

Documentaion | EN

I/O Analog Manual

Notes on I/O components with analog in and outputs



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1 Foreword

1.1 Notes on the documentation

Intended audience

This description is only intended for the use of trained specialists in control and automation engineering who are familiar with the applicable national standards.

It is essential that the documentation and the following notes and explanations are followed when installing and commissioning these components.

The qualified personnel is obliged to always use the currently valid documentation.

The responsible staff must ensure that the application or use of the products described satisfy all the requirements for safety, including all the relevant laws, regulations, guidelines and standards.

Disclaimer

The documentation has been prepared with care. The products described are, however, constantly under development.

We reserve the right to revise and change the documentation at any time and without prior announcement.

No claims for the modification of products that have already been supplied may be made on the basis of the data, diagrams and descriptions in this documentation.

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1.2 Safety instructions

Safety regulations

Please note the following safety instructions and explanations!
Product-specific safety instructions can be found on following pages or in the areas mounting, wiring, commissioning etc.

Exclusion of liability

All the components are supplied in particular hardware and software configurations appropriate for the application. Modifications to hardware or software configurations other than those described in the documentation are not permitted, and nullify the liability of Beckhoff Automation GmbH & Co. KG.

Personnel qualification

This description is only intended for trained specialists in control, automation and drive engineering who are familiar with the applicable national standards.

Signal words

The signal words used in the documentation are classified below. In order to prevent injury and damage to persons and property, read and follow the safety and warning notices.

Personal injury warnings

DANGER

Hazard with high risk of death or serious injury.

WARNING

Hazard with medium risk of death or serious injury.

CAUTION

There is a low-risk hazard that could result in medium or minor injury.

Warning of damage to property or environment

NOTICE

The environment, equipment, or data may be damaged.

Information on handling the product



This information includes, for example:
recommendations for action, assistance or further information on the product.

1.3 Application area

This analog manual provides basic and advanced content on the use of analog input and output devices from Beckhoff.

It is a mandatory supplement to the product-specific documentation for Beckhoff I/O components with analog inputs and outputs, such as:

- EtherCAT measuring terminals (ELM3xxx)
- EtherCAT Terminals (EL3xxx, ES3xxx, EL4xxx, ES4xxx)
- EtherCAT plug-in modules (EJ3xxx, EJ4xxx)
- Bus Terminals (KL3xxx, KS3xxx, KL4xxx, KS4xxx)
- EtherCAT Box modules (EP3xxx, EPP3xxx, EPI3xxx, EQ3xxx, ER3xxx EP4xxx, EPP4xxx, EPI4xxx, ER4xxx)
- Fieldbus Box modules (IP3xxx-Bxxx, IE3xxx, IP4xxx-Bxxx, IE4xxx)

It also explains the basics of sensor technology and includes notes on analog data values.

Product-specific information in the respective device documentation is primarily authoritative.

1.3.1 Further documentations

NOTICE



Refer product specific documentations

In addition, please refer to the product-specific documents for installation, parameterization, programming etc., which are available to you on the Beckhoff homepage at www.beckhoff.com in the download section of the respective product pages.

1.4 Documentation issue versions

Version	Comment
1.5	<ul style="list-style-type: none"> • Update of subchapter “Notices on analog specifications”/ “Dielectric strength” within chapter “Notes on analog data values” • Addenda of subchapter “Repeatability” within chapter “Notes on analog data values”
1.4	<ul style="list-style-type: none"> • Subchapter „Power supply“ added within chapter „Product overview measurement technology SG, TC, RTD“ (added to „ Product overview measurement technology SG, TC, RTD, Power Supply“) • Subchapter „RTD/resistance measurement“ und „Strain gauge (SG)“ updated within chapter „Product overview measurement technology SG, TC, RTD, Power Supply“ • Subchapter „Operation of inductive/capacitive loads on analog outputs“ added within chapter „Notes on analog data values“
1.3	<ul style="list-style-type: none"> • Updates within chapter “Product overview measurement technology SG, TC, RTD“: <ul style="list-style-type: none"> ◦ Subchapter “Thermocouple (TC)“ ◦ Subchapter “RTD/resistance measurement“ • Update within chapter “Basic considerations on analog technology“, subchapter “Further considerations...“ • Subchapter “Explanation of electrically (un)isolated channels“ and “On the mutual influence of non-isolated differential channels“ within chapter “Notes on analog data values“ as new subchapter “Electrically (un)isolated channels“ summarized (subchapter titel shortened to “Explanations“) • Subchapter “Wiring of differential current inputs“ added in chapter “Notes on analog data values“/ “Electrically (un)isolated channels“ • Update within chapter “Notes on analog data values“, subchapter “Electrically (un)isolated channels“/ “On the mutual influence of non-isolated differential channels“ • Subchapter “Safety instructions” (Foreword) updated
1.2	<ul style="list-style-type: none"> • Chapter “Product overview measurement technology SG, TC, RTD“ updated • Chapter “Basics of sensor technology“, subchapter “Basic principles of strain gauge technology“, section “Measuring body and natural frequency“ updated • Changes within Chapter “Notes on analog data values“ <ul style="list-style-type: none"> ◦ Subchapter “ Signal quality when outputting signals with digital analog outputs – distortion factor“ added ◦ Subchapter “Readjusting the specification“ updated • Chapter “Further considerations...“ shifted into chapter “Basic considerations on analog technology“
1.1	<ul style="list-style-type: none"> • Chapter “Basic considerations on analog technology“ updated • Chapter “Notes regarding analog equipment - shielding and earth“ updated
1.0	<ul style="list-style-type: none"> • First publication

2 Product overview measurement technology SG, TC, RTD, Power Supply

2.1 Strain gauge (SG)

Comparative overview of Beckhoff SG measuring devices (terminals, boxes, modules)

The following table is intended to provide a quick overview of the available Beckhoff I/O devices for the direct connection of ohmic mV/V sensors (strain gauges, scales, vibration sensors).

NOTICE

Device documentation is solely authoritative

The values may be shortened extracts from the respective documentation, which is decisive and recommended for detailed analysis.

For a possibly more up-to-date overview, please consult www.beckhoff.com.

	Design	Number of SG channels	Connection technology	Resolution	Oversampling
KL3351	K-bus terminal IP20	1	Cage Clamp	16 bit	-
KL3356	K-bus terminal IP20	1	Cage Clamp	16 bit	-
EL3351	EtherCAT terminal IP20	1	Cage Clamp	16 bit	-
EL3356	EtherCAT terminal IP20	1	Cage Clamp	16 bit	-
EL3356-0010	EtherCAT terminal IP20	1	Cage Clamp	24 bit	-
EL3356-0090	EtherCAT terminal IP20	1	Cage Clamp	24 bit	-
EL3751	EtherCAT terminal IP20	1	Cage Clamp	24 bit	X
ELM3502, ELM3504	EtherCAT terminal IP20	2/4	Push-In, LEMO	24 bit	X
ELM3702, ELM3704	EtherCAT terminal IP20	2/4	Push-In	24 bit	X
ELM3542, ELM3544	EtherCAT terminal IP20	2/4	Push-In	24 bit	X
EP3356-0022	EtherCAT Box IP67	1	M12	24 bit	-
EPP3504-0023	EtherCAT P Box IP20	4	Push-In	24 bit	X
ERP3504-0022	EtherCAT P Box IP67	4	M12	24 bit	X
ELX3351	EtherCAT terminal IP20	1	Cage Clamp	24 bit	-

Continuation:

	Full bridge	Half bridge	Quarter bridge	Maximum sampling rate per channel for control	Measurement uncertainty of the FSV in the SG modes ¹⁾
KL3351	X	only with external supplement	only with external supplement	15 sps	< ±0.1 %
KL3356	X	only with external supplement	only with external supplement	250 sps	< ±0.1 %
EL3351	X	only with external supplement	only with external supplement	400 sps	< ±0.1 %
EL3356	X	only with external supplement	only with external supplement	100 sps	< ±0.01 % for the calculated load value ²⁾
EL3356-0010	X	only with external supplement	only with external supplement	10,000 sps	< ±0.01 % for the calculated load value ²⁾
EL3356-0090	X	only with external supplement	only with external supplement	10,000 sps	< ±0.01 % for the calculated load value ²⁾
EL3751	X	X	X	10,000 sps	up to < ±0.05 %
ELM3502, ELM3504	X	X	X	10,000 / 20,000 sps	up to < ±0.0025 %
ELM3702, ELM3704	X	X	X	1,000 sps	up to < ±0.01 %
ELM3542, ELM3544	X	X	X	1,000 sps	up to < ±0.0025 %
EP3356-0022	X	only with external supplement	only with external supplement	15 sps	< ±0.1 %
EPP3504-0023	X	X	X	10,000 sps	up to < ±0.0025 %
ERP3504-0022	X	X	X	10,000 sps	up to < ±0.0025 %
ELX3351	X	only with external supplement	only with external supplement	625 sps	< ±0.5 % for the calculated load value

¹⁾ on this point in particular, the additional information in the respective device documentation must be evaluated.

²⁾ remaining linearity uncertainty after customer made offset and gain adjustment.

Continuation:

	Bridge voltage	Feed voltage	Supported nominal characteristic values	Bridge supply integrated	Distributed Clocks for timestamp operation
KL3351	up to ± 16 mV	up to ± 10 V	all, conversion must be carried out in the controller / PLC	Yes, 5 V	-
KL3356	up to ± 20 mV	up to ± 12 V	Adjustable in steps of 1 mV/V	-	-
EL3351	up to ± 20 mV	up to ± 12 V	all, conversion must be carried out in the controller / PLC	Yes, 5 V	-
EL3356	up to ± 27 mV	up to ± 13.8 V	Adjustable 0.5 to 4 mV/V	-	-
EL3356-0010	up to ± 27 mV	up to ± 13.8 V	Adjustable 0.5 to 4 mV/V	-	X
EL3356-0090	up to ± 27 mV	up to ± 13.8 V	Adjustable 0.5 to 4 mV/V	-	X
EL3751	up to ± 160 mV	up to ± 5 V	32/16 mV/V	Yes, adjustable up to 5 V	X
ELM3502, ELM3504	up to ± 160 mV	up to ± 5 V	32/8/4/2 mV/V	Yes, adjustable up to 5 V	X
ELM3702, ELM3704	up to ± 160 mV	up to ± 5 V	32/8/4/2 mV/V	Yes, adjustable up to 12 V	X
ELM3542, ELM3544	up to ± 160 mV	up to ± 5 V	Adjustable 0.5 to 4 mV/V	Yes, 10 V	X
EP3356-0022	up to ± 16 mV	up to ± 10 V	all, conversion must be carried out in the controller / PLC	Yes, 5 V	-
EPP3504-0023	up to ± 160 mV	up to ± 5 V	32/8/4/2 mV/V	Yes, adjustable up to 5 V	X
ERP3504-0022	up to ± 160 mV	up to ± 5 V	32/8/4/2 mV/V	Yes, adjustable up to 5 V	X
ELX3351	up to ± 18 mV	up to ± 10 V	Adjustable 0.5 to 4 mV/V	Yes, 10 V	-

