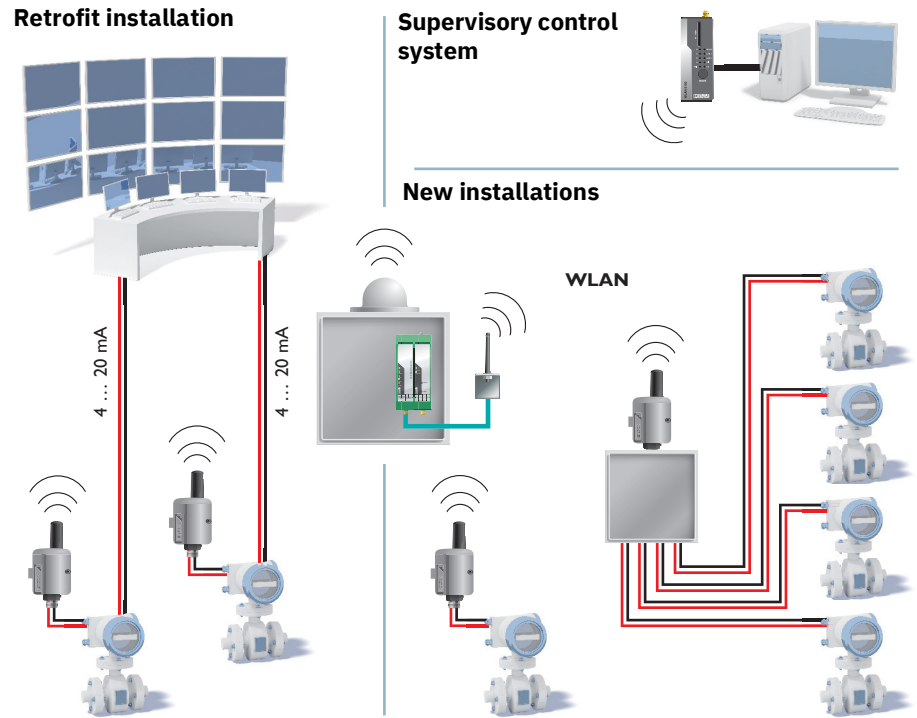
Bypassing of connections between field devices and control unit, which are not suitable for HART communication, can be done by means of wireless communication (WirelessHART). Specific wireless modules for connection to the field devices and the control unit are available.

 Like HART, WirelessHART is an open industrial standard, which was established in 2010 by IEC (International Electrotechnical Commission) as the international standard **IEC 62591**.

- Coverage of distances from 30 m to 250 m, depending on the building density
- Mesh-shaped layout (meshed network), in which each of the HART wireless modules simultaneously serves as a router and repeater
- Usage of installed tools and procedures for configuration, maintenance, and diagnostics

Topology

Figure 4-10 WirelessHART topology



Advantages

- Can be used when connections between field devices and control unit are not HART-compatible
- Better mobility and flexibility during system changes and extension
- Increased data throughput by means of simultaneous usage of multiple communication paths
- Compensation for transmission errors by means of automatic redirection of wireless signals around sources of interference

5 Application examples

The following examples show typical applications of signal conditioners. The application is briefly explained in each case. A circuit diagram shows how to connect the signal generator and the evaluation unit (e.g., the control system).

In the descriptive texts for the application examples, the term “signal conditioner” always refers to active signal conditioners with their own electrical supply. Passive signal conditioners without their own separate power supply are referred to as “passive isolators”.

A common application is temperature measurement. The function, design, advantages and disadvantages of various temperature measurement methods are described in detail in Section 4.2 on page 31. The measurement of temperature is therefore not discussed further below.

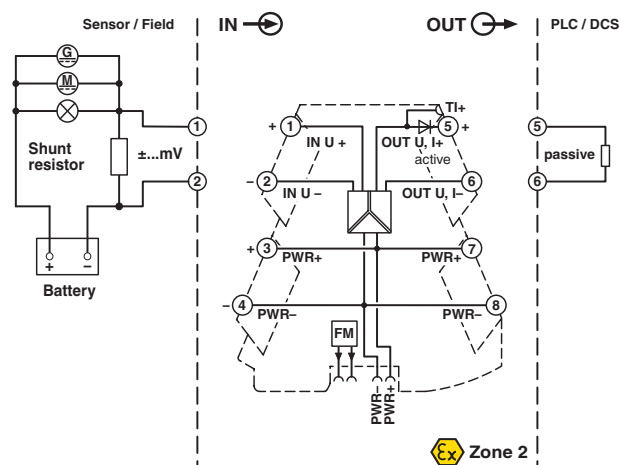
5.1 Analog IN/Analog OUT

5.1.1 Measuring the current consumption of a DC electric motor using a shunt

For current measurements in low and medium power ranges, a low-resistance (shunt) resistor is typically used within the circuit, which is connected in series with the load. An electric voltage drop takes place across the shunt, proportional to the current flowing through it. This voltage is measured. Based on this value, the strength of the electric current flowing across the shunt to the load is calculated according to Ohm’s law.

- The active sensor supplies a voltage signal, which is proportional to the motor current consumption, to the passive signal conditioner input.
- The signal conditioner supplies an active current output signal, which is analog to the input signal, to a passive input of the evaluation unit.

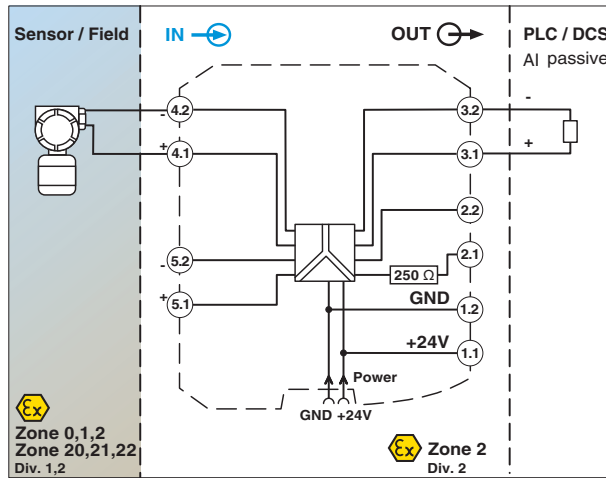
Figure 5-1 Current measurement with a shunt using a MINI MCR-2-U-UI multifunctional measuring transducer



5.1.2 Pressure measurement in an explosion-protected area

- The passive 2-wire sensor supplies a current signal, which is proportional to the pressure, to the active signal conditioner input.
- The signal conditioner supplies an active current output signal, which is proportional to the input signal, to a passive evaluation unit input.

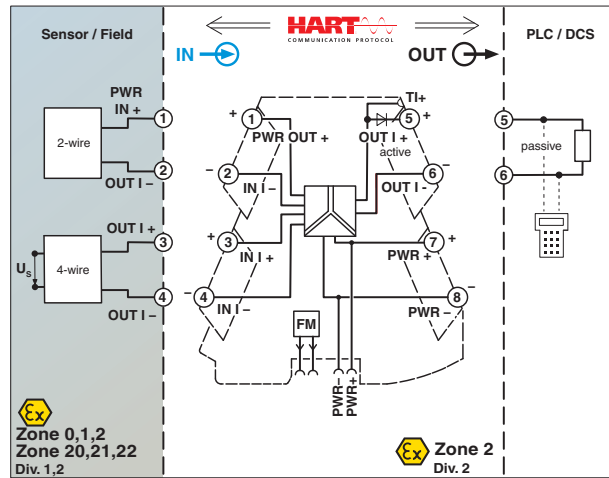
Figure 5-2 Pressure measurement in an explosion-protected area using a MACX MCR-EX-SL-RPSSI-I repeater power supply



5.1.3 Flow measurement in an explosion-protected area

- The active 4-wire sensor supplies a current signal, which is proportional to the flow rate, to the passive signal conditioner input.
- The signal conditioner supplies a passive current output signal, which is proportional to the input signal, to an active evaluation unit input.

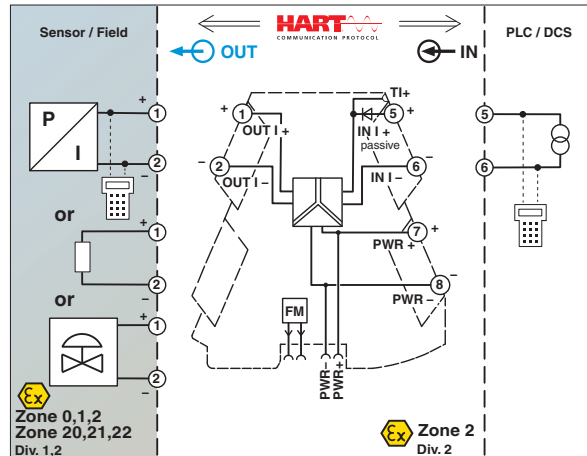
Figure 5-3 4-wire sensor for flow measurement in an Ex area using a MINI MCR-EX-RPSSI-I repeater power supply



5.1.4 Regulating valve control in an explosion-protected area

- The active output of the control unit supplies an analog current signal to the passive signal conditioner (output isolator) input.
- The signal conditioner supplies an active current output signal, which is proportional to the input signal, to the regulating valve. This signal is used for operating the regulating valve.

Figure 5-4 Regulating valve control in an Ex area using a MINI MCR-EX-IDS-I-I(-PT) signal conditioner

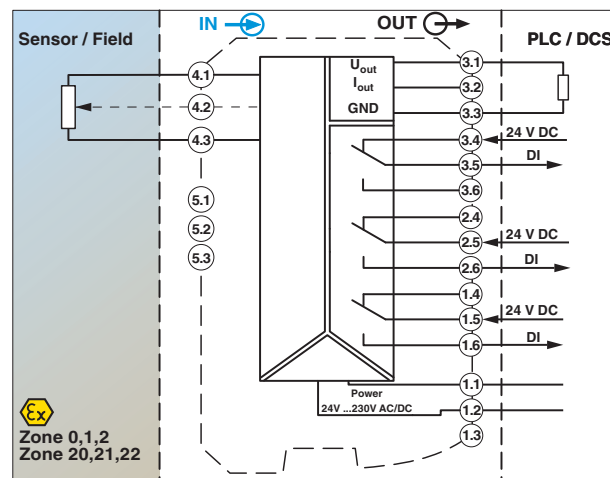


5.2 Analog IN, Digital OUT

5.2.1 Potentiometric position measurement with digital signal outputs

- The passive position sensor (potentiometer) supplies an analog signal to the active signal conditioner input.
- The signal conditioner supplies a digital output signal, which is dependent on the input signal, to three digital evaluation unit inputs.
- The three output signals can be configured independently of one another to certain input signal values (measured positions).
- In addition to the three digital outputs, the signal conditioner has an active analog current output or an active analog voltage output.

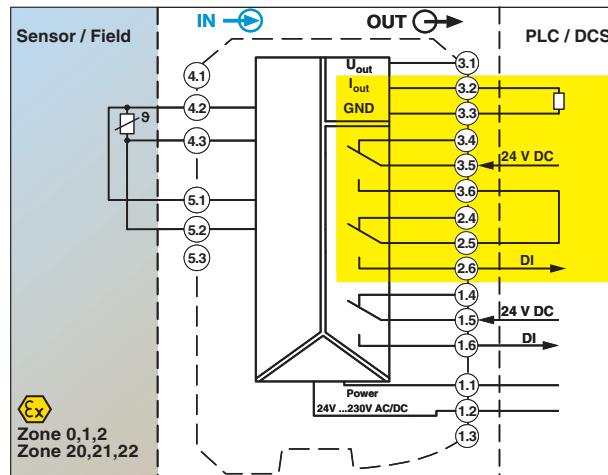
Figure 5-5 Potentiometric position measurement with digital signal outputs, e.g., with a signal conditioner of the MACX ... T-UIREL series



5.2.2 Temperature measurement with digital signal outputs

- The passive temperature sensor (RTD with 4-wire connection) supplies a resistance-dependent voltage signal to the active signal conditioner input.
- The signal conditioner supplies a digital output signal, which is dependent on the input signal, to two digital evaluation unit inputs.
- The two output signals can be configured independently of each other to certain input signal values (measured temperatures).
- As shown below, the two digital outputs (relay outputs as N/C contacts) 2 and 3 can be connected in series and used as redundant signals to be evaluated by the control unit, e.g., for switching off a system due to increased safety requirements.
- In addition to the two digital outputs, the signal conditioner has an active analog current output or an active analog voltage output.

Figure 5-6 Temperature measurement with digital signal outputs using the MACX MCR-EX-T-UIREL-UP-SP signal conditioner

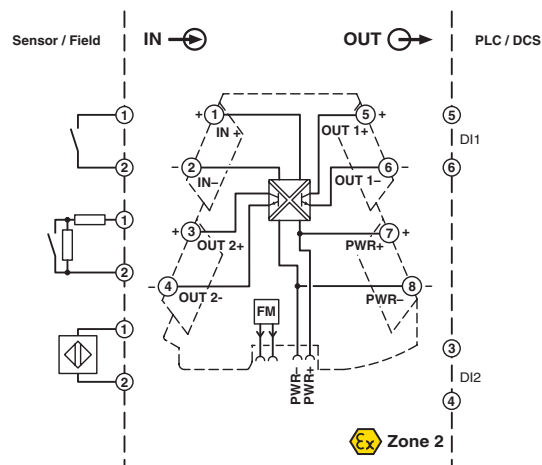


5.3 Digital IN, Digital OUT

5.3.1 Single-channel digital isolation of a proximity switch

- The passive NAMUR sensor (proximity sensor) supplies a digital pulse/frequency signal to the active signal conditioner input.
- The signal conditioner supplies a digital output signal, which is dependent on the input signal, to a digital input of the evaluation unit.
- The characteristic used to convert the input signal into the output signal can be configured.

Figure 5-7 Single-channel digital isolation of a proximity switch using the MINI MCR-2-NAM-2RO-PT signal conditioner

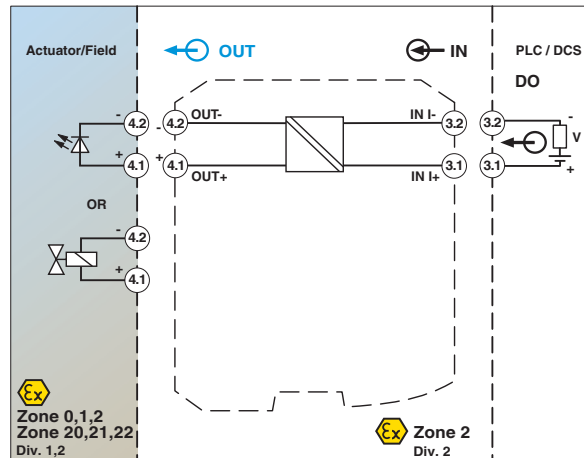


i Since the resistors for detecting measuring line interruptions and sensor failures are already integrated in the NAMUR proximity sensors, this error information is provided in the form of signals at both FM connections of the signal conditioner (fault monitoring). The FM signals are routed to the provided cables in the signal conditioner supply rail and can be evaluated by the control unit.

5.3.2 Digital valve control in an explosion-protected area

- The output of the control unit supplies a digital signal to the signal conditioner (output isolator) input.
- The signal conditioner supplies a digital signal, which is dependent on the input signal, to the regulating valve being operated by this signal (opened or closed).

Figure 5-8 Digital valve control in an explosion-protected area using a ... MCR-EX-SD-...-...-PT signal conditioner of the MACX Analog or MINI Analog Pro series

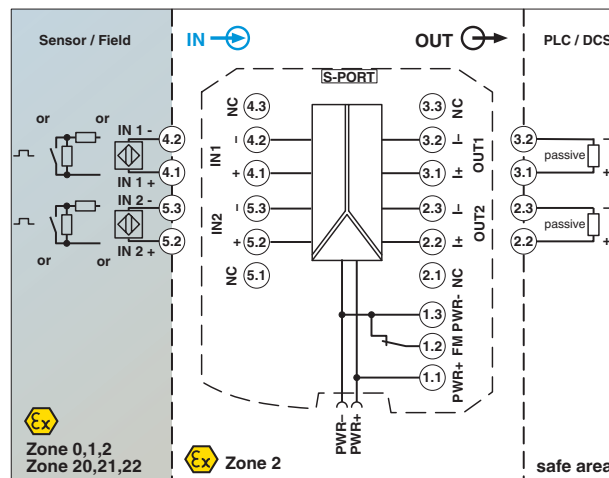


5.4 Digital IN, Analog OUT

5.4.1 Speed measurement

- In a mill that processes grain into flour, the speed monitoring system is to be retrofitted to a screw conveyor. For this purpose, a NAMUR sensor is to be installed above the screw at the upper outlet.
- With each full rotation, the so-called worm gear moves past the NAMUR sensor, causing it to deliver a pulse.
- The NAMUR sensor is connected to a signal conditioner. It transmits an active current signal to a passive input of an evaluation unit.
- The minimum and maximum frequencies can be configured as minimum and maximum values for the signal conditioner.

Figure 5-9 Speed measurement with a MACX MCR-EX-AP-2F-2I-SP signal conditioner

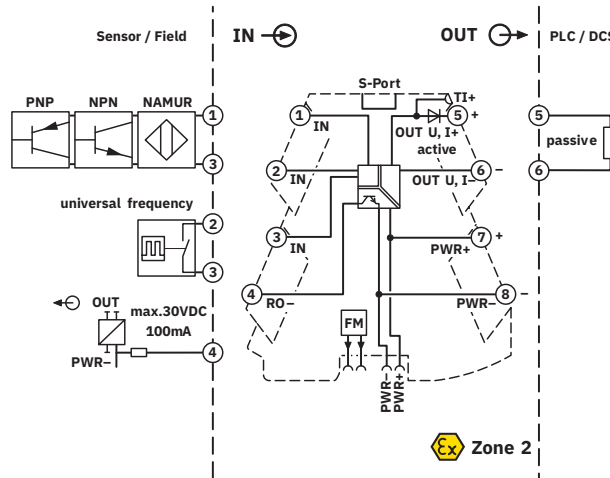


NOTE: Explosion hazard
The sensor and signal conditioner require approval for Ex areas as there is a risk of dust explosion from the flour.

5.4.2 Flow measurement

- A flow sensor with a frequency output is to be read by an evaluation unit that only provides a passive current input.
- A signal conditioner is configured so that the minimum and maximum frequency of the sensor corresponds to the values 4 mA and 20 mA .
- The active current output of the signal conditioner is connected to the passive current input of the evaluation unit.

Figure 5-10 Flow measurement with a MINI MCR-2-F-UI-PT signal conditioner



6 Digital fieldbuses

In systems using automation and process control engineering, two areas are connected by means of electrical cables:

- Field devices, i.e., the sensing devices (sensors) and actuating elements (actuators) in the system
- Evaluation and control unit(s)

To eliminate the need to connect each field device to the control unit by means of separate connecting cables, the first digital fieldbuses were developed and put in use in the 1980s. They enabled multiple field devices to be connected to the control unit via collectively used bus cabling, thus replacing multicore cable harnesses which had separate conductors for each field device:

- Each field device can be connected, at nearly any position, to the fieldbus cabling by means of an interface module.
- A digital bus protocol allows for communication between the field devices and the control unit, with the interface modules interpreting the sensor and control information sent and received by the field devices.



Since 1999, fieldbuses have been internationally standardized in accordance with **IEC 61158** (Digital data communication for measurement and control - Fieldbus for use in industrial control systems).

Today, most of the first generation fieldbuses are being amended or replaced by Ethernet. Ethernet is the protocol for connecting computers in a Local Area Network (LAN) which is most prevalent in the business world and in administration and science. Real-time-capable Ethernet has been developed for the requirements of industrial automation.

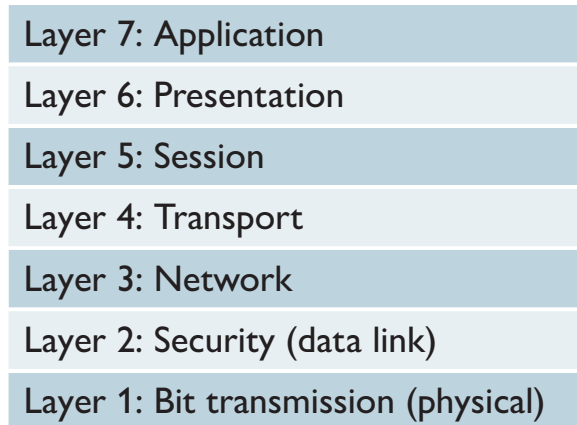
ISO/OSI reference model

In 1979, the International Organization for Standardization (ISO) developed a model for structuring and standardizing the world of data communication and networks. It is called the OSI reference model (Open Systems Interconnection). ISO was aiming at developing a reference model for the communication of two systems (computers, for instance).

According to the ISO/OSI reference model, a system A can communicate with a system B (two systems by different manufacturers). The ISO/OSI reference model consists of seven layers:

- Layer 1: Physical Layer
- Layer 2: Data Link Layer
- Layer 3: Network Layer
- Layer 4: Transport Layer
- Layer 5: Session Layer
- Layer 6: Presentation Layer
- Layer 7: Application Layer

Figure 6-1 ISO/OSI reference model



For most fieldbus systems, and in accordance with IEC standardizations, only the following layers of the ISO/OSI reference model are specified for communication protocols in computer networks:

- Layer 7: Application Layer
- Layer 2: Data Link Layer
- Layer 1: Physical Layer

In connection with the list of key advantages and disadvantages of the use of digital fieldbuses, two concepts of digital fieldbuses will be looked at more closely, as an example of numerous trends and products:

- The group of PROFIBUS protocols
- Ethernet-based systems

Advantages

- Relatively low cabling effort (savings in material and time during planning and installation)
- Improved signal availability, thanks to short signal paths especially for analog signals
- Standards facilitate the replacement of components made by different manufacturers.
- Relatively high flexibility in terms of modification and extension
- Parameterization, status requests, etc. can be done from the control room

Disadvantages

- These relatively complex systems require qualified personnel for planning, installation, maintenance, and troubleshooting. Initial cost savings may therefore be canceled out.
- Higher prices for components and smallest replaceable units
- Slightly higher response times
- Connecting a bus centrally results in broader consequences in the case of a malfunction, and may require a redundant design of the bus.
- Higher and partially complex requirements for the wiring and the grounding concept of systems

6.1 Serial fieldbuses

6.1.1 PROFIBUS

PROFIBUS is a multi-controller-capable bus system that transfers a so-called token during authorization for establishing communication between the controllers. Connected devices can be divided into controllers and devices. Controllers are usually automation or engineering systems.

- Automation systems, such as PLCs, are called class 1 controllers.
- An example of an engineering system is a PC that is connected to the bus for startup. These systems are called class 2 controllers.

Devices are field devices able to communicate only if they are requested to do so by the controller.

PROFIBUS offers different data exchange variants:

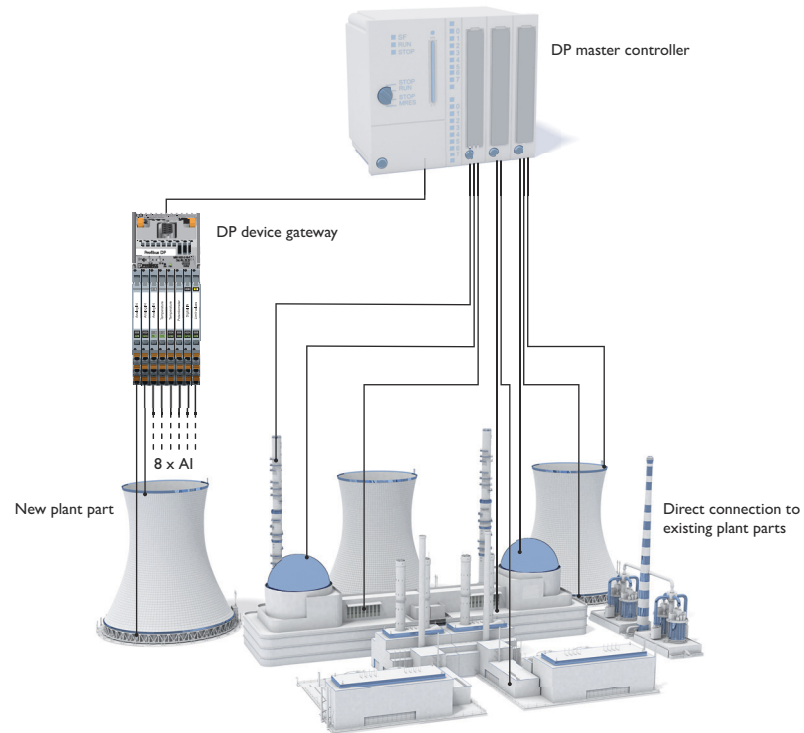
- Cyclic data exchange for process data
- Acyclic data exchange for parameterization data

Characteristics

- Mostly used in Europe, initially
- Can be used both in production automation and in process automation
- Bit-serial data transmission
- Topology: line or tree
- Multi-controller-capable communication
- Controlled access to the bus by combination of controller/device and token passing methods
- Special variants for Decentralized Peripherals (DP), Process Automation (PA), and Fieldbus Message Specification (FMS)
- Standardized in CPF3 in accordance with IEC 61784

Topology

Figure 6-2 PROFIBUS topology



Advantages

- Used in all sectors of industrial automation thanks to decades of proven technology and widespread use
- The world's most successful fieldbus with 67.4 million devices installed by the end of 2022
- Internationally standardized in accordance with IEC 61158

6.1.2 Modbus/RTU

The Modbus/RTU protocol was developed by Modicon in 1979. The open communication protocol was used for data exchange between PLCs and is widely used in industry and building automation.

Modbus is a single-client bus system that uses addresses to address devices directly. The client is usually an automation system such as PLCs.

The servers are field devices that must be addressed by the client in order to communicate. Due to the protocol, the number of servers is limited to 247.