Continuation:

	TwinSAFE SC	Extended diagnosis	Various predefined internal digital filters	Other digital filters	Special features
KL3351	-	-	X	-	-
KL3356	-	-	X	-	Auto-calibration
EL3351	-	-	X	-	-
EL3356	-	-	X	-	Auto-calibration
EL3356-0010	-	-	X	Dynamic filter	Auto-calibration, various dynamic functions, calibrated version EL3356-0030 available
EL3356-0090	X	-	X	-	Auto-calibration
EL3751	-	X	X	Freely parameterizable with TwinCAT Filter Designer	-
ELM3502, ELM3504	-	X	X	Freely parameterizable with TwinCAT Filter Designer	Calibrated version ELM350x-0030 available
ELM3702, ELM3704	-	X	X	Freely parameterizable with TwinCAT Filter Designer	-
ELM3542, ELM3544	-	-	X	-	Auto-calibration
EP3356-0022	-	-	X	-	-
EPP3504-0023	-	X	X	Freely parameterizable with TwinCAT Filter Designer	-
ERP3504-0022	-	X	X	Freely parameterizable with TwinCAT Filter Designer	-
ELX3351	-	-	X	-	-

2.2 Thermocouple (TC)

Comparative overview of Beckhoff thermocouple (TC) devices (terminals, boxes, modules)

The following table is intended to provide a quick overview of the available Beckhoff I/O devices for the direct connection of thermocouples for temperature and mV measurement.

NOTICE

Device documentation is solely authoritative

The values may be shortened extracts from the respective documentation, which is decisive and recommended for detailed analysis.

All devices feature:

- Transformation of many common TC types;
Note: the implemented measuring ranges may vary slightly in the end points,
- internal cold junction.

If applicable, the following functions are still available

- Wire break detection
- External cold junction

NOTICE

Measurement uncertainty in TC measurement

The measurement uncertainty in the table is only a rough orientating value, since it depends strongly on the TC type and the measuring temperature; details in the respective documentation.

For a possibly more up-to-date overview, please consult www.beckhoff.com.

	Design	Number of TC channels	Connection technology	Resolution	Maximum sampling rate per channel for control
KL3311, KL3312, KL3314	K-bus terminal IP20	1-4	Cage Clamp	0.1 °C	4 sps
EL3311, EL3312, EL3314, EL3318	EtherCAT terminal IP20	1-8	Cage Clamp	0.1/0.01 °C	50 sps
EL3314-0090	EtherCAT terminal IP20	4	Cage Clamp	0.1/0.01 °C	50 sps
EL3314-0010	EtherCAT terminal IP20	4	Cage Clamp	0.1/0.01/0.001 °C	50 sps
EL3314-0002	EtherCAT terminal IP20	4	Cage Clamp	0.1/0.01/0.001 °C	200 sps
ELM3344, ELM3348	EtherCAT terminal IP20	2/4	Push-In	0.1/0.01/0.001 °C	1,000 sps
ELM3344-0003, ELM3348-0003	EtherCAT terminal IP20	2/4	Mini-TC	0.1/0.01/0.001 °C	1,000 sps
ELM3702-xxxx, ELM3704-xxxx	EtherCAT terminal IP20	2/4	Push-In, LEMO	0.1/0.01/0.001 °C	10,000 sps
EP3314-0002	EtherCAT Box IP67	4	M8	0.1/0.01 °C	50 sps
EPP3314-0002	EtherCAT P Box IP67	4	M12	0.1/0.01 °C	50 sps
EJ3318	EtherCAT plug-in module	8	On application-specific signal distribution boards	0.1 °C/ digit	25 Sps

Continuation:

	Measurement uncertainty of temperature measurement incl. internal cold junction	Measuring ranges - mV measurement	Oversampling	Operation with external cold junction is possible	Distributed Clocks for timestamp operation
KL3311, KL3312, KL3314	< ±0.5 %	30/60/120 mV	-	-	-
EL3311, EL3312, EL3314, EL3318	< ±0.3 %	30/75 mV	-	X	-
EL3314-0090	< ±0.3 %	30/75 mV	-	X	-
EL3314-0010	< ±0.2 %	78 mV	-	X	-
EL3314-0002	< ±0.2 %	78 mV / 2.5 V	-	X	-
ELM3344, ELM3348	< ±0.1 %	20 mV to 10 V	X	X	X
ELM3344-0003, ELM3348-0003	< ±0.05 %	20 mV to 10 V	X	X	X
ELM3702-xxxx, ELM3704-xxxx	< ±0.1 %	20 mV to 10 V	X	X	X
EP3314-0002	< ±0.3 %	30/60/75 mV	-	X	-
EPP3314-0002	< ±0.3 %	30/60/75 mV	-	X	-
EJ3318	< ±0.3 %	30//6075 mV	-	X	-

Continuation:

	Electrically isolated channels	TwinSAFE SC	Measured value filtering	Extended diagnosis	Special features
KL3311, KL3312, KL3314	-	-	-	-	-
EL3311, EL3312, EL3314, EL3318	-	-	Various predefined internal digital filters	-	-
EL3314-0090	-	X	Various predefined internal digital filters	-	TSC variant of the EL3314-0000
EL3314-0010	-	-	Various predefined internal digital filters	-	Calibrated version EL3314-0030 available
EL3314-0002	Yes, 2500 V functional isolation	-	Various predefined internal digital filters	-	-
ELM3344, ELM3348	-	-	Various predefined internal digital filters Freely parameterizable with TwinCAT Filter Designer	Yes, with CommonMode measurement	-
ELM3344-0003, ELM3348-0003	-	-	Various predefined internal digital filters Freely parameterizable with TwinCAT Filter Designer	Yes, with CommonMode measurement	-
ELM3702-xxxx, ELM3704-xxxx	-	-	Various predefined internal digital filters Freely parameterizable with TwinCAT Filter Designer	Yes	Multi-function terminal
EP3314-0002	-	-	Various predefined internal digital filters	-	-
EPP3314-0002	-	-	Various predefined internal digital filters	-	-
EJ3318	-	-	Various predefined internal digital filters	-	-

2.3 RTD/resistance measurement

Comparative overview of Beckhoff R/RTD measuring devices (terminals, boxes, modules)

The following table is intended to provide a quick overview of the available Beckhoff I/O devices for the direct connection of RTD sensors for temperature and resistance measurement.

NOTICE

Device documentation is solely authoritative

The values may be shortened extracts from the respective documentation, which is decisive and recommended for detailed analysis.

For a possibly more up-to-date overview, please consult www.beckhoff.com.

	Design	Number of RTD channels	Connection technology	Resolution	Conversion time/sampling rate ¹⁾
KL3201	K-bus terminal IP20	1	Cage Clamp	0.1 °C/0.5 °C	~200...250 ms
KL3202	K-bus terminal IP20	2	Cage Clamp	0.1 °C/0.5 °C	~200...250 ms
KL3204	K-bus terminal IP20	4	Cage Clamp	0.1 °C/0.5 °C	~200...250 ms
KL3204-0030	K-bus terminal IP20	4	Cage Clamp	0.1 °C	~250 ms
KL3208-0010	K-bus terminal IP20	8	Cage Clamp	0.01 °C/0.1 °C	~250 ms
KL3228	K-bus terminal IP20	8	Cage Clamp	0.01 °C/0.1 °C	~250 ms
KL3222	K-bus terminal IP20	2	Cage Clamp	0.01 °C/0.1 °C	~50 ms
KL3214	K-bus terminal IP20	4	Cage Clamp	0.01 °C/0.1 °C	~170 ms
EL3201	EtherCAT Terminal IP20	1	Cage Clamp	0.01 °C/0.1 °C	4...500 ms
EL3201-0010	EtherCAT Terminal IP20	1	Cage Clamp	0.01 °C/0.1 °C	4...500 ms
EL3202	EtherCAT Terminal IP20	2	Cage Clamp	0.01 °C/0.1 °C	2...800 ms
EL3202-0010	EtherCAT Terminal IP20	2	Cage Clamp	0.01 °C/0.1 °C	4...500 ms
EL3204	EtherCAT Terminal IP20	4	Cage Clamp	0.01 °C/0.1 °C	2...800 ms
EL3204-0162	EtherCAT Terminal IP20	4	Cage Clamp	0.01 °C/0.1 °C	33...833 ms
EL3204-0200	EtherCAT Terminal IP20	4	Cage Clamp	0.01 °C/0.1 °C	4...500 ms
EL3208	EtherCAT Terminal IP20	8	Cage Clamp	0.01 °C/0.1 °C	4.5...1600 ms
EL3208-0010	EtherCAT Terminal IP20	8	Cage Clamp	0.01 °C/0.1 °C	12.8...7800 ms
EL3214	EtherCAT Terminal IP20	4	Cage Clamp	0.01 °C/0.1 °C	5...1600 ms
EL3214-0090	EtherCAT Terminal IP20	4	Cage Clamp	0.01 °C/0.1 °C	5...1600 ms
EL3218	EtherCAT Terminal IP20	8	Cage Clamp	0.01 °C/0.1 °C	20...1600 ms
EL3692	EtherCAT Terminal IP20	2	Cage Clamp	>= 12 µΩ	10 ... 400 ms
EL3751	EtherCAT Terminal IP20	1	Cage Clamp	0.01 °C	>= 100 µs (10 kSps)
EL3751-0004	EtherCAT Terminal IP20	1	Cage Clamp	0.01 °C	>= 100 µs (10 kSps)
ELM3244, ELM3246	EtherCAT Terminal IP20	4/6	Push-in	0.1/0.01/0.001 °C	> 1 ms (1 kSps) per channel
ELM3502	EtherCAT Terminal IP20	2	Push-in	0.1/0.01/0.001 °C	>= 50 µs (20 kSps) per channel
ELM3504	EtherCAT Terminal IP20	4	Push-in	0.1/0.01/0.001 °C	>= 100 µs (10 kSps) per channel
ELM3702, ELM3704	EtherCAT Terminal IP20	2/4	Push-in	0.1/0.01/0.001 °C	>= 100 µs (10 kSps) per channel
ELM3702-0101	EtherCAT Terminal IP20	2	LEMO	0.1/0.01/0.001 °C	>= 100 µs (10 kSps) per channel
EP3204-0002, EPP3204-0002	EtherCAT Box IP67, EtherCAT P Box IP67	4	M12	0,1 °C	2 ... 800 ms
EJ3202	EtherCAT plug-in module	2	On application-specific signal distribution boards	0,01 °C/0,1 °C	2 ... 800 ms
EJ3214	EtherCAT plug-in module	4	On application-specific signal distribution boards	0,01 °C/0,1 °C	5 ... 1600 ms