Characteristics

- Used worldwide
- Used in industry automation and process control
- Bit-serial data transmission
- Topology: line
- Servers are addressed using addresses
- Standardized in accordance with IEC 62769

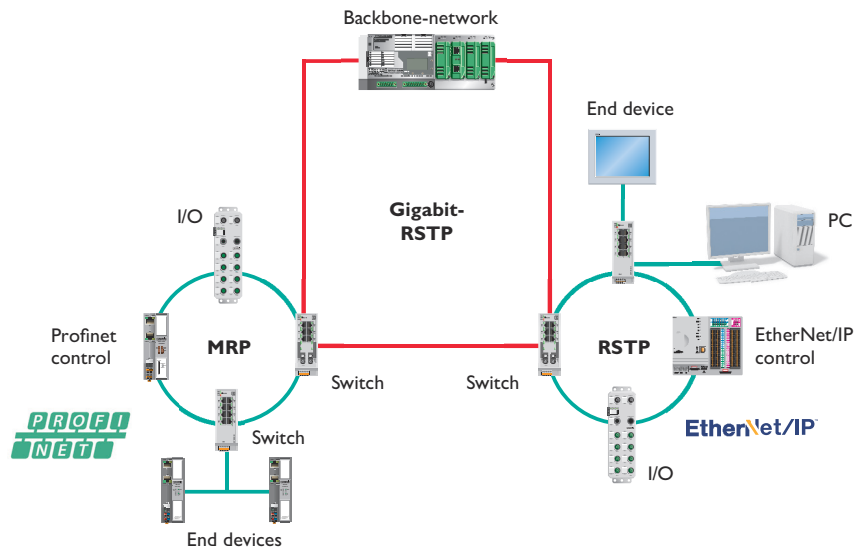
Advantages

- Used worldwide through open standard
- Management and ongoing development by the Modbus organization

6.2 Ethernet-based fieldbuses

The proportion of Ethernet-based fieldbus systems (Industrial Ethernet) has been gaining in importance within automation technology for several years. Especially on the management level, but also on control level, Industrial Ethernet is state of the art today.

Figure 6-3 Topology of Ethernet-based systems



6.2.1 EtherCAT

Beckhoff Automation developed the EtherCAT protocol and introduced it in 2003. It was declared an IEC standard in 2007.

EtherCAT is a real-time-capable Industrial Ethernet that also provides short cycle and synchronization times.

Characteristics

- Real-time capable, usable for hard and soft real-time requirements
- Any type of topology possible
- Safety over EtherCAT (FSoE) fulfills the requirements up to SIL 3
- The standard Internet protocols can be transmitted with Ethernet over EtherCAT
- Transmission speeds of up to 10 Gbps possible
- Additionally transmit two times 24 V with up to 3 A using EtherCAT P
- Standardized in accordance with IEC 61158 and IEC 61784
- Allows the transmission of other protocols via the EtherCAT network

Advantages

- Internationally standardized in accordance with IEC 61158 and IEC 61784
- Future-proof thanks to ongoing development by the EtherCAT Technology Group (ETG)

6.2.4 EtherNet/IP

EtherNet/IP (EtherNet Industrial Protocol) is a form of real-time Ethernet mainly used in the field of automation technology. EtherNet/IP or EIP was developed by Rockwell Automation and later handed over to ODVA as an open standard.

EtherNet/IP is also standardized in IEC 61158, the series of standards for fieldbuses.

Characteristics

- Supports TCP/IP and UDP protocols so that EIP can be seamlessly integrated into existing networks.
- Real-time-capable
- Uses the CIP (Common Industrial Protocol) so that it can also be used in conjunction with ControlNet and DeviceNet.
- Can be used flexibly thanks to the option of cyclic and acyclic communication

6.2.5 Single Pair Ethernet (SPE)

Single Pair Ethernet (SPE) is one of the key technologies for Industry 4.0. SPE makes it possible to create networked plants and systems without having to become unnecessarily complex.

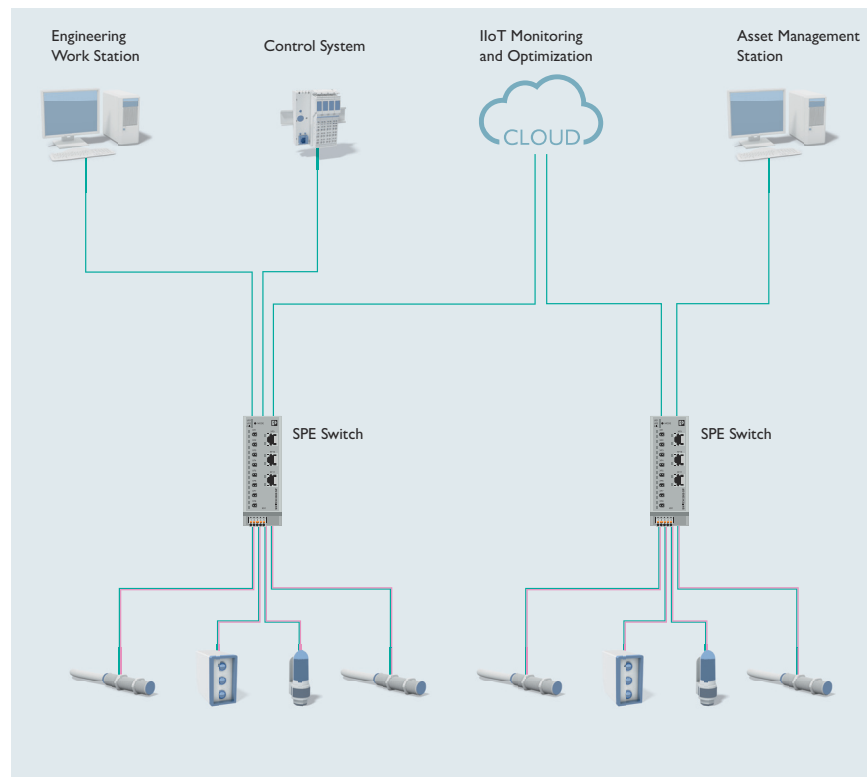
SPE describes an Ethernet connection via a wire pair, i.e., two lines. Transmission speeds of up to 10 Gbps or distances of up to 1000 m are bridged.

With SPE, a device is not bound to a transmission protocol.

Characteristics

- All Ethernet-based industrial protocols also support transmission via SPE
- Offers the option of using existing cables within certain limits
- It is possible to supply connected devices via PoDL
- Includes technologies that can be used in Ex zones – [“Ethernet-APL” on page 67](#)
- Manufacturer-independent and standardized worldwide by IEC and IEEE

Figure 6-4 Ethernet/SPE topology

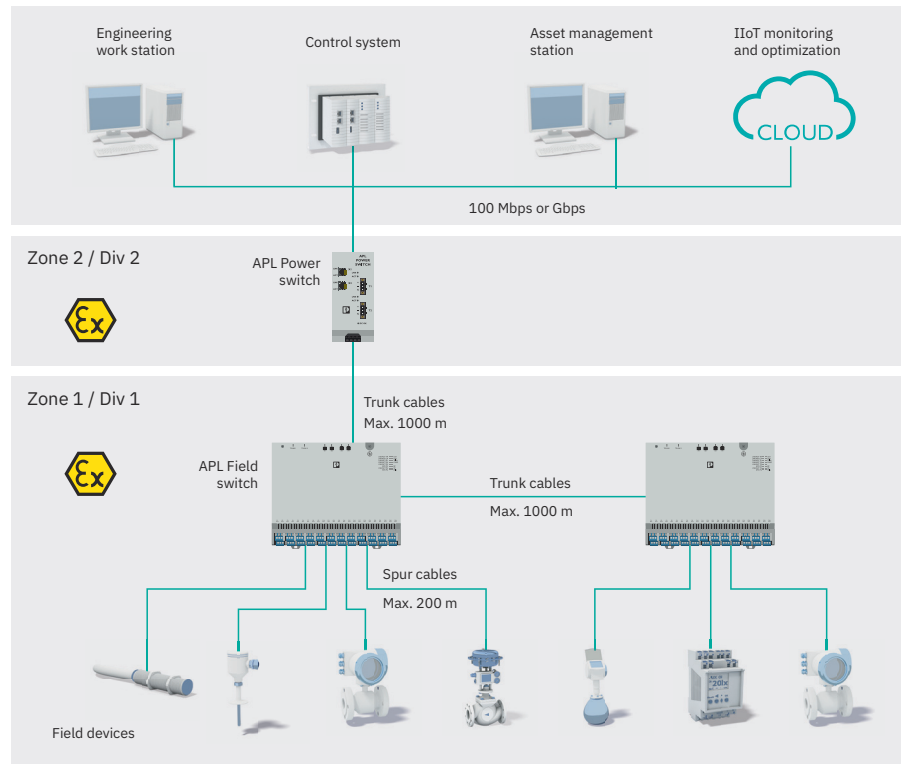


6.2.6 Ethernet-APL

Ethernet-APL stands for Advanced Physical Layer and is part of Single Pair Ethernet. The ongoing development of the layer makes it possible to transmit Ethernet data via two wires. It also offers power supply options via the same wire pair.

Ethernet-APL uses the 10Base-T1-L standard from IEEE 802.3cg and the IEC TS 60079-47, 2021-03 (2-WISE) standard. This stands for Intrinsically Safe Ethernet and therefore allows use in Ex zones and where intrinsic safety is required.

Figure 6-5 Ethernet-APL topology



7 Basics of functional safety

7.1 Functional safety in accordance with the safety integrity level (SIL)

The safety integrity level (SIL) is based on the following standards for the process industry:

Table 7-1 SIL standards for process industry

Name		Target group
IEC/EN 61508	Functional safety of electrical/electronic/programmable electronic safety-related systems	Device and system manufacturers
IEC/EN 61511	Functional safety - Safety instrumented systems for the process industry sector	Planners, installers, and operators of systems

Special standards are available for the functional safety of machines.

The following objectives are aimed at assessing the SIL and designing the devices and systems:

- Assessment regarding the probability of failure and reliability of safety functions
- Traceable measurability and quantification of the probability of failure or risk reduction
- Use of safety-related design principles to minimize the desired low level of malfunctions to an acceptable residual risk
- Finally, the protection of life, health, environment, and goods

In the so-called hazard assessment of systems used to determine their SILs two factors are taken into consideration:

- Reliability and probability of failure of the system
- Hazard potential of the system

According to the above-mentioned standard, there are four SILs ranging from level 1 (low) to level 4 (high). Systems with a low hazard potential can be operated with a low SIL. Systems with SIL 1 and 2 can be assessed by manufacturers at their own responsibility. Systems with a high hazard potential need a high SIL. Systems with SIL 3 and 4 need to be assessed and certified by independent third parties.

SIL assessment, however, cannot be restricted to individual modules and safety equipment, as the standard requirements refer to safety circuits or, essentially, the interconnection of equipment such as sensors, actuators, control elements, etc.

If subsystems are assigned to different SILs, the overall system will have the lowest SIL of the subsystems. In order to increase the SIL of a subsystem, it is possible, for example, to use components that are set up in order to ensure redundancy. In process industry, measuring circuits are most often assigned to SIL 2 or occasionally to SIL 3 which usually occurs when the subsystems are set up to be redundant.

7.1.1 SIL inspection

The following process sequence is subject to SIL standards, whereby the “four eyes principle” (double checking) is required with regard to all steps of assessment, planning and verification.

1. Risk analysis: Determining the required risk reduction (specification of SIL requirement)
2. Implementing the risk reduction (implementation and SIL assessment of safety equipment)

1. Risk analysis

- a. Identifying all risks (using a risk identification method)
- b. Determining the reduction requirement for each risk
- c. Quantifying the required risk reduction for each risk (using a risk assessment method from which the SIL requirement may be derived as a result)

Risk identification and risk assessment are often carried out using software. Commonly used methods:

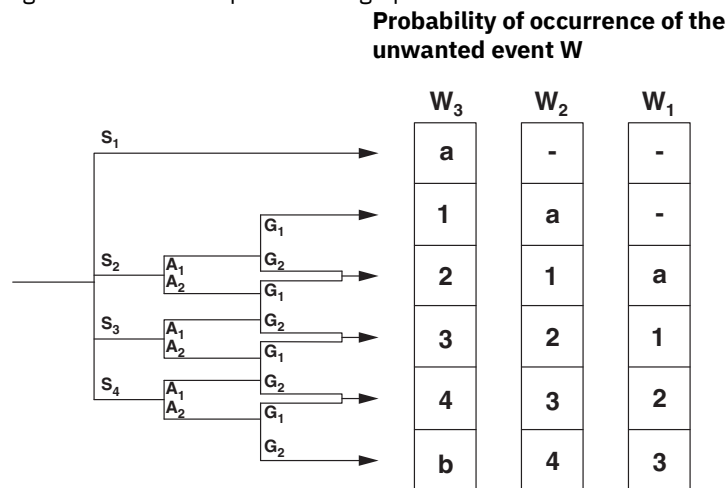
Risk identification methods

- HAZOP (“Hazard and operability study”)
- Event tree analysis (ETA)
- Fault tree analysis (FTA)

Risk assessment and quantification methods

- Risk graph (see [Figure 7-1](#))
- LOPA (“Layer of protection analysis”)
- Risk matrix (see [Figure 7-2](#))

Figure 7-1 Example of a risk graph



- 1, 2, 3, 4** Safety integrity level, SIL
- tolerable risk, no safety requirements
- a** no special safety requirements
- b** a single E/E/PE system is not sufficient

Risk parameters

Severity of injury and damage

- S₁** Slight injury or damage
- S₂** Serious, irreversible injury or death of a person, temporary serious damage
- S₃** Death of several people, long-term damage
- S₄** Many deaths, catastrophic consequences

Frequency/duration of stay

- A₁** Seldom to frequent stay in the danger zone
- A₂** Frequent to permanent stay in the danger zone

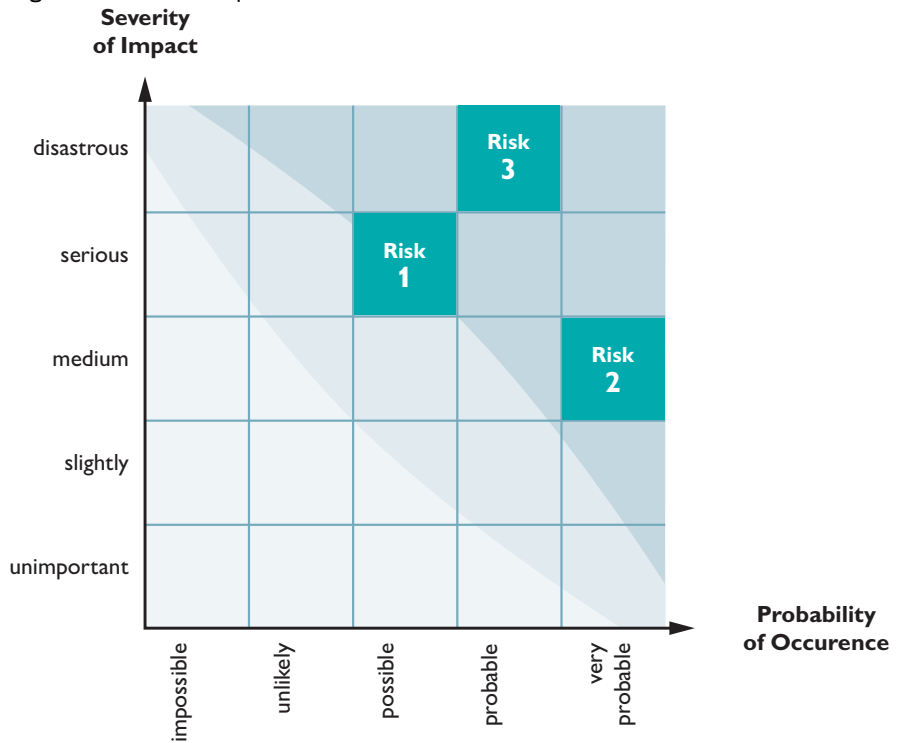
Avoidance of danger

- G₁** Possible
- G₂** Not possible, scarcely possible

Probability of occurrence of the unwanted event

- W₁** Very low, scarcely
- W₂** Low
- W₃** High, frequent

Figure 7-2 Example of a risk matrix



2. Risk reduction

The operational control equipment of a system enables normal operation and, in general, already includes safety functions. However, these functions can rarely cover all avoidable risks up to the acceptable residual risk. For this reason, additional operational control and safety equipment is used that is only activated in the event of malfunctions.

The design of operational control and safety equipment may prevent incidents or limit consequences/damages and must be adapted to the risk:

- The tolerable residual risk must be sufficiently low.
- The expense with regard to planning, installation, and operation must be reasonable.

The objective is thus to achieve that the operational control and safety equipment fulfills the required risk reduction (SIL requirement) as precisely as possible:

- Instructions for the design of the safety equipment can be found in the **IEC/EN 61508** and **IEC/EN 61511** standards (see above) and the **VDI/VDE 2180** directive “Safeguarding of industrial process plants by means of process control engineering (PCE)”.
- It is necessary to examine whether a possible safety equipment failure would be due to random or systematic reasons, how likely it is that it will occur and if it can be avoided or not.
- The practical implementation of the safety equipment should cover the following three aspects:
 - a) **Fault avoidance** using an FSM (Functional Safety Management) system
 - b) **Fault control** by means of redundancy, diagnostic coverage, safe states in the event of a fault
 - c) Quantification of **probability of failure** due to random errors (PFD/PFH calculation, see below)

7.1.2 SIL-relevant parameters

The SIL-relevant safety parameters are provided by the device manufacturers in the device documentation in order to help the planners and users with the SIL classification of measuring chains in which the devices will be used.

The abbreviations used in the following two examples are explained from [page 74](#) onward.

Example taken from a data sheet

Safety integrity requirements

Error rates

- Type B device (in accordance with IEC/EN 61508-2)
- Safety integrity level (SIL) 2
- HFT = 0
- 1oo1 architecture

λ_{sd}	λ_{su}	λ_{dd}	λ_{du}	SFF	DC _D	HFT
$4.61 * 10^{-7}$	$1.50 * 10^{-7}$	$3.18 * 10^{-8}$	$3.23 * 10^{-7}$	91.3%	90.2%	0

The total failure rate is: $9.62 * 10^{-7}$

MTTF (Mean Time To Failure) is: 119 years.

The probability of a dangerous failure per hour for “continuous demand” operating mode and the average probability of the specified function failing on demand for “low demand” operating mode are determined based on the error rates:

PFD_{avg} values

T[PROOF] =	1 year	2 years	3 years	5 years	7 years	8 years
PFD _{avg} =	$1.3 * 10^{-4}$	$2.6 * 10^{-4}$	$3.91 * 10^{-4}$	$6.51 * 10^{-4}$	$9.11 * 10^{-4}$	$1.04 * 10^{-3}$

PFH* = $3.23 * 10^{-8}$ /h

The calculation is performed assuming a checking interval of 1 year and a repair time of 8 hours.

On the basis of the value determined for the average probability of failure PFD_{avg}, the checking interval can be increased to up to 7 years.

Example of an FMEDA table

Table 7-2 FMEDA¹ table taken from a TÜV approval for a device (TÜV: German abbreviation for Technischer Überwachungsverein, English: technical inspection association)

SFF	Type A subsystems			Type B subsystems		
	Hardware fault tolerance (HFT)					
Safe failure fraction	0	1	2	0	1	2
< 60%	SIL 1	SIL 2	SIL 3	Not permitted	SIL 1	SIL 3
60% - < 90%	SIL 2	SIL 3	SIL 4	SIL 1	SIL 2	SIL 4
90% - < 99%	SIL 3	SIL 4	SIL 4	SIL 2	SIL 3	SIL 4
≥ 99%	SIL 3	SIL 4	SIL 4	SIL 3	SIL 4	SIL 4
Safety integrity level (SIL)	Operating mode with low requirement level (average probability of failure on demand of a safety function = PFD)					
4	≥ 10 ⁻⁵ to 10 ⁻⁴					
3	≥ 10 ⁻⁴ to 10 ⁻³					
2	≥ 10 ⁻³ to 10 ⁻²					
1	≥ 10 ⁻² to 10 ⁻¹					

¹ FMEDA = Failure Mode Effect and Diagnostic Analysis

Explanation of the abbreviations in the examples (data sheet, FMEDA table)

PFD_{avg}

Average probability of failure on demand

- Average probability of dangerous failures on demand of a safety function
- Determined for low-demand mode. Protection systems of process technology systems for the chemical industry usually operate with a low demand rate:
 - a) The safety function is only used in case of danger, in order to transfer the system to be monitored into the defined safe state.
 - b) The safety function is demanded less than once a year.

PFH

Probability of a dangerous failure per hour

- Probability of failure per hour for the safety function
- Determined for high-demand mode or essentially if it is required to permanently keep the system to be monitored in its normal safe state (e.g., for speed monitoring on machines).

SFF

Safe failure fraction

- Safe failure fraction: Rate of failures without the potential to set the safety-related system to a dangerous or impermissible function state
- For example, a value of 91.3% implies that, on average, 91.3 of 100 failures are not critical for the safety function.

HFT

Hardware fault tolerance

- Hardware fault tolerance:
Ability of a function unit to continue with the execution of a demanded function despite existing errors or deviation
- The value 0 indicates that there is “no hardware redundancy”. A fault (hardware failure) will result in the loss of the safety function. Value 1 (simple redundancy) means that at least two faults are required to cause a loss of the safety function.

Type A/B

Type A devices

- Simple devices for which the failure behavior of the components can be completely described, e.g., 4 mA ... 20 mA repeater power supply

Type B devices

- Complex devices for which the failure behavior is not fully known, e.g., microprocessor software and device firmware

$\lambda_d, \lambda_{dd}, \lambda_{du}, \lambda_s$

λ_d	Rate of dangerous failures	Rate of dangerous failures per hour
λ_{dd}	Rate of dangerous detected failures	Rate of detected dangerous failures per hour
λ_{du}	Rate of dangerous undetected failures	Rate of undetected dangerous failures per hour
λ_s	Rate of safe failures	Rate of safe failures per hour

8 Basics of explosion protection

8.1 Safety in potentially explosive areas



Explosion protection is a subfield of safety technology and plays a particularly important role with regard to design and operation of technical systems in the following sectors:

- Chemical industry
- Mining industry, oil and natural gas production
- Wood-processing and textile industry
- Food industry
- Coating technology

Explosion protection must also be taken into account in fields which, at first glance, seem not to be affected, e.g., for chocolate production:

- Cocoa powder in connection with atmospheric oxygen may constitute the danger of a dust explosion.
- High-proof alcoholic solutions that are used to clean mixing vessels and pipes can form explosive gas mixtures.

Explosion protection needs to be technically implemented wherever flammable substances in the form of gas, vapor, mist, or dust can react with oxygen if source of ignition is present. Depending on the propagation velocity of this chemical reaction, the following rough classification is made which goes beyond the combustion process:

- Deflagration [cm/s]
- Explosion [m/s]
- Detonation [km/s]

Sources of ignition

The following table provides an overview of ignition sources.

Table 8-1 Sources of ignition

Source of ignition	Examples of causes
Sparks	Mechanically created sparks (e.g., caused by friction, impact or abrasion processes), electric sparks
Electric arcs	Short circuit, switching operations
Hot surfaces	Heater, metal-cutting production, heating up during operation
Flames and hot gases	Combustion reactions, flying sparks during welding
Electrical systems	Opening/closing of contacts, loose contact A PELV (U < 50 V) is not an explosion protection measure. Low voltages can still generate sufficient energy to ignite a potentially explosive atmosphere.
Static electricity	Discharge of charged, separately arranged conductive parts, as with many plastics, for example
Electrical compensating currents, cathodic corrosion protection	Reverse currents from generators, short circuit to exposed conductive part/ground fault in case of errors, induction

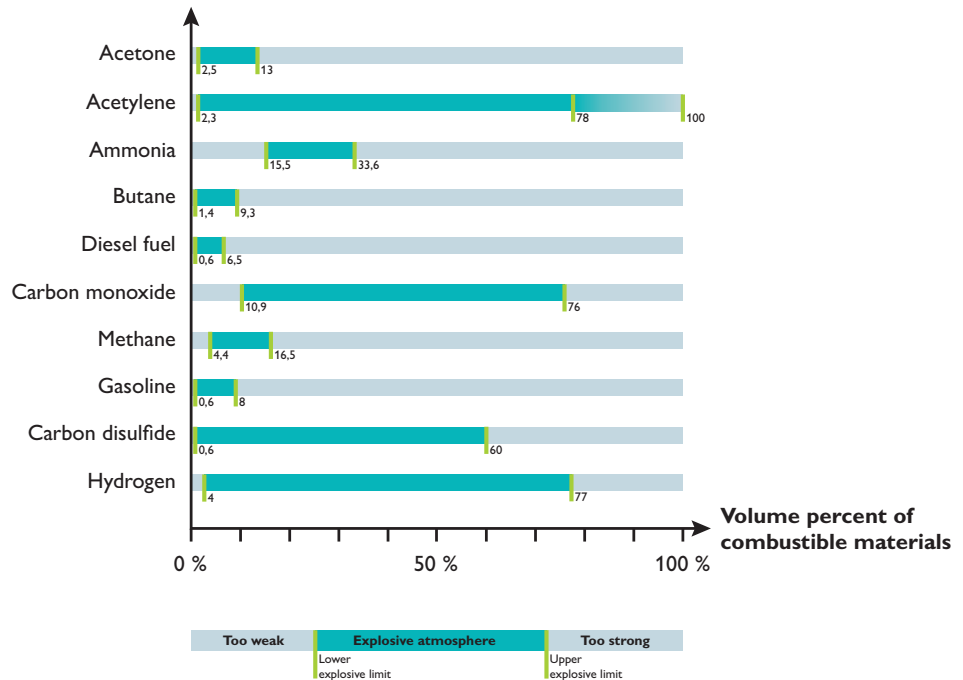
Table 8-1 Sources of ignition [...]

Source of ignition	Examples of causes
Electromagnetic waves in the range of 3×10^{11} Hz ... 3×10^{15} Hz	Laser beam for distance measurement, especially for focusing
High frequency 10^4 Hz ... 3×10^{12} Hz	Wireless signals, industrial high-frequency generators for heating, drying, or cutting
Lightning strike	Atmospheric weather disturbances
Ionizing radiation	X-ray machine, radioactive material, absorption of energy leads to heating up
Ultrasound	Absorption of energy in solid/liquid materials leads to heating up
Adiabatic compression and shock waves	Sudden opening of valves
Exothermic reactions	Chemical reaction leads to heating up

Gas concentration

The concentration of gases in the gas/air mixture determines whether or not an explosion can take place. The mixture can only be ignited if the concentration of the material is between the lower explosive limit (LEL) and the upper explosive limit (UEL).*

Figure 8-1 Examples of flammable gas concentrations in the air at normal pressure
Examples of gases under normal pressure



The table is based on normal pressure and room temperature. The explosion range of a material expands as the pressure and temperature rise.

Dust concentration

Similar specifications as those defined for gases can also be made for dusts even though the explosive limits do not have the same meaning here. Clouds of dust are generally heterogeneous and the concentration within the same cloud fluctuates greatly. A lower flammability limit (of approximately 20 g/m³ ... 60 g/m³) and an upper flammability limit (of approximately 2 kg/m³ ... 6 kg/m³) can be determined for dust.

*Some chemically non-resistant materials (e.g., acetylene, ethylene oxide) can also undergo exothermal reactions without oxygen through self-decomposition. The upper explosive limit (UEL) changes to 100 percent by volume.