¹⁾ depending on settings, e.g. active input channels and filters, for complete and authoritative information see respective documentation

Continuation:

	Measurement uncertainty ²⁾	Oversampling	Distributed Clocks for time-stamp operation	Electrically isolated channels	TwinSAFE SC
KL3201	< ±1 °C	-	-	-	-
KL3202	< ±1 °C	-	-	-	-
KL3204	< ±1 °C	-	-	-	-
KL3204-0030	< ±1 °C	-	-	-	-
KL3208-0010	< ±1.5 °C	-	-	-	-
KL3228	< ±1 °C	-	-	-	-
KL3222	< ±0.1 °C	-	-	-	-
KL3214	< ±0.5 °C	-	-	-	-
EL3201	< ±0.5 °C	-	-	-	-
EL3201-0010	< ±0.1 °C	-	-	-	-
EL3202	< ±0.5 °C	-	-	-	-
EL3202-0010	< ±0.1 °C	-	-	-	-
EL3204	< ±0.5 °C	-	-	-	-
EL3204-0162	< ±0.5 °C	-	-	-	-
EL3204-0200	< ±0.3 % ³⁾	-	-	-	-
EL3208	< ±0.5 °C	-	-	-	-
EL3208-0010	-20...+60 °C: ±0.25 °C -50...+150 °C: ±1.5 °C	-	-	-	-
EL3214	< ±0.5 °C	-	-	-	-
EL3214-0090	< ±0.5 °C	-	-	-	X
EL3218	< ±0.5 °C	-	-	-	-
EL3692	< ±0.5 % ³⁾	-	-	-	-
EL3751	< ±0.5 °C for Pt100 < ±0.13 °C for Pt1000	x	x	-	-
EL3751-0004	< ±0.5 °C for Pt100 < ±0.13 °C for Pt1000	x	x	-	-
ELM3244, ELM3246	< ±0.1 °C for Pt100	x	x	-	-
ELM3502	< ±0.07 °C for Pt100	x	x	-	-
ELM3504	< ±0.07 °C for Pt100	x	x	-	-
ELM3702, ELM3704	< ±0.05 °C for Pt100	x	x	-	-
ELM3702-0101	< ±0.1 °C for Pt100	x	x	X	-
EP3204-0002, EPP3204-0002	< ±0.5 °C (Pt sensors in 4-wire connection)	-	-	-	-
EJ3202	< ±0,5 °C	-	-	-	-
EJ3214	< ±0,5 °C	-	-	-	-

²⁾ If several specifications are shown for a device, the best value is given here; for complete and authoritative specifications, see the respective documentation

³⁾ of the respective full scale value

Continuation:

	Measured value filtering	Sampling type	Digital resolution	Special features
KL3201	Various predefined internal digital filters	simultaneous	16-bit	
KL3202	Various predefined internal digital filters	multiplex	16-bit	
KL3204	Various predefined internal digital filters	multiplex	16-bit	
KL3204-0030	Various predefined internal digital filters	multiplex	16-bit	
KL3208-0010	Various predefined internal digital filters	multiplex	16-bit	B parameters possible
KL3228	Various predefined internal digital filters	multiplex	16-bit	B parameters possible
KL3222	Various predefined internal digital filters	multiplex	16-bit	for precise measurements; reduced measuring range Pt100: -200..+320 °C
KL3214	Various predefined internal digital filters	multiplex	16-bit	Siemens S5 data format
EL3201	Various predefined internal digital filters	simultaneous	16-bit	-
EL3201-0010	Various predefined internal digital filters	simultaneous	16-bit	for precise measurements; reduced measuring range Pt100 -200..+320 °C EL3201-0020: with factory working standard calibration certificate EL3201-0030: with external ISO17025/DAkkS calibration certificate
EL3202	Various predefined internal digital filters	multiplex	16-bit	-
EL3202-0010	Various predefined internal digital filters	multiplex	16-bit	for precise measurements; reduced measuring range Pt100 -200..+320 °C EL3202-0020: with factory working standard calibration certificate EL3202-0030: with external ISO17025/DAkkS calibration certificate
EL3204	Various predefined internal digital filters	multiplex	16-bit	-
EL3204-0162	Various predefined internal digital filters	multiplex	16-bit	additional 2 channels for 12 bit voltage measurement +/-10 V, $\pm 0.3\%$
EL3204-0200	Various predefined internal digital filters	multiplex	16-bit	for sensor types up to 240 k Ω which otherwise cannot be measured; temperature calculation according to Steinhart-Hart, B-parameter, IEC 60751, free table
EL3208	Various predefined internal digital filters	multiplex	16-bit	-
EL3208-0010	Various predefined internal digital filters	multiplex	16-bit	Measuring range limited to -50...+150 °C, NTC possible
EL3214	Various predefined internal digital filters	multiplex	16-bit	-
EL3214-0090	Various predefined internal digital filters	multiplex	16-bit	EL3214-0090: TwinSAFE SC
EL3218	Various predefined internal digital filters	multiplex	16-bit	-
EL3692	Various predefined internal digital filters	multiplex	24-bit	Autorange EL3692-0020: with factory working standard calibration certificate EL3692-0030: with external ISO17025/DAkkS calibration certificate
EL3751	Various predefined internal digital filters Freely parameterizable with TwinCAT Filter Designer	simultaneous	24-bit	EL3751-0020: with factory calibration certificate
EL3751-0004	Various predefined internal digital filters Freely parameterizable with TwinCAT Filter Designer	simultaneous	24-bit	EL3751-0024: with factory calibration certificate

	Measured value filtering	Sampling type	Digital resolution	Special features
ELM3244, ELM3246	Various predefined internal digital filters Freely parameterizable with TwinCAT Filter Designer	multiplex	24-bit	Output in °C/ °F/K possible;
ELM3502	Various predefined internal digital filters Freely parameterizable with TwinCAT Filter Designer	simultaneous	24-bit	Output in °C/ °F/K possible; ELM3502-0030: with external ISO 17025/DAkkS calibration certificate
ELM3504	Various predefined internal digital filters Freely parameterizable with TwinCAT Filter Designer	simultaneous	24-bit	Output in °C/ °F/K possible; ELM3504-0030: with external ISO 17025/DAkkS calibration certificate
ELM3702, ELM3704	Various predefined internal digital filters Freely parameterizable with TwinCAT Filter Designer	simultaneous	24-bit	Output in °C/ °F/K possible;
ELM3702-0101	Various predefined internal digital filters Freely parameterizable with TwinCAT Filter Designer	simultaneous	24-bit	Output in °C/ °F/K possible;
EP3204-0002, EPP3204-0002	Various predefined internal digital filters	multiplex	16-bit	-
EJ3202	Various predefined internal digital filters	multiplex	16-bit	B parameters possible
EJ3214	Various predefined internal digital filters	multiplex	16-bit	-

Continuation:

	RTD connection ⁴⁾	Resistance measuring range	RTD sensor types
KL3201	3-wire	0...1200 Ω, 0...5000 Ω	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000
KL3202	3-wire	0...1200 Ω, 0...5000 Ω	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000
KL3204	2-wire	0...1200 Ω, 0...5000 Ω	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000
KL3204-0030	2-wire	0...250 kΩ	NTC10k (Carel characteristic, 0 °C: 27280 Ω)
KL3208-0010	2-wire	0...650 kΩ	Pt1000, Ni1000, NTC
KL3228	1-wire (single-ended)	0...6500 Ω	Pt1000, Ni1000,
KL3222	4-wire	0...1200 Ω, 0...5000 Ω	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000, KTY
KL3214	3-wire	0...1200 Ω, 0...4000 Ω	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000, KTY
EL3201	3-, 4-wire	0...1200 Ω, 0...4000 Ω	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000, KTY
EL3201-0010	4-wire	0...1200 Ω, 0...4000 Ω	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000, KTY
EL3202	3-wire	0...1200 Ω, 0...4000 Ω	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000, KTY
EL3202-0010	4-wire	0...1200 Ω, 0...4000 Ω	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000, KTY
EL3204	2-wire	0...1200 Ω, 0...4000 Ω	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000, KTY
EL3204-0162	2-wire	0...1200 Ω, 0...4000 Ω	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000, KTY
EL3204-0200	2-wire	0 ... 6.5/65.5/240 kΩ	various Ni/Pt characteristics, any RTD in the range 100 Ω...240 kΩ
EL3208	2-wire	0...1200 Ω, 0...4000 Ω	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000, KTY
EL3208-0010	2-wire	0...1 kΩ, 0...5 kΩ, 0...10 kΩ 0...1.3 MΩ	Pt1000, Ni1000, NTC 1.8 k/2.2 k/3 k/5 k/ 10 k/20 k/100 k
EL3214	2-, 3-wire	0...1200 Ω, 0...4000 Ω	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000, KTY
EL3214-0090	2-, 3-wire	0...1200 Ω, 0...4000 Ω	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000, KTY
EL3218	2-, 3-wire	0...1200 Ω, 0...4000 Ω	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000, KTY
EL3692	2-, 4-wire	0..0.1 Ω, 0..1 Ω, 0..10 Ω, 0..100 Ω, 0..1 kΩ, 0..10 kΩ, 0..100 kΩ, 0..1 MΩ, 0..10 MΩ	-
EL3751	2-, 3-, 4-wire	0...5 kΩ	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000, various KT/KTY
EL3751-0004	2-, 3-, 4-wire	0...5 kΩ	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000, various KT/KTY
ELM3244, ELM3246	2-, 3-, 4-wire	0...50 Ω, 0...200 Ω, 0...500 Ω, 0...2 kΩ, 0...5 kΩ	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000, various KT/KTY
ELM3502	2-, 3-, 4-wire	not usable	Pt1000
ELM3504	2-, 3-, 4-wire	not usable	Pt1000
ELM3702, ELM3704	2-, 3-, 4-wire	0...50 Ω, 0...200 Ω, 0...500 Ω, 0...2 kΩ, 0...5 kΩ	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000, various KT/KTY
ELM3702-0101	2-, 3-, 4-wire	0...50 Ω, 0...200 Ω, 0...500 Ω, 0...2 kΩ, 0...5 kΩ	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000, various KT/KTY
EP3204-0002, EPP3204-0002	2-, 3-, 4-wire	0...4095 Ω	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000
EJ3202	2-, 3-wire	0...1200 Ω, 0...4000 Ω	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000, KTY
EJ3214	2-, 3-wire	0...1200 Ω, 0...4000 Ω	Pt100, Pt200, Pt500, Pt1000, Ni100, Ni120, Ni1000, KTY

⁴⁾ if a sensor with fewer lines is to be connected, jumpers must be set on the device

2.4 Power supply

Comparative overview of Beckhoff Supply Terminals

The following table is intended to provide a quick overview of the available Beckhoff EtherCAT IO devices for direct supply of devices/sensors/actuators. Depending on the design, output powers of up to several 10 W are possible. More power is offered by Beckhoff power supplies [PSxxxx Power supplies \(24 V and 48 V DC\)](#) | [Beckhoff Germany](#).