Procedures

Explosion protection procedures are classified as follows:

1. Primary explosion protection: **Avoidance of explosive atmospheres**
Replacement, dilution, passivation of explosive substances, e.g., by adding nitrogen or carbon dioxide
2. Secondary explosion protection: **Avoidance of effective ignition sources**
Avoidance of all ignition sources, reducing the expansion of the potentially explosive zone
3. Tertiary explosion protection: **Constructive explosion protection**
Explosion suppression by means of extinguishing devices, pressure-resistant and pressure shock-resistant design of devices and buildings, automated sealing and pressure relief systems

The integrated explosion protection considers all classes of procedures in their sequence indicated above with regard to priority and order.

8.1.1 Directives, standards, and regulations

ATEX Directives

In Europe, explosion protection is specified by ATEX Directives:

- ATEX Product Directive 2014/34/EU (also known as ATEX 114) applies to manufacturers of devices and equipment carrying a risk of ignition.
- ATEX Operational Directive 1999/92/EC (also known as ATEX 118a or ATEX 137) applies to system operators.

Equipment group, equipment category

In the ATEX Directives, equipment is divided into groups and categories. Details are shown in the following table:

- Equipment group I (mines) with categories M1 and M2
- Equipment group II (other equipment) with categories 1, 2, 3

Table 8-2 Equipment groups and categories in accordance with ATEX Directives

Equip-ment group	Category	Degree of protection	Protection guarantee	Operating conditions
I	M1	Very high degree of safety	Two independent protective measures Safe if two errors occur independently of one another	For reasons of safety, it must be possible to continue operating a device even if the atmosphere is potentially explosive
I	M2	High degree of safety	In normal operation, protective measures remain effective even under difficult conditions	It must be possible to switch off these devices if a potentially explosive atmosphere occurs
II	1	Very high	Two independent protective measures. Safe if two errors occur independently of one another	Devices can still be used in zones 0, 1, 2 (G) ¹ , and 20, 21, 22 (D) ² and continue to be operated
II	2	High	Safe in normal operation and if common errors occur	Devices can still be used in zones 1, 2 (G) ¹ , and 21, 22 (D) ² and continue to be operated
II	3	Normal	Safe in normal operation	Devices can still be used in zones 2 (G) ¹ and 22 (D) ² and continue to be operated

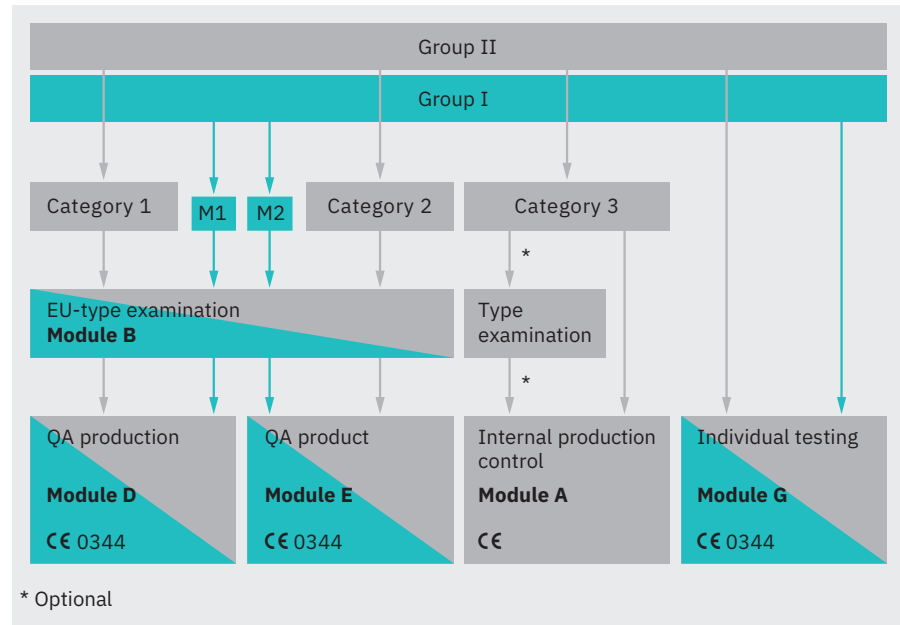
¹ (G) = Gas

² (D) = Dust

Conformity assessment

Depending on the assignment of a device to the equipment group and category and if used for its intended purpose, the method of conformity assessment is determined according to Figure 8-2:

Figure 8-2 Determining the conformity assessment method



The ATEX Directives specify the basic requirements for health and safety that are to be implemented in the so-called harmonized standards or in manufacturer's and operator's own standards and guidelines.

Before a product can be placed on the market in the European Union, every manufacturer must conduct a conformity assessment procedure. There are several so-called Modules that the manufacturer can use for this depending on the group and category the product is classified into. A combination of Modules B and D is generally used for Category 1 and 2 electrical devices (see Figure 8-2). The identification number of the Notified Body that is monitoring the production process is then added after the CE marking, for example, CE 0344. In the case of individual testing (Module G – unit verification), the identification number of the Notified Body that conducted the individual testing must be appended to the CE marking. Module A (internal control of production) is used for Category 3 electrical devices. In this case, a Notified Body identification number may not be used.

With regard to the different standards for different applications, the following fields of application can be differentiated. In general, there are correlations between the European (EN), international (IEC), US (NEC, FM, UL), and Canadian (CSA) regulations:

- Electrical equipment in areas with a danger of gas explosions
- Electrical equipment in areas with a danger of dust explosions
- Non-electrical equipment in potentially explosive areas
- Operation of process technology systems

8.1.2 Zone classification

The areas in which an explosive atmosphere may arise are divided into zones. The probability of danger serves as the main classification criterion. If there are doubts about how the zones are to be divided, the protective measures must be based on the highest possible probability of occurrence of a hazardous, potentially explosive atmosphere.

Table 8-3 Requirements for electrical equipment in Ex zones

Zone	Approval of electrical equipment
0	Explicit approval for zone 0 and examination certificate of a recognized testing body
1	Examination certificate of a recognized testing body
2	Requirements in accordance with VDE 0165/9.83, Clause 6.3

The zone classification in prevailing European standards is based on the following dependencies:

- separation between hazardous areas with a danger of gas or dust explosions
- according to type of danger
- according to equipment category (see [Table 8-2](#))

Table 8-4 Zones for areas with a danger of gas explosions in accordance with IEC/EN 60079-10-1

Zones	Type of danger
Zone 0	Continuous, long periods, frequent
Zone 1	Occasional
Zone 2	Not usually present, short periods only

Table 8-5 Zones for areas with a danger of dust explosions in accordance with IEC/EN 60079-10-2

Classification in Germany prior to ATEX	Classification in accordance with ATEX	Type of danger
Zone 10	Zone 20	Continuous, long periods, frequent
	Zone 21	Occasional
Zone 11	Zone 22	Not usually present, short periods only

Table 8-6 Assignment of zones and equipment categories according to 1999/92/EC Operator Directive

Zone	Equipment category
0, 20	1
1, 21	1, 2
2, 22	1, 2, 3

8.1.3 Types of protection

The types of protection define design principles to be used in the different areas in order to provide protection from explosions. Details are described in IEC/EN standards. The following four tables provide information on type of protection standards for electrical equipment.

Furthermore, there are protection type standards available for non-electrical equipment (e.g., gears, pneumatic pumps, conveyor belts).

Table 8-7 Types of protection for electrical equipment in gas atmospheres

Type of protection		Protection principle	IEC/EN	Zone	Application
Ex ia, ib, ic	Intrinsic safety	Intrinsic safety, intrinsically safe systems, intrinsically safe (FISCO, Fieldbus Intrinsically Safe Concept) and non-sparking (FNICO, Fieldbus Non-Incendive Concept) fieldbus systems	60079-11, 60079-25, 60079-27	0, 1, 2	Measurement and control technology, sensors, actuators, instrumentation
Ex d	Flameproof enclosure	Flameproof enclosure	60079-1	1, 2	Switching, control, and signaling devices, controllers, motors, power electronics
Ex e	Increased safety	Increased safety	60079-7	1, 2	Branch and connection boxes, housings, motors, terminal blocks
Ex px, py, pz	Pressurized enclosure	Pressurized enclosure	60079-2	1, 2	Control cabinets, motors, measuring and analysis devices, computers
Ex o	Oil immersion	Oil immersion	60079-6	1, 2	Transformers, relays, startup controllers, switching devices
Ex ma, mb, mc	Molded encapsulation	Exclusion of an explosive atmosphere	60079-18	1, 2	Coils of relays and motors, electronics, solenoid valves, connection systems
Ex q	Sand filling	Sand filling	60079-5	1, 2	Transformers, relays, capacitors
Ex nA, nC, nL, nR, nP	Type of protection for Zone 2	Different	60079-15	2	Zone 2 only
Ex op is, op pr, op sh	Optical radiation	Limiting or preventing the transmission of energy from optical radiation	60079-28	1, 2	Optoelectronic devices

Intrinsic safety Ex i

Main characteristics of the “intrinsic safety” type of protection:

- Applies to the entire circuit in which the electrical equipment is operated
- Voltage limitation reduces the ignition spark energy
- Current limitation reduces surface temperatures
- Limitation of energy stored in the circuit (in capacitances and inductances)
- Separation of intrinsically safe circuits from non-intrinsically safe ones by wiring resistors and Zener diodes or via electrical isolation

With regard to intrinsic safety, the IEC/EN 60079-11 differentiates between three protection levels:

Table 8-8 Protection levels for the “intrinsic safety” type of protection

Safety level	Approved for Ex zone	Fault tolerance	
ia	0 ¹ , 1, 2	Two-fault safety	The occurrence of a fault or any combination of two faults cannot cause ignition in normal operation (e.g., by wiring with 3 redundant Zener diodes ²)
ib	1, 2	Single-fault tolerance	The occurrence of a fault cannot cause ignition in normal operation (e.g., by the wiring of two redundant Zener diodes ²)
ic	2	None	The device cannot cause ignition during normal operation

¹ In Ex Zone 0, the IEC/EN 60079-14 recommends electrical isolation in addition to Ex ia

² Zener diodes used for voltage limitation are semiconductor components, classed as being susceptible to interference, and need to be protected through redundant elements. Film or wire wound resistors for current limitation are classed as components that are not susceptible to interference. In the event of a fault, they change to the high-impedance state and can be operated without redundancy.

Type of protection Ex n

The n type of protection can be described as an improved industrial quality that is designed for normal operation. An additional error consideration is not carried out and therefore the type of protection n is only suitable for use in Zone 2 or Zone 22. This can only be used in device group II (ATEX) or in groups II and III (IECEx).

The manufacturer specifies the technical data for normal operation.

In the case of type of protection n, a distinction is made between five different versions, which can be derived in part from the familiar types of protection: increased safety, intrinsic safety, flameproof enclosure, pressurized enclosure, and molded encapsulation.

The type of protection n includes the types of protection nA, nC, and nR. The types of protection nZ and nL are no longer included since the IEC 60079-15:2005 and IEC 60079-15:2010 editions.

nZ has been included in protection level pzc in the IEC 60079-2:2014 standard. nL has been included in protection level ic in the IEC 60079-11:2006 standard. nA type of protection is no longer included in the current edition IEC 60079-15:2017. It has already been adopted into IEC 60079-7:2015 as safety level "ec".

Table 8-9 Subdivision of type of protection n in accordance with IEC/EN 60079

Abbreviation	Meaning	Comparable to ...	Method	Subdivision of the groups in accordance with IECEx
A	Non-sparking	Ex e	Occurrence of electric arcs, sparks, or hot surfaces is minimized.	As of IEC 60079-0:2007, subdivided into IIA, IIB, IIC
C	Sparking equipment	To some extent, Ex d, Ex m	Enclosed switching device, nonflammable components, hermetically sealed, sealed, or encapsulated installations.	IIA, IIB, IIC, and IEC 60079-0:2007
R	Restricted breathing housing	---	Ingress of explosive gases is limited.	As of IEC 60079-0:2007, subdivided into IIA, IIB, IIC

Table 8-10 Types of protection for electrical equipment in dust atmospheres

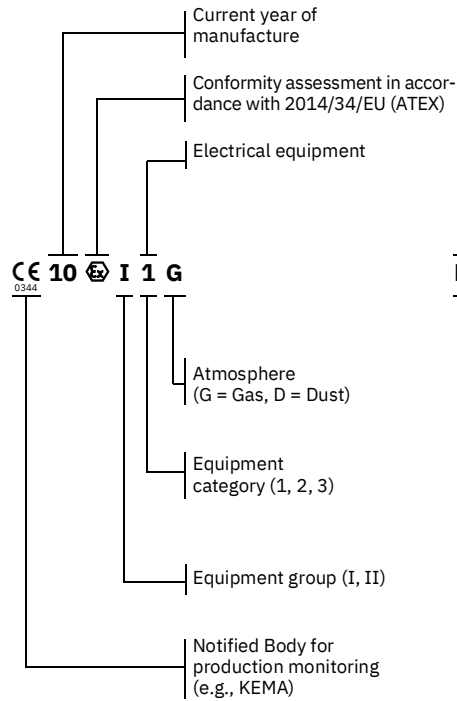
Type of protection	Protection principle	IEC/EN	Zone	Application
Ex pD New: P	Pressurized enclosure	60079-2	21, 22	Control cabinets, motors, measuring and analysis devices
Ex iD New: ia, ib, ic	Intrinsic safety	60079-11	20, 21, 22	Measurement and control technology, sensors, actuators, instrumentation
Ex mD New: ma, mb, mc	Molded encapsulation	60079-18	20, 21, 22	Coils of relays and motors, electronics, and connection systems
Ex tD New: ta, tb, tc	Protection provided by enclosure	60079-31	21, 22	Switching, control, and signaling devices, lamps, branch and connection boxes, housings