NOTICE

Device documentation is solely authoritative

The values may be shortened extracts from the respective documentation, which is decisive and recommended for detailed analysis.

For a possibly more up-to-date overview, please consult www.beckhoff.com.

	Description	Application recommendation	Number of outputs	Electrical isolation
EL2595	EtherCAT Terminal, 1-channel LED output, 48 V DC, 0.7 A	current-controlled continuous light > 300 mA; power supply applications	1	E-bus/field: yes Supply/output: no
EL2596	EtherCAT Terminal, 1-channel LED output, 24 V DC, 3 A	Standard terminal for the vision application on illumination up to 24 V DC; power supply applications	1	E-bus/field: yes Supply/output: no
EL2596-0010	EtherCAT Terminal, 1-channel LED output, 48 V DC, 3 A	Standard terminal for the vision application on illumination up to 48 V DC, power supply applications	1	E-bus/field: yes Supply/output: no
EL9501	Power supply terminal 0..20 V, 0..2 A	adjustable power supply terminal with diagnostics for small output	1	E-bus/field: yes Supply/output: no
EL9561	Power supply terminal 0..20 V, 0..2 A, electrically isolated	adjustable power supply terminal with diagnostics for small output, isolated applications	1	E-bus/field: yes Supply/output: yes
EL9562	EtherCAT Terminal, power supply unit, 2 x 24 V DC, 0.2 A, electrically isolated	Fixed voltage power supply terminal with diagnostics for small output, isolated applications	2	E-bus/field: yes Supply/output: yes
EL9562-0015	EtherCAT Terminal, power supply unit, 2 x 15 V DC, 0.3 A, electrically isolated	Fixed voltage power supply terminal with diagnostics for small output, isolated applications	2	E-bus/field: yes Supply/output: yes
EL9505/8/10/12/15	Power supply terminal 5 V DC (8 V DC/ 10 V DC/ 12 V DC/ 15 V DC)	Fixed voltage power supply terminal with diagnostics for small output	1	E-bus/field: yes Supply/output: no
EL9560	Power supply terminal 24 V DC/ 24 V DC, 0.1 A	Fixed voltage power supply terminal with diagnostics for small output	1	E-bus/field: yes Supply/output: yes

Continuation:

	Input voltage	Output power	Output voltage	Output current	Output rate
EL2595	24 V DC (-15 %/+20 %)	33 W	2...48 V DC (up/down control)	300...700 mA	5 kHz / 200 µs
EL2596	24 V DC (-15 %/+20 %)	14.4 W	Continuous light mode: 0...U _{in} (down control); for further details see documentation	Pulsed operation: 0...3 A Continuous operation: 0...1.2 A for further details see documentation	40 kHz / 25 µs
EL2596-0010	24 V DC (-15 %/+20 %)	14.4 W	Continuous light mode: 0...U _{in} (down control); for further details see documentation	Pulsed operation: 0...3 A Continuous operation: 0...1.2 A for further details see documentation	40 kHz / 25 µs
EL9501	24 V DC (-15 %/+20 %)	15 W	2 output ranges: 0.5..5 V; 1..20 V (down control)	0...2 A for further details see documentation	1 kHz / 1 ms
EL9561	24 V DC (-15 %/+20 %)	4.8 W	2 output ranges: 0.5..5 V; 1..20 V (down control)	0...2 A for further details see documentation	1 kHz / 1 ms
EL9562	24 V DC (-15 %/+20 %)	2x 4.8 W	2x 24 V	2x 0...0.2 A	-
EL9562-0015	24 V DC (-15 %/+20 %)	2x 4.5 W	2x 15 V	2x 0...0.3 A	-
EL9505/8/10/12/15	24 V DC (-15 %/+20 %)	U _{out} · 0.5 A	EL9505: 5 V DC EL9508: 8 V DC EL9510: 10 V DC EL9512: 12 V DC EL9515: 15 V DC (down control)	0... 0.5 A	-
EL9560	24 V DC (-15 %/+20 %)	2.4 W	24 V (up/down control)	0... 0.1 A	-

Continuation:

	Load type	Resolution	Output uncertainty	Changeover times	Special features
EL2595	LED (ohmic)	11 bits (10 mV)	tbd.	TON/TOFF < 1 μ s typ., pulses from 200 μ s	Operation mode: constant current CC; optional automatic operation in case of communication interruption, flash operation from 200 μ s up to LED continuous operation
EL2596	LED (ohmic)	11 bits (10 mV)	tbd.	TON/TOFF < 1 μ s typ., pulses from 25 μ s...10 s	Operation modes: constant voltage CV, constant current CC, PWM; extensive real-time diagnostics; voltage divider connection option, TriggerOut; LED continuous operation, RGB/common anode mode
EL2596-0010	LED (ohmic)	11 bits (10 mV)	tbd.	TON/TOFF < 1 μ s typ., pulses from 25 μ s...10 s	Operation modes: constant voltage CV, constant current CC, PWM; extensive real-time diagnostics; voltage divider connection option, TriggerOut; LED continuous operation, RGB/common anode mode
EL9501	ohmic, inductive, capacitive up to 1 mF	11 bits (10 mV)	Voltage: < ± 0.5 % (at 25 $^{\circ}$ C ± 5 $^{\circ}$ C and up to 100 mA, referred to the output end value, for further details see documentation)	-	Operation mode: constant voltage (CV); two output ranges 5/20 V, output current measurement ± 1 %, output voltage measurement ± 0.5 %, max. rate of change 1000 V/sec
EL9561	ohmic, inductive, capacitive up to 1 mF	11 bits (10 mV)	Voltage: < ± 0.5 % (at 25 $^{\circ}$ C ± 5 $^{\circ}$ C and up to 100 mA, referred to the output end value, for further details see documentation)	-	Operation mode: constant voltage (CV); two output ranges 5/20 V, output current measurement ± 1 %, output voltage measurement ± 0.5 %, max. rate of change 1000 V/sec electrical isolation
EL9562	ohmic, inductive, capacitive	-	< ± 5 %	-	Operation mode: constant voltage (CV); automatic restart after short circuit, diagnostics U_{IN}/U_{OUT} , outputs switchable, can be used as symmetric ± 15 V DC power supply e.g. for power supply for bipolar supplied precision current transformers
EL9562-0015	ohmic, inductive, capacitive	-	< ± 5 %	-	Operation mode: constant voltage (CV); automatic restart after short circuit, diagnostics U_{IN}/U_{OUT} , outputs switchable, can be used as symmetric ± 15 V DC power supply e.g. for power supply for bipolar supplied precision current transformers
EL9505/8/10/12/15	ohmic, inductive, capacitive	-	< ± 1 %	-	Operation mode: constant voltage (CV)
EL9560	ohmic, inductive, capacitive	-	< -15 %/+5 %	-	Operation mode: constant voltage (CV)

Continuation:

	Diagnostics in the process image	Distributed Clocks	Switching output	Digital input
EL2595	yes	yes	-	1 (electrically isolated, 8 mA typ., 5...24 V DC)
EL2596	yes	yes	1 (electrically isolated, max. 10 mA push-pull, 10...24 V DC, voltage adjustable via externally connectable voltage distributor)	1 (electrically isolated, 3 mA typ., 4...24 V DC, sensitivity switchable)
EL2596-0010	yes	yes	1 (electrically isolated, max. 10 mA push-pull, 10...24 V DC, voltage adjustable via externally connectable voltage distributor)	1 (electrically isolated, 3 mA typ., 4...24 V DC, sensitivity switchable)
EL9501	yes	no	-	-
EL9561	yes	no	-	-
EL9562	yes	no	-	-
EL9562-0015	yes	no	-	-
EL9505/8/10/12/15	yes	no	-	-
EL9560	yes	no	-	-

3 Basic considerations on analog technology

You want to use Beckhoff devices (terminals, boxes, modules) with analog input or output function. This also includes metrological applications, i.e. applications with the goal of the lowest possible measurement uncertainty, or colloquially, high measuring accuracy.

Then, before the design-in process, but especially at the point of software creation and commissioning, you should take a moment for the following basic considerations:

- **Diagnostics**

In the event of problems, elements that are *not directly relevant to the solution* are frequently pushed aside on the path to the solution. However, take your time and program the diagnostic options available in EtherCAT (or other fieldbus used), TwinCAT (or other control software) and devices! Remember that software diagnostics is possible in each of the following levels:

- fieldbus/EtherCAT,
- device (terminal, box module, module) and
- analog channel (several per device if applicable)

which means that at the end of each bus cycle, you have information on whether you can trust the measured value. You should not assume that the measured value is up to date and correct, just because it lies within a plausible range.

See the respective product page in the chapter "General commissioning instructions for the EtherCAT slave" on the [Beckhoff homepage](http://www.beckhoff.de) www.beckhoff.de, the [EtherCAT system documentation](#), and the Beckhoff Information System.

- **False measurement – assessing the severity of the consequences**

You wish to carry out a measurement. There is a certain (small) probability that this can lead to an incorrect result; refer to the "Diagnostics" section. However, internal or external influences on the measuring device can also lead to an incorrect measurement, e.g. in the form of an unexpectedly high measuring error. For your application, consider whether you can respond quickly enough in this situation, repeat the measurement if necessary, or whether other actions are necessary. A plausibility check of the measured value is usually useful. If there is a considerable potential for damage, a redundant measurement with a second/nth sensor and analog input could be useful and cost-effective.

- **Shielding and earth**

Consider environmentally dependent influences on the production plant/measurement environment, which can differ significantly from the laboratory and prototype conditions. This can lead to considerable measuring errors and operational disruptions.

Refer to the chapter "[Analog information - shield and earth \[▶ 104\]](#)"

- **Environmental conditions**

In particular, the ambient temperature at the place of installation of the device, in conjunction with air movements (forced ventilation, still air, self-convection) and the installation position can influence the measurement operation.

Consider the static and dynamic thermal processes that can take place at different times of the day, such as the failure of cooling units, the incidence of light, or handling of hot parts in the vicinity. If the cooling is expected to fail, for example, a device should be switched off (de-energized) to protect it from damage due to overheating.

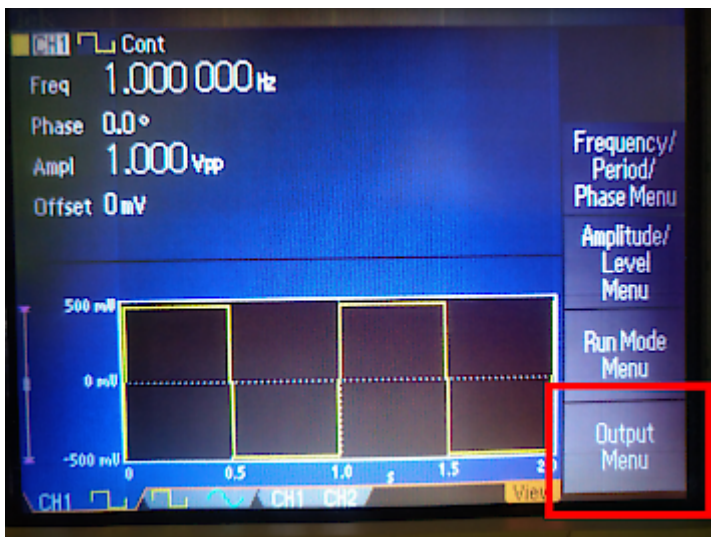
Special environmental influences (humidity, temperature, gases) can also lead to corrosion or, more generally, to altered transmission properties of contacts or connectors (including inside the device). Appropriate protective measures may then be required.

3.1 Further considerations...

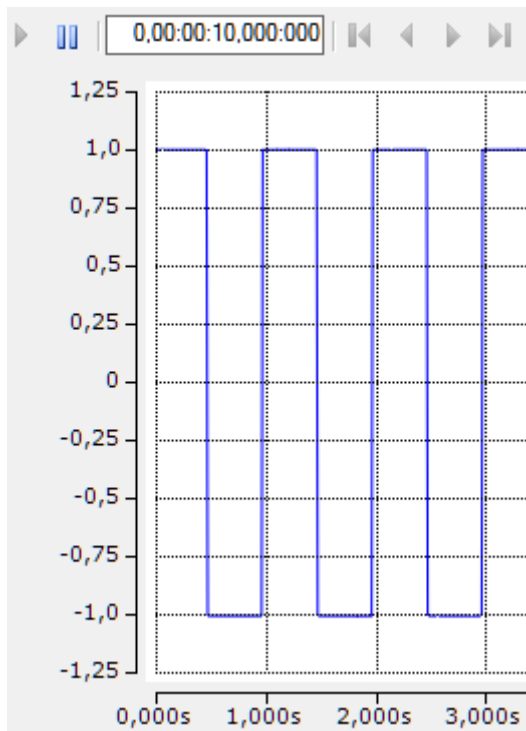
The following section contains some practical notes from everyday use of analog measurement technology:

- Temperature plays a significant role in the verification of analog measurements with higher accuracy. In particular, many (all?) electronic processes are more or less **temperature-dependent**. On the device side, considerable effort is sometimes made to reduce this temperature dependency. Nevertheless, both sources (power supply units, sensors) and measuring devices (EtherCAT Terminal, reference devices) should have stabilized thermally before use (see corresponding documentation); time ranges of >30 minutes are often required here. Temperature changes can have a falsifying influence on the logged data, especially in the case of long-term measurements >1 h. Examples of (hidden) temperature influence would be:
 - initial device heating after switching on,
 - drafts, heat radiation from nearby devices/people, radiation effects e.g. from the sun (also in the non-visible range!),
 - variable operation of the air conditioning
 - Change of the installation position/adjacent terminals.
 - Change of internal load (current flow, voltage level)
 - Hand-held connections (plugs)
- This **temperature dependence** particularly applies to the **load/source/sensor** to be measured, e.g. an SG full bridge connected for testing. If, for example, a full bridge is modeled based on simple resistances, the resulting temperature coefficient is significantly higher than that of the measuring device (Beckhoff Terminal/Box). However, the voltage of a simple battery cell also shows a considerable temperature dependence!
- Current inputs can have a **current-dependent internal resistance**. Therefore, a control based on a voltage-controlled signal (e.g. power supply unit) may have misleading results
- Influences on the signal lines from electrodynamic/magnetic radiation must be taken into account; suitable **shielding/grounding/protection components** must be provided. The smaller (the amplitude of) the transmitted signals, the more important this becomes: analog level in the < 10 V range and mV and μV (thermocouples, measuring bridges/strain gages), and mA/ μA in particular must be protected with effective shielding, if applicable with twisted pair cabling, or by routing cables at a distance from high-voltage/high-current cables.
Refer to the chapter [Notes regarding analog equipment - shielding and earth \[► 104\]](#) in this documentation for more information on this.
- When testing the behavior under **changing signal amplitudes**, the behavior of the source under changing load (= load shedding, load switching, level adjustment) also has to be considered. Attention: the load of the sensor may change even if self test routines are running in the measuring device (terminal, box).
- When using **calibrators** (= devices that output a target voltage/current/... according to the display) for testing/laboratory purposes, it is highly recommended that they are also measured with high-quality measuring devices (multimeters). If it is not explicitly ensured that the specific combination of calibrator (source) <-> Beckhoff analog input (sink: terminal, box) is harmonized, the display value of the calibrator is not to be trusted! The EMC protection circuits in the Beckhoff products required for industrial use can lead to oscillations and pumping effects that change the "true" signal on the line and bring it into conflict with the calibrator display value if the latter does not have its own back measurement function. An analytical look with the oscilloscope or the use of different calibrators can provide clarity.
- In general, it is advisable to consider the **vendor data** regarding the load/source/sensor, e.g. with regard to the last adjustment, thermal behavior, etc..
- For example, the information about the **inherent noise of the source** must be observed if the specified noise of the Beckhoff devices is to be checked with it. However, such noise data can only be found in high-order sources.
- The difference between **calibration and adjustment/compensation** is to be observed. A recent calibration (= assessment of the remaining deviation from a trusted normal) in itself is only meaningful, if the measurement took place within the tolerance assured by the vendor or was set accordingly based on an adjustment/compensation. The residual error after the adjustment, which is stated on the calibration certificate, may have to be taken into account manually.

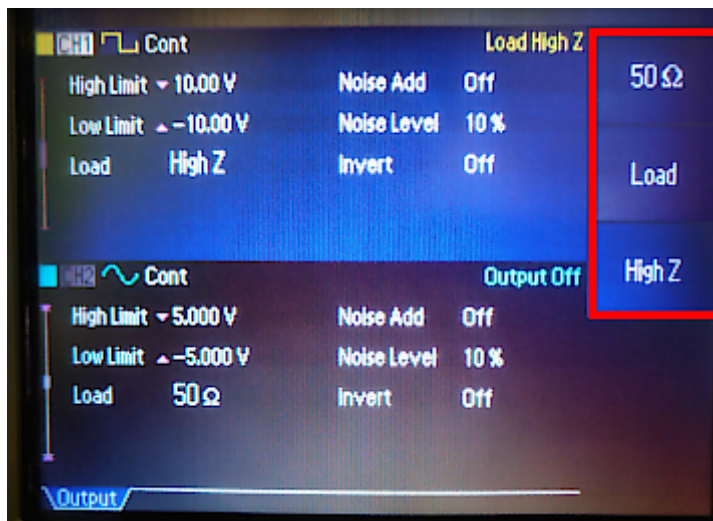
- Many electrical measurements from sensor and measuring device are subject to an initial electrical offset, which can have a significant effect on the measurement. Examples include zero load of weighing scales (solution: tare) or open-circuit voltage in cables during voltage measurements. Especially (but not exclusively) for strain gauge measurements, it is helpful to carry out an **offset correction** immediately before the actual measurement, as this considerably reduces the offset component of the measuring channel of the terminal itself (see chapter Specification).
- If the terminal was exposed to **condensation** after transport/storage, it should be stored in a de-energized state until it is completely dry.
- Optional **ventilation openings** are to be kept generously free for free convection. See clearance recommendations in chapter "Mounting and wiring".
- For high-precision measurements, interference may also occur through **thermovoltages** in the mV/ μ V range. Specifically, this may occur if ferrules on stranded copper wire are used at the terminal point contact, due to a local shift of the point of different material pairing. In such cases it may be worth trying to plug the stranded wire directly into the terminal contact or to clean the contact.
- For measurements with currents $> 100 \mu\text{A}$, e.g. 20 mA current loop, loose connections such as **hand-held measuring tips** are not permitted under any circumstances! They lead to strong and fast fluctuating transition resistances which usually cannot be compensated quickly enough by the power source. Any connections must be clamped/screwed/soldered to ensure a reliable contact. By the way: hand-held test probes can heat up as a result and lead to variable thermovoltage
- Two aspects are particularly relevant when using signal generators as signal transducers, especially during initial measurement trials with analog terminals or during filter trials:
 - The amplitude of the output signal often drops suddenly with increasing frequency. For example, if 1 Vpp is set as the target amplitude, this is usually achieved cleanly for "slow" signals (less than 100 Hz, depending on the device), but not at frequencies greater than 100 Hz. This is then interpreted as an apparent measuring error of the analog input, since the analog input measures the real level. It is strongly recommended not to trust the graphical display of the signal generator but to measure the output signal with a third device, ideally a proven oscilloscope. It may be necessary to manually increase the amplitude at the signal generator, depending on the frequency, until the device reaches its control limit.
 - Signal generators with graphic display (screen) are easy to set up, but only provide a target output signal that may not necessarily correspond to the actual measurable signal. The impedance setting of the output and the ground reference can be partly responsible for this. Example: a Tektronix AFG3022B signal generator is connected on channel 1 in two-pole/differential mode to an ELM3004 in $\pm 10 \text{ V}$ mode and a signal with 1 Vpp, 1 Hz is set.



However, the terminal actually sees 2 Vpp, represented below by an associated TwinCAT Scope output:



The reason for the "wrong" display of the signal generator is its output setting of "50 Ω" or "Load", i.e. it assumes a power-based level adjustment and thus also 50 Ω on the input side.



However, industrial analog terminals usually have input resistances of several 100 kΩ to MΩ. Therefore the impedance setting "HighZ" is the correct one in this case:



Electrically, the output signal has not changed during the changeover! Only the display on the screen changes.

Again, it is recommended to measure the output signal with a third device, a multimeter or oscilloscope, before starting the test. No dynamic signal [kHz] is required for this test, a DC or slow AC signal is sufficient.

- A few basic thoughts on **resolution vs accuracy/measurement uncertainty**:

High resolution (e.g. 24-bit) is stipulated in many cases for analog measurements, when it is in fact low measurement uncertainty = high measuring accuracy (e.g. $\pm 0.005\%$ of the full scale value) that is required. The implicit assumption is that measurements with high resolution will automatically provide low measurement uncertainty. However, both properties are initially independent of each other. The resolution quantifies the interval size that leads to a digital distinguishability in the measurement result, e.g. a change of 20 mV in the analog signal is only detected if the resolution is also smaller than 20 mV, the resolution being technically determined by the reference voltage and the number of bits. However, this is still independent of the extent to which the resolvable value corresponds to the true value.

Basically, the following applies: resolution results from the circuit design, low measurement uncertainty/high accuracy (above all) from the adjustment - wherein *both* fields are demanding.

There are various influencing factors that worsen the measuring accuracy:

If an influencing factor is known and describable, it is to be assigned to the **systematic** measurement uncertainty. For example, a temperature or characteristic curve influence can be quantified and then usually compensated for in the production adjustment or at operating time; the resulting effort can be reduced here by clever design.