8.1.4 Marking of Ex products

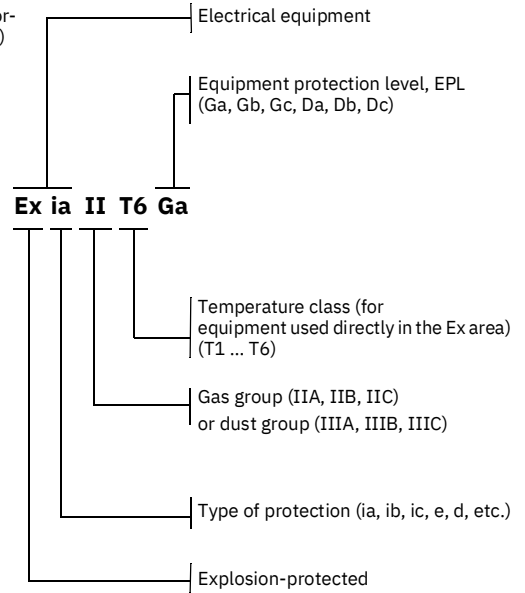
8.1.4.1 ATEX Directive and IEC/EN 60079-0

Figure 8-3 Marking of Ex products

Marking in accordance with ATEX Directive



Marking in accordance with IEC/EN 60079-0:2009



ATEX category, IEC/EN 60079 protection level

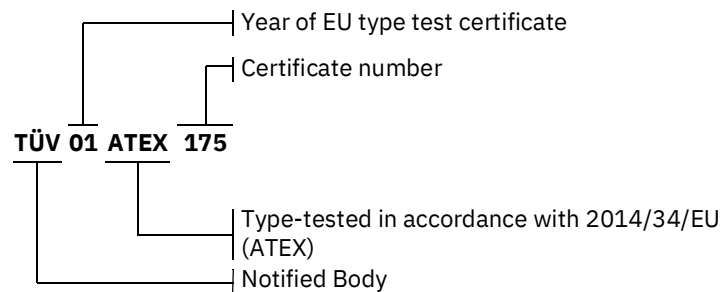
The following table shows the assignment of the equipment category in accordance with ATEX and the equipment protection level in accordance with IEC/EN 60079-0:2009:

Table 8-11 Assignment of equipment category in accordance with ATEX and equipment protection level in accordance with IEC/EN 60079-0:2009

	Equipment category in accordance with ATEX Directive 2014/34/EU	Equipment protection level (EPL)	Zone	Type of danger
Gas	1G	Ga	0	Continuous, long periods, frequent
	2G	Gb	1	Occasional
	3G	Gc	2	Not usually present, short periods only
Dust	1D	Da	20	Continuous, long periods, frequent
	2D	Db	21	Occasional
	3D	Dc	22	Not usually present, short periods only
Mining	M1	Ma		Continuous, long periods, frequent
	M2	Mb		Occasional

8.1.4.2 EU type test

Figure 8-4 Information provided in an EU type test certificate



i For more information about explosion protection, please refer to the brochure entitled "Explosion protection - Theory and practice" (MNR 5107652).

9 Basics of surge protection

Web code: #0144

9.1 Basic knowledge

Risk assessment

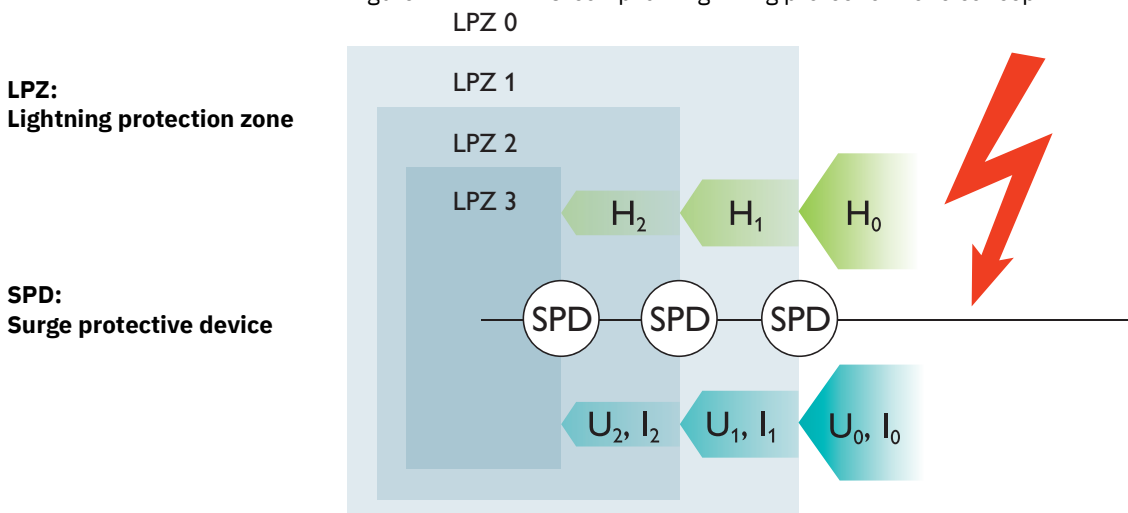
Systems and buildings are evaluated by a risk assessment in accordance with IEC/EN 62305. The aim is to avoid and/or minimize possible personal injury and damage to property as well as operational downtimes. At the end of the assessment and following the implementation of measures there should only be a small, known residual risk that is covered or insured. Lightning and surge protection also represents an important part of the assessment. Valuable evaluation points can be scored here in the risk calculation with comparatively little expenditure. Furthermore, lightning and surge protection is no longer deemed optional by many insurance companies, it is actually mandatory. In accordance with the generally recognized technical regulations and corresponding standards, industrial plants must be equipped with technical systems with lightning and surge protection. This is the only way to ensure a high level of system safety and availability.

Lightning protection zone concept

Part 4 of IEC/EN 62305 shows the principles according to which this type of basic concept for lightning and surge protection can be implemented. To this end, the entire system should be divided into lightning protection zones (LPZs). The area outside of the building envelope is referred to as zone 0. This zone is then further subdivided into zone 0A and zone 0B. In zone 0A, the threat is due to direct lightning strikes and the resulting full electromagnetic field. Due to external lightning protection, the probability of a direct strike, except to the lightning rods, is very low in zone 0B. Nevertheless, in the event of a lightning strike a full electromagnetic field is created.

The area inside the building envelope is subdivided into “nested” zones. In the different zones, varying threat values can be expected with regard to conducted transient overvoltages and electromagnetic fields. Due to the cascaded design of the protection zones, the level of threat gradually decreases. The disturbance variables that occur on the electrical equipment within the individual lightning protection zones are still so small that no damage is caused as a result. Accordingly, the best protection is provided in the innermost zone.

Figure 9-1 EMC-compliant lightning protection zone concept



With regard to the electromagnetic fields, the nested arrangement of the various forms of room shielding results in progressive attenuation. In industrial buildings, the steel constructions, reinforcing elements in concrete floors and walls, and other metal components such as facade cladding can be used for room shielding if they can be connected together electroconductively. In new buildings, clever planning and effective coordination between trades can mean that good room shielding can be provided by structural elements that are already planned, with relatively little additional expenditure. In existing buildings, the attenuation behavior of the LPZ can be improved by retrofitting ring feeders and reinforcing elements. For example, LPZ 3 can be implemented quite easily if the electrical modules are installed in metal control cabinets. Here the control cabinet itself represents the envelope around the zone. Electrical equipotential bonding and grounding using the best available technology should always be taken into consideration.

The internal lightning and surge protection is also incorporated in several stages with the aim of limiting transient overvoltages on electrical cables. Ideally, a surge protective device (SPD) is installed at every zone transition.

i Web code: #0143

9.2 Surge protection for power supply systems

Three types of arresters are provided for the surge protection of power supply systems:

- Type 1 at the transition from zone 0 to zone 1
This should be placed directly at the entry point and is often found in the main power distribution in practice
- Type 2 at the transition from zone 1 to zone 2
In practice, these are usually located in intermediate distributors
- Type 3 as close as possible to the sensitive devices to be protected

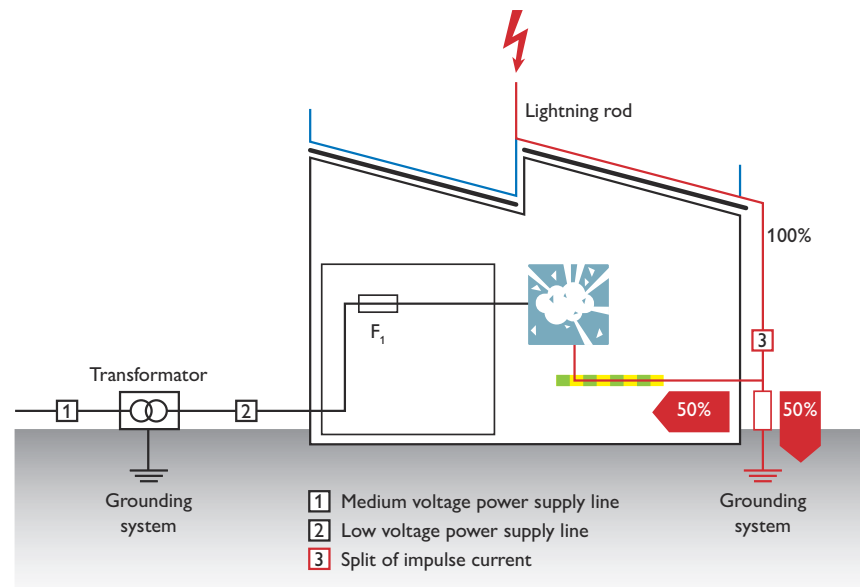
The types differ in their discharge capacity, response time, and residual voltage that remains downstream of the device.

Type 1 is capable of discharging up to 100 kA (10/350 μ s), which means that lightning currents of up to 100 kA (10/350 μ s) can be controlled, as it can be assumed that the lightning current is split 50:50 and only half of it couples into the building. The other half is discharged directly to ground. Even downstream of the type 1 arrester, there is a fairly high residual surge voltage.

Type 2 and type 3 surge protection systems are therefore subsequently installed. Type 2 has significantly lower discharge currents compared to type 1, but the residual voltage downstream of the surge voltage system is lower and the response time is shorter.

Type 3 has the lowest discharge capacity, but has the shortest response time and lowest residual surge voltage across all three types.

Figure 9-2 Effects of lightning current distribution



The existing supply system configuration should be taken into consideration when selecting surge protective devices. In the case of modern products from the same manufacturer, type 1 and type 2 arresters can be coordinated without a gap between the individual protection levels since the technology is already optimally coordinated and features high-quality trigger electronics.

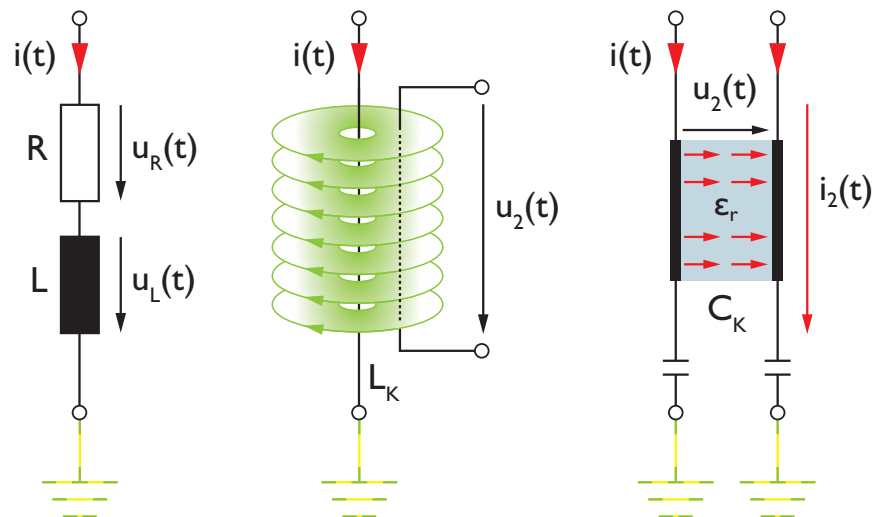
The newest generation of products operate with virtually no line follow current. When the SPD discharges a transient pulse, there is a very low-impedance state between the energy-carrying conductors and ground. In this case, modern SPDs limit the current from the power supply network, which then also flows via the arrester, to a minimum. The SPD and the entire system are spared, which in turn has a bearing on the durability of the installation and uninterrupted operation, even in the event of frequent surge voltages.

9.3 Coupling types

In total, there are three types of coupling for surge voltages: galvanic, inductive, and capacitive coupling. The most important properties are briefly described below.

- Galvanic coupling
Here, the surge voltage couples directly into the conductive system. This could be caused by a direct lightning strike to the supply system.
- Inductive coupling
In the event of a lightning strike, a very high current of over 100 kA flows, generating a strong magnetic field around the conductor. This induces a voltage in cables that lie within this magnetic field.
- Capacitive coupling
A high voltage difference, also known as a potential difference, creates an electric field. As soon as the surge voltage subsides, the energy stored in the field is dissipated again and a current is coupled into the cables.

Figure 9-3 Possible forms of coupling surge voltages, from the left: galvanic or direct, inductive, and capacitive coupling



In addition to lightning strikes, surge voltages can also be caused by switching operations, especially of inductive loads.