The other major influence on the effective measuring accuracy is due to **random** influencing variables: the inherent noise of the electronics, as well as others in the entire measurement chain. These measurement uncertainties are characterized by the fact that they cannot be described deterministically and the deviation of the measurement results from measurement to measurement is of a purely random nature. Here, the user has a large scope of action, because by averaging over several measurements, the measuring accuracy of the calculated result can be increased. Because truly random fluctuations are considered to have no mean values, their effect on the measured value can be reduced by mean value filtering. The disadvantage of this is a later completion time of the measurement: "the result is available".

The one extreme is to process unchanged "raw data", i.e. the individual noisy measured values in the control cycle without delay, i.e. individually. The other extreme is to average or smooth over (almost infinitely) many measured values - this leads to a corresponding time delay, which is very unfavorable for a control loop. However, this effectively eliminates the random influence on the measurement result and the output value approaches the true (practically indeterminable) value more and more - under the above-mentioned assumption, of course, that the noise is equally distributed and thus the "Filter" tool may also be applied to the data for this purpose or does not distort the result.

Between these two extremes lies the range in which the user now has to select the filters in the application in view of the max. permitted delay and the required smoothing.

In general, it can be assumed that the faster a channel samples, i.e. the higher the usable data rate, the higher its inherent electrical noise will be. It is not for nothing that high-precision measuring devices operate with sample rates in the range of 1/min or slower.

Two examples for a measuring range of $\pm 10\text{ V}$ and comparable sampling rate:

Note: 24 bits/bit positions result in a value space of $2^{24} = 16,777,216$ digits. Since the first bit is usually used as a sign, $2^{23} = 8,388,608$ digits remain as the available unipolar number range.

Example 1: 24-bit resolution incl. sign over measuring range $\pm 10\text{V} \rightarrow 1.19 \mu\text{V}/\text{digit}$
 Assumption: inherent noise of the measuring electronics of 10 bits (the lower 10 bits) and thus "many wiggling bits, i.e. few standing bits"
 Result: a measurement inaccuracy to be expected from this alone (without averaging) of 2^{10} digits * $1.19 \mu\text{V}/\text{digit} = 1.2 \text{ mV}$

Example 2: 16-bit resolution incl. sign over measuring range $\pm 10 \text{ V} \rightarrow 305 \mu\text{V}/\text{digit}$ (i.e. 256x worse resolution)

Assumption: inherent noise of the measurement electronics of 1 bit (15 standing bits)
 . Result: a measurement inaccuracy to be expected from this alone (without averaging) of 0.6 mV

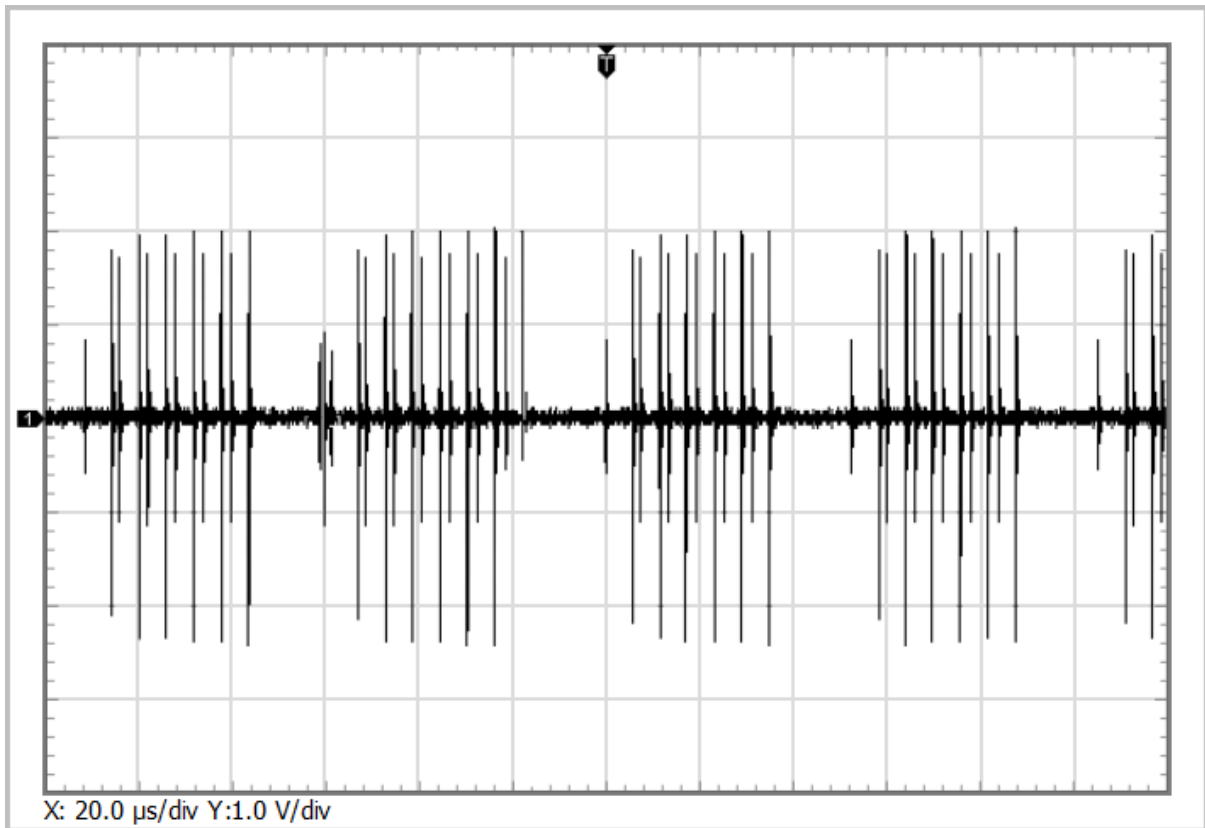
Note: of course, a lot of other factors like resolution step, temperature, etc. contribute to the total measuring error, but in this section the focus is on the noise of the electronics.

So in this not unrealistic example, the 16-bit channel would effectively be more accurate than the 24-bit channel.

By averaging (statistics) over a (high) number of samples, the effective measurement uncertainty of both example channels could now be lowered. This is only dependent on the time available. The longer the averaging period, the more "standing bits" can be determined from the noisy data stream: in the above 16-bit example, the 15 standing bits can account for 16 or even more (17 or 18) bits, e.g. by activating the terminal's internal mean value filter – provided the user is prepared to accept a slower update rate or a long signal delay, corresponding to a low-pass filter. This calculation could take place locally in the measuring device (and in fact reduce the output rate) or it must take place in the central PLC.

Conclusion: a high digital resolution is not the sole cause of good measurement quality, but it is useful as a basis for subsequent sophisticated data manipulation with the aim of achieving the truest possible measured value as quickly as possible.

- The source impedance in relation to the measuring device impedance is of great importance for correct measurement! Increased source impedance (high output resistance) means that the source can only drive a small amount of current. This has implications in three areas:
 - In general, the effect of the unavoidable voltage divider $R_{\text{Source}}/R_{\text{Measuring device}}$ can be observed: the measurable signal amplitude sometimes changes considerably if overall "slow" changes occur at one point in the system (measuring source - measuring device): e.g. the device of one side is exchanged or the resistances change due to temperature (self-heating, daylight, ...).
 - Signals in the LF/HF range are affected by unavoidable capacitive/inductive cable loads: if necessary, an intended voltage amplitude is not achieved because the source "does not provide sufficient power" due to the high source impedance and the "low-pass effect" of the cable load on an alternating quantity becomes apparent in such a way that "too little time is available to build up the signal".
 - Furthermore, "fast" changes to the system can eventually lead to irritation of the low-power source and to resonances (see also [Note on oscillation effects with analog 20 mA inputs](#) [▶ 147]).
- The previously mentioned effects can lead to a problem area when measuring small signal voltages, which would have to be considered for low-power sources such as thermocouples.
 Example: IR sensors (respond to temperature radiation, comparatively like thermocouples) are usually high impedance (some 10 k Ω) and low power. In connection with a multiplex input circuit (keyword: "fast" system change) and a standard thermocouple terminal, there may be a reaction on the connecting line, a measurement close to the application is hardly possible:



A simultaneous acquisition (e.g. EL3314-0002) or very high-impedance measuring devices (e.g. ELM3344) provide a remedy.

4 Basics of sensor technology

4.1 Basics of thermocouple technology

● General term: "device"

i This chapter is used in the documentation of several Beckhoff products. It is therefore written in general terms and uses the generic term "device" for the different device types such as terminal (EL/ELM/KL/ES series...), box (IP/EP/EPP series...), module (EJ/FM series...).

Thermocouples are temperature sensors. The application areas of thermocouples are widespread due to their low cost, fast detection of temperature differences, wide temperature ranges, high temperature limits and availability in a wide range of types and sizes.

Measuring principle and configuration

Temperature measurement with a thermocouple is based on the Seebeck effect, which was discovered in the 1820s by the German physicist Thomas Johann Seebeck. The Seebeck effect, also known as thermoelectric effect, describes a charge shift in a conductive material due to a temperature gradient along the conductor. The magnitude of the charge shift depends on the magnitude of the temperature difference and the respective conductor material.

In thermocouples this charge shift is used to generate a voltage. Two different conductor materials are connected at one end. This is the measuring point at which the temperature T_m is to be determined. At the other end the conductors are not connected. This open end, where the transition to the measuring electronics is located, is the comparison point with comparison temperature or also the cold junction with cold junction temperature T_{CJ} . A temperature difference ΔT (T_{thermo}) occurs between the cold junction and the measuring point, which can be measured via the voltage between the conductors at the open end (thermovoltage U_{th}). The voltage depends on the conductor materials used and the temperature difference. It is in the range of a few mV.