9.4 Special features of surge protection in MCR technology

Modern protective devices for signal interfaces feature a combination of fast-responding and highly resilient components so as to combine both features in one product. It is extremely difficult to disconnect cables for MCR circuits and data technology at the lightning protection zone transitions. This is why in practice a protection stage is often not installed at every transition as per the standard. The protective devices are installed as close as possible to the device that is to be protected.

Shielded cables are used in order to reduce the risk of crosstalk and couplings. You must take into account that it is often not just the device that is located centrally that is worth protecting, but also the field device. In such cases, you must include protective devices at both ends of the line.

The dielectric strength of an electrical device is determined in accordance with IEC/EN 61000-4-5, for example, which describes the immunity of the device itself.

9.5 Surge protection in the explosion-protected area

The IEC/EN 60079 series of standards contains various references indicating that surge protection is also mandatory in this sensitive area. The type of protection for the signal circuit and installation location are key factors when selecting suitable protective devices.

A basic decision criterion for selecting a surge protective device for Ex-protected areas is the type of protection and the associated approval. The Ex i type of protection is often found in the surge protection products, which are approved in accordance with ATEX and IECEx. Depending on the overall evaluation, the signal circuits can be routed to Ex zone 0. The surge protective devices are usually installed at the end points in the non-Ex area and in the Ex zones (up to zone 1).

For surge protection in intrinsically safe Ex circuits, IEC/EN 60079-14 specifies that 10 pulses of the form (8/20) μ s must be able to be safely managed with a discharge surge current of 10 kA.

Another type of protection that is available is the increased safety Ex e. The use of such products is possible in Ex zone 2, taking certain conditions into consideration.

Some products that are installed directly on the field device also feature Ex d type of protection approval and, together with the field device, form a flameproof unit. This solution can be installed in Ex zone 1 or 2.

Approvals in accordance with NEC/UL are also available for surge protection products and are certified and considered separately.

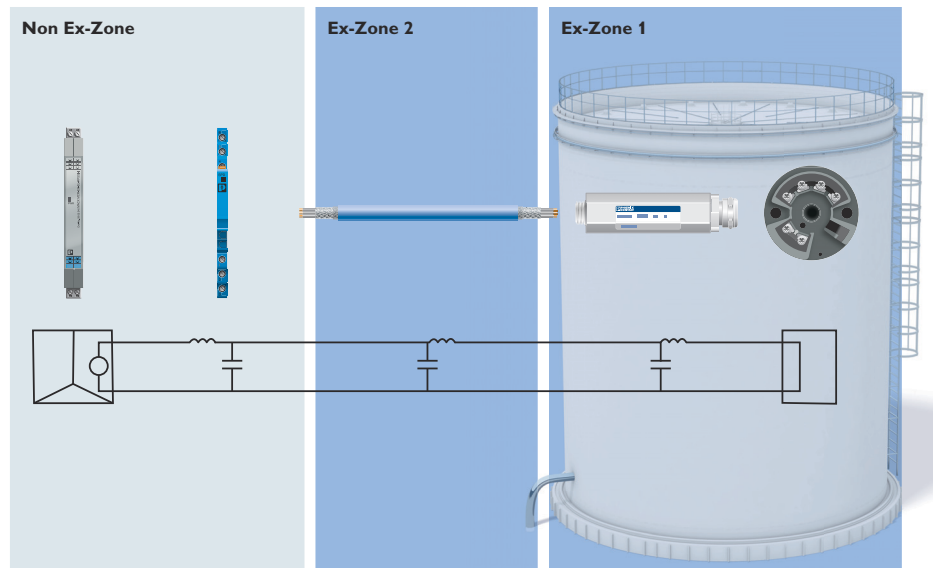
9.5.1 Proof of intrinsic safety

If surge protection products are incorporated into the intrinsically safe circuit, then this must be taken into consideration when demonstrating intrinsic safety in accordance with IEC/EN 60079-25, Paragraph 13/Appendix A. The data required for the calculation can be found in the ATEX/IEC certificate and the data sheets. Instances where individual parameters are not listed with an explicit value can be ignored. The following example illustrates how demonstration of proof might be carried out.

Example: Tank farm

A level measurement device on a fuel tank is connected to the control board via a long line path of 500 m. Due to the explosive atmosphere that is always present inside the tank, Ex zone 0 prevails there. The measurement values are converted to a unit current signal directly at the tank (4 mA ... 20 mA) and then transmitted to the control board. This function unit is located in Ex zone 1. The SPD in the field is built directly on the measuring transducer. The distance of 1 m from Ex zone 0 should not be exceeded. The cables between the measuring sensor and the SPD must be designed so that they are protected against direct lightning interference. One possibility here would be to install the cables in a metal conduit. A much simpler approach is to use surge voltage protection items that can be mounted directly on the measuring head. An SPD is likewise deployed at the opposite end, so that the surge voltage is also effectively limited at the second line end. See IEC/EN 60079-14, Paragraph 16.3 and other related materials for important contexts on the topic of surge protection in intrinsically safe circuits.

Figure 9-4 Tank farm



Ex i signal isolators	Surge protection	Cables	Surge protection	Transmitters
MACX MCR-EX-SL-RPSSI-I	TTC-6P-1X2-EX-24DC-UT-I		S-PT-EX(I)-24DC	FA MCR-EX-HTTS-I-OLP-PT
$U_0 = 25.2 \text{ V DC}$	$U_{i1} = 30 \text{ V DC}$		$U_{i2} \leq 30 \text{ V DC}$	$U_{i3} \leq 30 \text{ V DC}$
$I_0 = 93 \text{ mA}$	$I_{i1} = 400 \text{ mA}$ ($T_A < 50^\circ\text{C @ T4}$)		$I_{i2} \leq 350 \text{ mA}$ ($T_A < 50^\circ\text{C}$)	$I_{i3} \leq 130 \text{ mA}$
$P_0 = 0.587 \text{ W}$	$P_{i1} = \text{--}$		$P_{i2} = 3 \text{ W}$	$P_{i3} = 800 \text{ mW}$
$L_0 = 2 \text{ mH}$	$L_{i1} = \text{negligible}$	$L_C = 0.8 \text{ mH/km} * 00 \text{ m} = 0.4 \text{ mH}$	$L_{i2} = 1 \mu\text{H}$	$L_{i3} = \text{negligible}$
$C_0 = 107 \text{ nF}$	$C_{i1} = \text{negligible}$	$C_C = 140 \text{ nF/km} * 500 \text{ m} = 70 \text{ nF}$	$C_{i2} = 2 \text{ nF}$	$C_{i3} = \text{negligible}$

Verification

$U_0 = 25.2 \text{ V} \leq U_{i1} = 30 \text{ V} \checkmark$	$U_0 = 25.2 \text{ V} \leq U_{i2} = 30 \text{ V} \checkmark$	$U_0 = 25.2 \text{ V} \leq U_{i3} = 30 \text{ V} \checkmark$
$I_0 = 93 \text{ mA} \leq I_{i1} = 400 \text{ mA} \checkmark$	$I_0 = 93 \text{ mA} \leq I_{i2} = 350 \text{ mA} \checkmark$	$I_0 = 93 \text{ mA} \leq I_{i3} = 130 \text{ mA} \checkmark$
	$P_0 = 587 \text{ mW} \leq P_{i2} = 3 \text{ W} \checkmark$	$P_0 = 587 \text{ mW} \leq P_{i3} = 800 \text{ mW} \checkmark$
L_0 and C_0 can be fully utilized.		
$L_0 = 2 \text{ mH} \geq L_{i1} + L_C + L_{i2} + L_{i3} = 0.4 \text{ mH} + 1 \mu\text{H} = 0.4001 \text{ mH}$		
$C_0 = 107 \text{ nF} \geq C_{i1} + C_{i2} + C_{i3} = 2 \text{ nF} + 50 \text{ nF} = 52 \text{ nF}$		

9.6 Surge protection in connection with safety applications

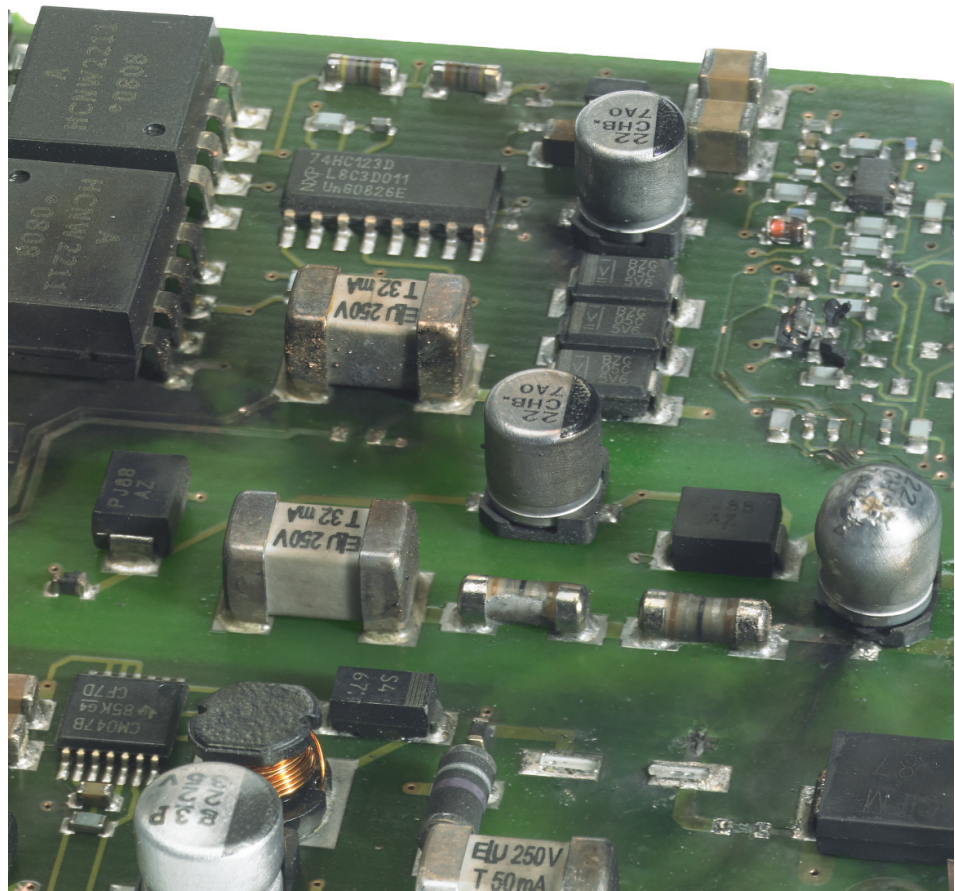
In accordance with IEC 61508, surge protection is regarded as a type A subsystem. Protective devices are therefore simple systems whose possible errors are 100% known. In order that system planners can perform an overall assessment in safety circuits that also takes surge protection into account, the determined error rates of products must be provided. The planner can verify which safety integrity level will be achieved based on the implementation of the safety circuit structure and inclusion of a time frame for maintenance intervals. In addition, it must be ensured that possible state changes of components in the protective device do not result in an undetected dangerous signal state, such as End of Life mode.

9.7 Predictive monitoring of surge protection modules

In MCR technology, surge protection is an important core component for continuous and safe operation. In order to ensure the long-term functionality of a technical system, it is necessary to know the condition of the safety equipment. At the same time, the running costs of the system should be kept as low as possible. In addition, more and more products offer the option of remote monitoring, which can forward error messages centrally to the maintenance and service team.

However, today's products go one step further. It is now possible for surge protection products to register and evaluate internal "wear and tear". This makes it possible to replace the individual surge protection module when the wear limit is reached.

Figure 9-5 Damage caused by surge voltages on an electronic module



9.8 Application examples

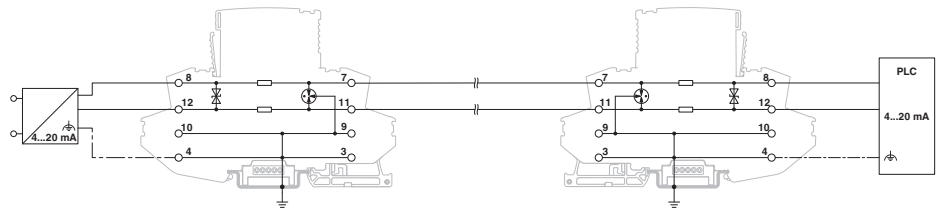
The right surge protection depends on the application, the devices, and the transmission methods used.

The following application examples provide an overview and introduction to surge protection technology.