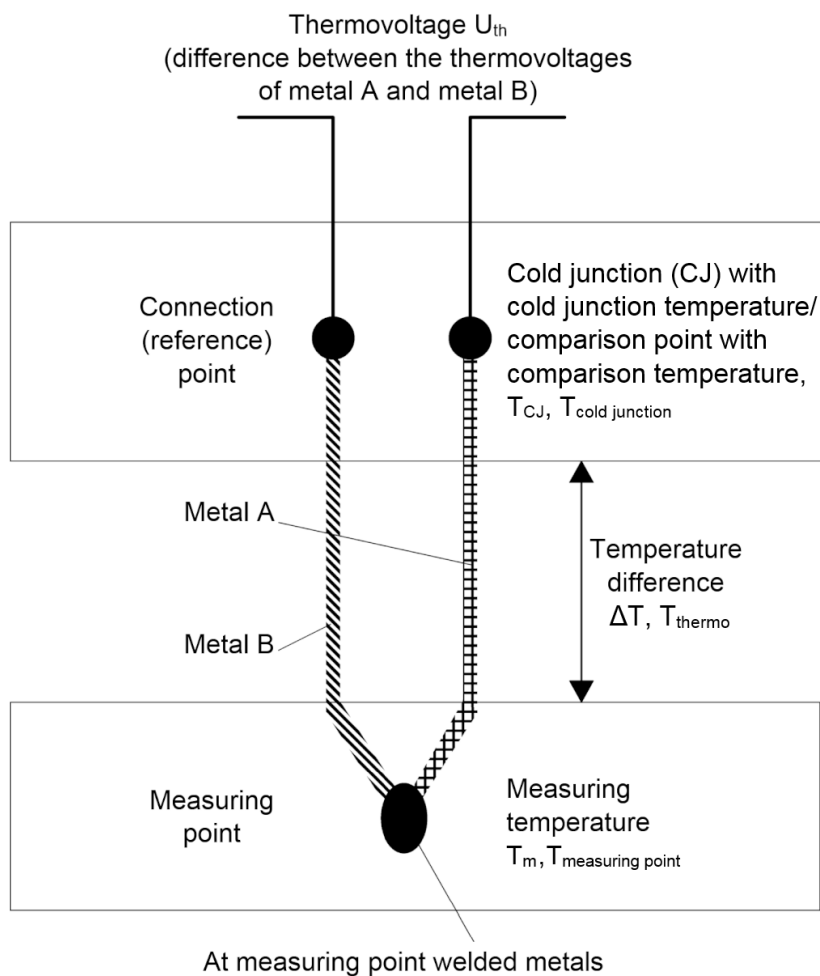


Fig. 1: Structure and principle of a thermocouple

If only one material were used for a thermocouple, the charge shift in both conductors would be identical, so that no potential difference between the two conductors at the open end could be measured.

The temperature measurement with thermocouples is therefore actually a voltage measurement, based on which a temperature can be determined from the known characteristic curve. In addition, the measuring procedure is not absolute but differential, since no absolute temperature with the reference point 0 °C is determined, but the temperature difference between the measuring point and the cold junction.

For the evaluation of thermocouples, measuring electronics are required that can evaluate small voltages in the mV range with sufficiently high resolution and accuracy. Thermocouples are active sensors, which means that no sensor supply is required to measure the temperature due to the voltage will be generated by the thermocouple itself.

Thermocouple types

There are different types of thermocouples, which consist of different combinations of conductor materials. Each material combination has specific properties and is suitable for certain applications. The different types or thermocouple types are named with letters.

Due to the different material combinations, the different thermocouple types have different characteristic values. They differ in the temperature limits and the characteristic voltage/temperature curve. In order to be able to differentiate between the thermocouple types, the color codes for the sheath, the positive pole and the negative pole are defined in various standards.

The following table shows common thermocouple types with the specification of the materials used, the defined temperature ranges and the color coding.

Type (conforms to EN60584-1)	Element	Technically usable measuring range ¹⁾		Average temperature coefficient (measuring range, recommended)	Voltage at min	Voltage at max	Color coding (sheath - positive pole - negative pole) according to IEC 60584-3
		min	max				
A-1	W5%Re - W20%Re	0 °C	2500 °C	14.7 µV/K	0 mV	33.64 mV	red - white - red
A-2	W5%Re - W20%Re	0 °C	1800 °C	15.7 µV/K	0 mV	27.232 mV	red - white - red
A-3	W5%Re - W20%Re	0 °C	1800 °C	15.4 µV/K	0 mV	26.773 mV	red - white - red
Au/Pt	Au-Pt	0 °C	1000 °C	39.0 µV/K	0 mV	17.085 mV	not standardized
B	Pt30%Rh-Pt6Rh	200 °C	1820 °C	10.3 µV/K	0.178 mV	13.82 mV	grey - grey - white
C ²⁾	W5%Re-W26%Re	0 °C	2320 °C	16.8 µV/K	0 mV	37.107 mV	not standardized
D	W3%Re-W25%Re	0 °C	2490 °C	174.0 µV/K	0 mV	40.792 mV	not standardized
E	NiCr-CuNi	-270 °C	1000 °C	74.2 µV/K	-9.835 mV	76.373 mV	violet - violet - white
G	W-W26%Re	1000 °C	2300 °C	186.9 µV/K	14.5 mV	38.8 mV	not standardized
J	Fe-CuNi	-210 °C	1200 °C	57.1 µV/K	-8.095 mV	69.553 mV	black - black - white
K	NiCr-Ni	-270 °C	1372 °C	40.3 µV/K	-6.458 mV	54.886 mV	green - green - white
L ³⁾	Fe-CuNi	-50 °C	900 °C	59.0 µV/K	-2.51 mV	53.14 mV	blue - red - blue
N	NiCrSi-NiSi	-270 °C	1300 °C	36.5 µV/K	-4.345 mV	47.513 mV	pink - pink - white
P	Pd31%Pt14%Au-Au35%Pd	0 °C	1395 °C	40.2 µV/K	0 mV	55.257 mV	not standardized
Pt/Pd	Pt-Pd	0 °C	1500 °C	38.3 µV/K	0 mV	22.932 mV	not standardized
R	Pt13%Rh-Pt	-50 °C	1768 °C	12.6 µV/K	-0.226 mV	21.101 mV	orange - orange - white
S	Pt10%Rh-Pt	-50 °C	1768 °C	11.1 µV/K	-0.236 mV	18.693 mV	orange - orange - white
T	Cu-CuNi	-270 °C	400 °C	48.5 µV/K	-6.258 mV	20.872 mV	brown - brown - white
U ³⁾	Cu-CuNi	-50 °C	600 °C	57.2 µV/K	-1.85 mV	34.31 mV	brown - red - brown

1) The specified measuring range refers to the maximum possible measuring range of the specified thermocouple type. The technically reasonable usable measuring range with the thermocouple measuring instruments may be limited. The possible measuring ranges of the thermocouple measuring devices are specified in the technical data in the documentation.

2) not standardized according to EN60584-1

3) according to DIN 43710

The thermocouple must be selected according to the operating conditions. Therefore, not only the uncertainty must be taken into account, but also the other properties of the different thermocouple types. For an application with small temperature fluctuations, it is advantageous to select a thermocouple type with a high thermovoltage per temperature change. In an application where the temperature to be measured is very high, it is important to observe the maximum operating temperature.

Characteristic curves of thermocouples

Type-specific reference tables are available for determining the temperature difference ΔT to a measured thermovoltage. A simple conversion of the voltage into a temperature with a temperature coefficient, as is often approximated in resistance thermometers, is not possible because the relationship between voltage and temperature is clearly non-linear over the entire measuring range. The changing temperature coefficient results in a non-linear characteristic voltage/temperature curve. This characteristic curve is in turn dependent on the thermocouple type, so that each type has its own non-linear characteristic voltage/temperature curve. As an example, the characteristic curves for typical thermocouple types are shown in the following diagram “Characteristic voltage/temperature curves..”. The non-linearity is particularly evident in the temperature range below 0 °C.

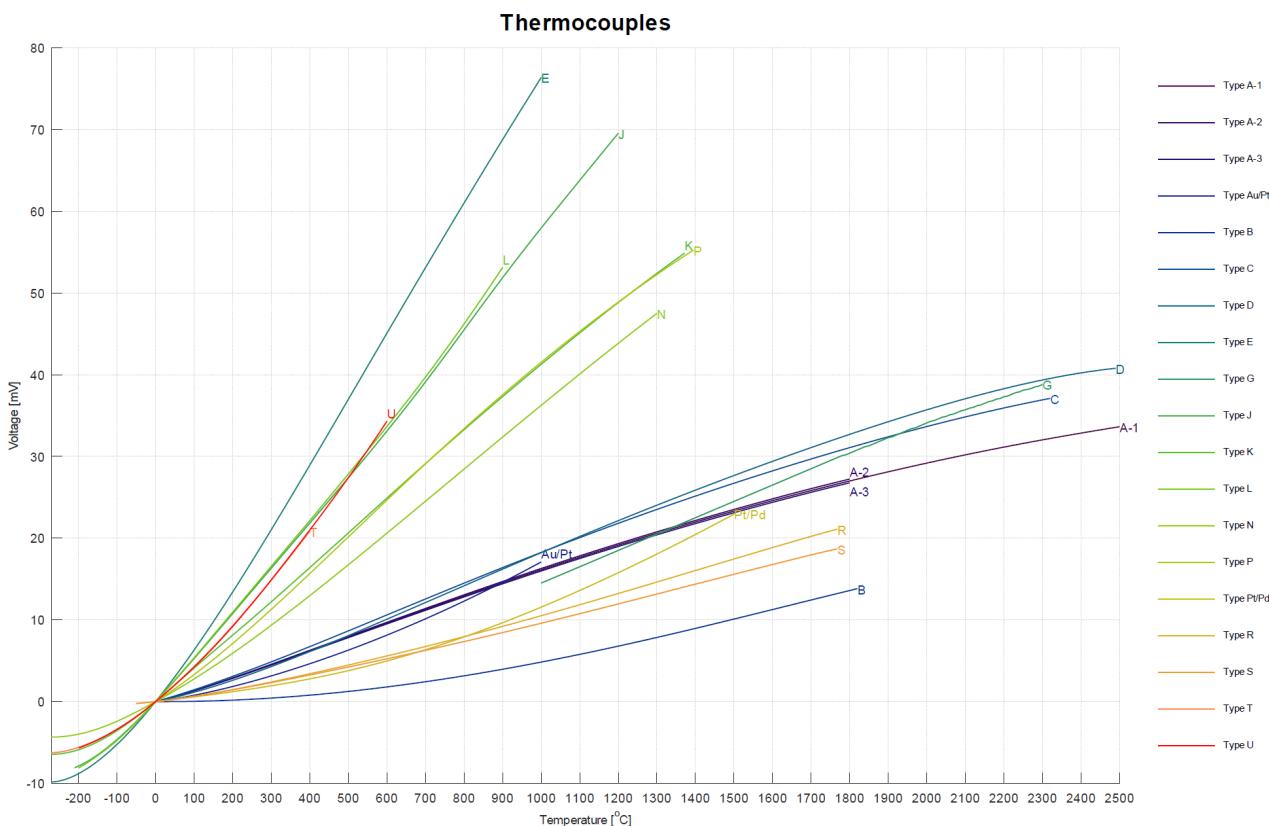


Fig. 2: Characteristic voltage/temperature curves of different thermocouple types

Thermocouples are subject to unavoidable and irreversible changes during practical application, which leads to ever-increasing measurement uncertainties over time. In other words: the measurement becomes more and more incorrect over time. These changes are also referred to as aging and depend on various influencing factors. Examples of these influences are mechanical and chemical stresses on the thermocouples. Mechanical stresses are deformations of the conductors, which change the crystal structure of the metals. This leads to incorrect thermovoltages. Chemical stresses are also changes in the crystal structure of the metals or oxidation, which change the thermal properties of the conductors, resulting in a change in the characteristic curve. This influence can be reduced by installation in gas-tight protection tubes.