9.8.1 Protection of an analog measurement

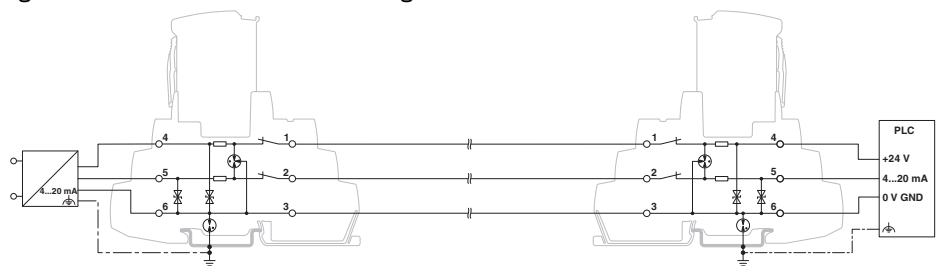
PT-IQ

Figure 9-6 Protection of an analog measurement with PT-IQ



TERMITRAB

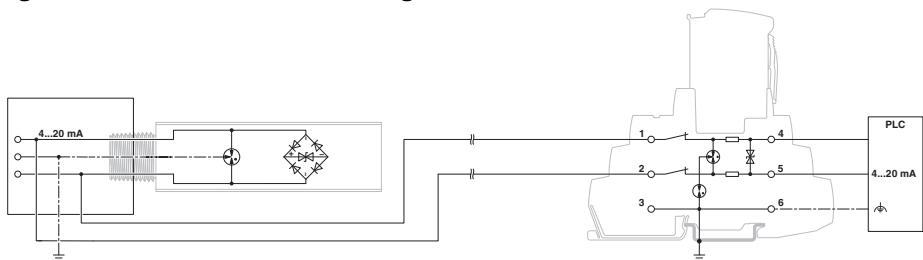
Figure 9-7 Protection of an analog measurement with TERMITRAB



9.8.2 Protection of an analog measurement; intrinsically safe circuit

SURGETRAB/TERMITRAB

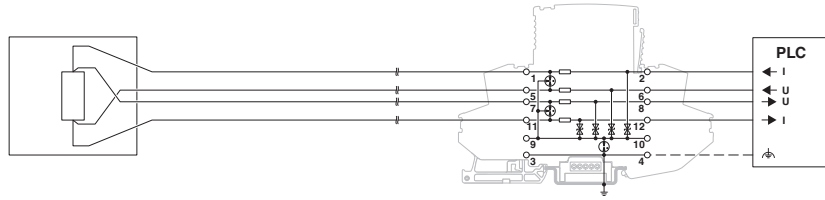
Figure 9-8 Protection of an analog measurement with SURGETRAB/TERMITRAB



9.8.3 Protection of a 4-wire measurement

PT-IQ

Figure 9-9 Protection of a 4-wire measurement with PT-IQ



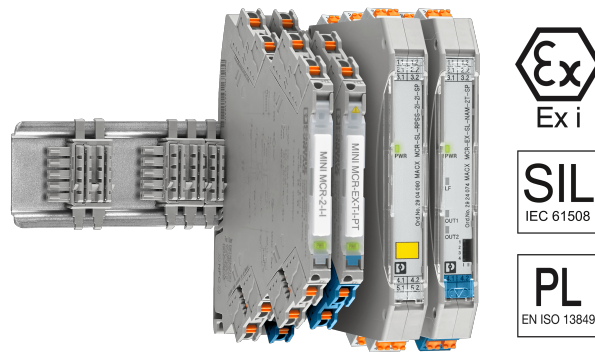
A Technical appendix

A 1 Signal conditioners and measuring transducers

Web code: #1135

Signal conditioners and measuring transducers ensure interference-free signal transmission in measurement and control technology. In addition, intrinsically safe, SIL-certified signal conditioners and measuring transducers provide explosion protection and ensure the safety of people, the environment, and the system.

Figure A-1 Signal conditioners and measuring transducers



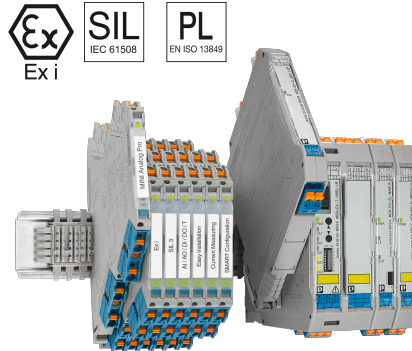
Phoenix Contact offers the following product categories:

- “Signal conditioners and measuring transducers for explosion protection” on page 100
- “Signal conditioners and measuring transducers for standard applications” on page 102
- “Signal marshalling for standard I/O systems” on page 103
- “Signal marshalling for universal I/O systems” on page 104
- “Process displays and field devices” on page 105

A 1.1 Signal conditioners and measuring transducers for explosion protection

i Web code: #1137

Figure A-2 Signal conditioners and measuring transducers for explosion protection



In addition to the standard functions, signal conditioners and measuring transducers for explosion protection guarantee electrical explosion protection for all substance groups and areas in accordance with the relevant standards. Due to the consistent product development and evaluation in accordance with SIL IEC 61508 and PL DIN EN ISO 13849, our signal conditioners and measuring transducers minimize hazards to an acceptable residual risk and ensure the protection of people, machines, and the environment.

Your advantages

- Reliable and safe signal isolation, conditioning, filtering, and amplifying with our signal conditioners and measuring transducers for explosion protection
- Safer and more space-saving than ever: Ex i and SIL 3 with an overall width of just 6.2 mm with highly compact signal conditioners and measuring transducers
- Maximum explosion protection for all Ex zones and gas groups with one-channel and two-channel Ex i signal conditioners and measuring transducers
- High operational safety with signal conditioners, all of which have SIL certification
- Integrate analog signals easily into the safety chain according to the Machinery Directive using signal conditioners with performance level

	MINI Analog Pro	MACX Analog
	High-end core portfolio for all signal directions	Expanded portfolio with additional functions
Consistent SIL 3 1oo1 functional safety: AI, AO, DI, DO	✓	-
Functional safety up to SIL 2 SC 3 or SIL 3, type-specific: AI, AO, DI, DO	-	✓
PL d, PL c functional safety	-	✓
Two-channel design, versions with wide-range supply	-	✓
Variants with passive output, Ex i relay, Ex i frequency measuring transducer	-	✓
Uninterruptible measurement of the current loops	✓	-

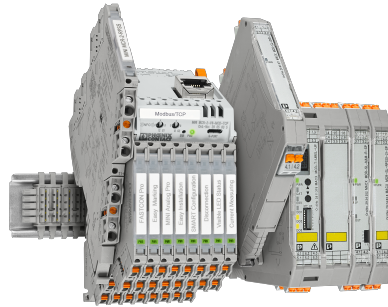
Signal conditioners and measuring transducers

	MINI Analog Pro High-end core portfolio for all signal directions	MACX Analog Expanded portfolio with additional functions
Ambient temperature range of -40°C ... +70°C without derating	✓	-
Plug-in gateways for fieldbus and network connection	✓	-
Information retrieval via Signal Conditioner App	NFC and QR code	QR code

A 1.2 Signal conditioners and measuring transducers for standard applications

i Web code: #2039

Figure A-3 Signal conditioners and measuring transducers for standard applications



Signal conditioners and measuring transducers isolate, convert, filter, and amplify signals as an interface between field and controller. MACX Analog und MINI Analog Pro offer flexible solutions for AI, AO, DI, temperature, frequency, and limit values. MINI Analog Pro is a user-friendly and space-saving product family. MACX Analog guarantees the safety of people, the environment, and the system with functional safety.

Your advantages

- Safe isolation, conditioning, filtering, and amplification with comprehensive solutions for analog signal processing
- Integrate field signals into industrial networks while also benefiting from safe electrical isolation with signal conditioners with a bus and network connection
- Achieve space savings of up to 65% compared to other isolators on the market with highly compact signal conditioners
- Precise transmission and high operational safety with signal conditioners, all of which have the SIL certification
- Integrate analog signals easily into the safety chain according to the Machinery Directive using signal conditioners with performance level

	MINI Analog Pro	MACX Analog
	Unrivaled compact design in terms of overall width and installed height	The proven, comprehensive range of solutions
Functional safety up to SIL 2 SC 3 or SIL 3, type-specific: AI, AO, DI, DO	-	✓
PL d, PL c functional safety	-	✓
Two-channel design, versions with wide-range supply	-	✓
Uninterruptible measurement of the current loops	✓	-
Ambient temperature range of -40°C ... +70°C without derating	✓	-
Plug-in gateways for fieldbus and network connection	✓	-
Information retrieval via Signal Conditioner App	NFC and QR code	QR code

A 1.3 Signal marshalling for standard I/O systems

i Web code: #3578

Figure A-4 Signal marshalling for standard I/O systems



Our Termination Carrier provides you with a plug-and-play solution for signal marshalling for standard I/O systems. The module carriers help you to quickly and smoothly connect our classic signal conditioners of the MINI Analog Pro and MACX Analog families to the standard I/O cards of your automation system using preassembled VARIOFACE system cabling.

Your advantages

- Space-saving due to the compact design
- High system availability due to the robust housing and mechanically decoupled termination PCB
- Simple wiring with pluggable, coded cable sets and preassembled system cables
- Optimum adaptation with a wide range of system connectors and front adapters for I/O cards of various automation systems
- Service-friendly due to hot-swap module replacement and easily accessible connection elements
- Only one engineering design required for DIN rail and system applications

Comparison of I/O signal marshalling for universal I/O and standard I/O

In I/O signal marshalling for standard I/O systems, the field signals are sorted in the marshalling level according to their signal type and processed via the interface level. They are then wired to the signal-specific I/O cards on the control unit. In contrast, I/O signal marshalling and conversion for universal I/O systems allows flexible channel assignment from the field to the controller.

	Universal I/O signal marshalling	Standard I/O signal marshalling
Control input	Universal I/O cards with flexible channel assignment (one I/O card for all signal types)	I/O cards with fixed assignment according to signal type (one I/O card is required per signal type)
Signal marshalling	Combined marshalling and interface level	Separate marshalling and interface levels
Signal processing	Pluggable input-output accessories, upright wiring on field and control side	Termination Carrier with DIN rail devices, vertical wiring on the control side

A 1.4 Signal marshalling for universal I/O systems

i Web code: #3204

Figure A-5 Signal marshalling for universal I/O systems



Design your universal marshalling with our flexible I/O marshalling system: VIP I/O marshalling. The system combines signal marshalling and processing in a controller-independent solution for your universal I/O system. Pluggable input/output accessories with various interface functions enable universal configuration of individual channels. How universal marshalling should be: consistent from the field to the control level.

Your advantages

- Shorter project duration with a consistent universal I/O approach
- Changes to the I/O assignment are possible in every project phase with pluggable IOAs
- Lower number of control cabinets because additional marshalling cabinets are not necessary
- Reduction of the wiring work with various system cabling solutions for connection to distributed control systems (DCS)
- Easy migration into existing systems by reducing downtimes during retrofit work

A 1.5 Process displays and field devices

i Web code: #3573

Figure A-6 Process displays and field devices



Field Analog series process displays and field devices enable you to acquire, monitor, and locally display analog and temperature signals, and to control them via digital and analog inputs and outputs. Loop-powered temperature measuring transducers acquire signals from resistance thermometers, thermocouples, resistance-type sensors, and voltage sensors directly in the field and convert them into standard and HART® signals.

Your advantages

- Multifunctional and universal: Process displays with universal input for current, voltage, and the signals from RTDs, TCs, and resistance-type sensors
- Output loop powered and HART® communicative: Display for 4 mA ... 20 mA and HART® signals for mapping up to four alternating measured values of a sensor via HART®
- Compact and cost-efficient: 7-segment LED display with integrated setpoint adjuster for cost-efficient monitoring of standard, current, and voltage signals as well as frequency and pulse signals
- Acquire and convert signals in the field: Loop-powered temperature measuring transducers for acquiring resistance thermometers, thermocouples, resistance-type sensors, and voltage sensors
- HART® communication: Easy online configuration and diagnostics of HART®-compatible field devices and continuous documentation of process variables and states via PC or management system

A 2 Surge protection

Phoenix Contact offers the following product categories:

- [“PLUGTRAB PT-IQ” on page 106](#)
- [“TERMITRAB complete” on page 108](#)
- [“SURGETRAB” on page 108](#)

A 2.1 PLUGTRAB PT-IQ

Forward-looking surge protection system

PLUGTRAB PT-IQ is a system comprising a supply and fault signaling module as well as the actual surge protection. The supply and fault signaling module supplies power to the protective devices, and provides the group remote signaling for up to 28 protection modules.

The multi-stage signaling and remote signaling of the protective devices is of particular interest. Each voltage-limited component of the protective circuit is monitored intelligently.

A yellow status signal indicates that the performance limit has been reached as a result of frequent surge voltages. The arresters are still functional and your system is still protected. However, replacement is recommended in order to avoid unnecessary servicing.

Special protection for potentially explosive areas

Potentially explosive areas: Install PT-IQ Ex directly in Ex Zone 2

With PLUGTRAB PT-IQ Ex products, surge protective devices are available for the first time with an auxiliary power supply for the “intrinsic safety” type of protection which may be installed directly in Ex Zone 2.

PT-IQ Ex permanently monitors intrinsically safe circuits up to Ex Zone 0. Protective devices with pre-existing damage are also directly detected and reported.

Approvals according to ATEX and IECEx enable worldwide use.

Figure A-7 PLUGTRAB PT-IQ product family



- Service can be planned thanks to self-monitoring protective devices with status indicator
- Vibration-resistant installation – the new latching ensures a secure hold even for installations in harsh environments
- Space-saving installation: up to five signal wires can be protected on an overall width of just 17.5 mm
- Energy efficient, as the green LEDs on all protection modules can be switched off centrally at the supply and fault signaling module
- Variable connection technology: Choose between conventional screw connection or convenient Push-in connection technology

A 2.2 TERMITRAB complete

Protection in the terminal block

The multi-stage surge protective devices for protecting up to four wires serve as fine and medium protection between the signal wires and as coarse protection between the signal wires and ground. With screw or Push-in connections and as a version with disconnect knives or for the Ex area.

Figure A-8 TERMITRAB product family



A 2.3 SURGETRAB

Protection directly at the measuring head

The screw-on modules are available for all common standard signals. The extremely robust housing made from V4A stainless steel protects against unwanted outages even in harsh industrial environments and is ready to be used in the Ex area.

Figure A-9 SURGETRAB product family



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