Pluggable connections

Open wire ends or suitable thermocouple connectors can be used to connect thermocouples to measuring devices and evaluation electronics or to connect a thermocouple to thermo or compensating cables.

Ideally, the contacts of such a thermocouple connector are made of the material of the respective thermocouple. This results in an almost thermovoltage-free transition at the connection points. The connectors usually have fixed housing colors (normed by IEC or ANSI) depending of their type, e.g. type K is green. Labelling on the housing and different contact shapes are intended to avoid polarity reversal.

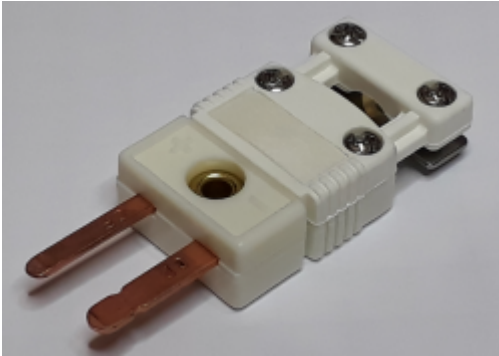


Fig. 3: Example of a thermocouple plug connector: there are several common sizes: standard, mini or micro.

A special feature is the white connector, which is designed with normal copper contacts, almost like a simple non-thermocouple connector. This makes it universally applicable for all thermocouple types, although it has the disadvantage that it does not create a thermovoltage-free transition. Far more common than the white plug is the white "universal" socket on the measuring device. This allows any thermocouple plug to be plugged into the device. In the measuring device, the cold junction temperature must then be determined at this plug transition (see section "[Measuring principle and configuration](#)" [► 35]).

Extensions and connection of thermocouples

In some cases it is useful to extend the thermocouple and thus to move the cold junction to a particular location, where the temperature can be kept constant or measured by simple means. For this purpose the thermocouple must be extended. This can be done with a thermo or compensation wire. Thermo cables are made of the same material as the thermocouple itself. Compensating cables, on the other hand, are usually made of cheaper materials with the same thermo-electric properties. Both types are therefore suitable for extending a thermocouple to a remote cold junction. The wires for thermo and compensating cables are standardized by DIN 43713.

With compensating cables, care must be taken to ensure that the material used has similar thermo-electric properties but not necessarily identical properties. The thermal properties only apply in a narrowly limited temperature range. At the transition from thermocouple to compensation wire, another thermocouple is created. This results in small thermovoltage distortions, which influence the measurement result. If the compensating cables are used outside the specified temperature range, the accuracy of the temperature measurement will be further affected and the measurement result will deteriorate.

For both thermal and compensation wires, there are two accuracy classes that indicate the limit deviations. These are defined in DIN 43722. When selecting the thermocouple extension, the resulting uncertainty should be considered and evaluated.

● Sensor circuit

i Changing the sensor circuit through additional elements such as selector switches or multiplexers can affect the measuring accuracy. In such switches, small local thermovoltages can be generated which distort (partly strong non-linear) the measurement. If such components cannot be avoided in the application, their influence should be carefully examined.

● Maximum cable length to the thermocouple

i Without additional protective measures, the maximum cable length from the measuring device to the thermocouple is 30 m. For longer cable lengths, suitable surge protection should be provided.

Cold junction compensation / CJC

The correction of the thermovoltage value to determine the absolute temperature value is referred to as cold junction compensation. In order to determine an absolute temperature value that is as accurate as possible, the temperature at the cold junction must either be kept constant at a known value or measured continuously during the measurement with the smallest possible uncertainty. In some applications, the cold junction may

be in an ice bath (0 °C), for example. In this case the temperature determined via the thermovoltage corresponds to both the temperature difference ΔT and the absolute temperature. In many applications, however, this option cannot be implemented, so that cold junction compensation is necessary.

For thermocouple evaluation with EtherCAT and Bus Terminals in an IP20 housing, the cold junction temperature is measured at the transition from the thermocouple to the copper contacts in the conductor connection plane of the Beckhoff module/ terminal. During operation this value is continuously measured within the terminal via a sensor in order to correct the measured values. This continuous measurement can optionally be disabled in cases where external cold junction compensation is used, for example.

With the EJ plug-in modules for the PCB, the cold junction measurement is not integrated in the module. In this case, the cold junction must be measured externally. This temperature can then be transferred to the module for cold junction compensation and calculation of the absolute temperature.

For IP67 modules and for EJ plug-in modules, the cold junction is located outside the module. For cold junction compensation, Pt1000 measuring resistors must be connected externally. For IP67 modules Beckhoff offers the ZS2000-3712 connector with integrated Pt1000 measuring resistor for this purpose.

Determination of the absolute temperature

Temperature measurement with a thermocouple is a differential temperature measurement, in which the temperature difference between the measuring point and the reference/ comparison junction, also known as cold junction, is determined. To determine the absolute temperature at the measuring point, the measured thermovoltage must therefore be corrected by the thermovoltage at the cold junction. With the corrected thermovoltage, the absolute temperature at the measuring point can then be determined from suitable tables or characteristic curves. Due to the non-linearity of the characteristic curve, it is imperative that this calculation is carried out with the voltages and not with the temperature. Otherwise, there would be a significant error in the measurement.

● Difficulties in measuring temperature with thermocouples

- i**
- Linearization
 - Cold junction compensation

In general, the absolute temperature is calculated using the following relationship:

$$U_{\text{measuring point}} = U_{\text{thermo}} + U_{\text{cold junction}}$$

$$T_{\text{measuring point}} = f(U_{\text{measuring point}})$$

In the following section, the absolute temperature is determined as an example based on correction of the thermovoltages and the temperature. The example calculation can be used to illustrate the error resulting from incorrect calculation.

Sought: $T_{\text{measuring point}}$

Known: Thermocouple type K, $U_{\text{thermo}} = 24.255 \text{ mV}$, $T_{\text{cold junction}} = 22 \text{ °C}$

Option 1: Calculation of thermovoltages – CORRECT

The thermovoltage at the cold junction $U_{\text{cold junction}}$ must be determined based on the known temperature $T_{\text{cold junction}}$ from the characteristic voltage/temperature curve or table for thermocouple type K:

$$U_{\text{cold junction}} = U(22 \text{ °C}) = 0.879 \text{ mV}$$

The thermovoltage at the measuring point can then be determined with reference to 0 °C:

$$U_{\text{measuring point}} = U_{\text{thermo}} + U_{\text{cold junction}} = 24.255 \text{ mV} + 0.879 \text{ mV} = 25.134 \text{ mV}$$

The corresponding temperature value can then be determined for thermocouple type K based on the determined thermovoltage from the characteristic voltage/temperature curve or table:

$$T_{\text{measuring point}} = T(25.134 \text{ mV}) \approx 605.5 \text{ °C}$$

Option 2: Temperature calculation – WRONG

In principle, the temperature difference between the cold junction and the measuring point T_{thermo} could be determined based on the known thermovoltage U_{thermo} from the characteristic voltage/temperature curve or table for thermocouple type K:

$$T_{thermo} = T(24.255 \text{ mV}) = 585 \text{ }^\circ\text{C}$$

The temperature of the measuring point could then be determined with reference to 0 °C:

$$T_{measuring \text{ point}} = T_{thermo} + T_{cold \text{ junction}} = 585 \text{ }^\circ\text{C} + 22 \text{ }^\circ\text{C} = 607 \text{ }^\circ\text{C}$$

Note that there is a temperature difference of 1.5 °C between the value with the proper calculation (voltage calculation, option 1) and the value with the incorrect calculation (temperature calculation, option 2). This is a measurement deviation over 2400 ppm.

Evaluation of thermocouples with thermocouple measuring devices

Beckhoff thermocouple measuring devices can evaluate thermocouples of different types. Linearization of the characteristic curves and determination of the reference temperature takes place directly in the measuring device. The measuring device can be fully configured via the Bus Coupler or the controller. Different output formats may be selected or own scaling activated. Linearization of the characteristic curve and determination and calculation of the reference temperature (temperature at the connection contacts of the measuring device) can be disabled, so that the device can be used as a mV measuring device or with an external cold junction. In addition to the internal evaluation of the measured voltage for conversion into a temperature, the raw voltage value can be transferred from the measuring device to the control system for further processing.

Temperature measurement with thermocouples generally comprises three steps:

- Measuring the electrical voltage,
- optional: Temperature measurement of the cold junction,
- optional: software-based K conversion of the voltage into a temperature value according to the set thermocouple type (K, J, ...)

All three steps can take place locally in the Beckhoff measuring device. Transformation in the measuring device can be disabled if it is to take place in the higher-level control system. Depending on the measuring device type, several thermocouple conversion options are available, which differ in terms of their software implementation.

Uncertainties in the evaluation of thermocouples with thermocouple measuring devices

The thermocouple measurement consists of a chain of measuring and computing elements that affect the attainable measurement deviation:

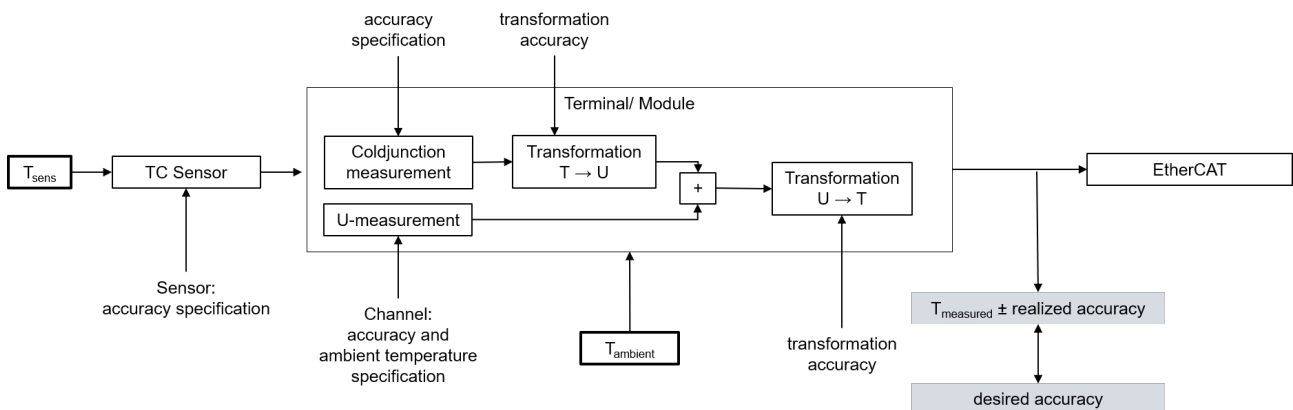


Fig. 4: Concatenation of the uncertainties in temperature measurement with thermocouples

When measuring a temperature, there are various factors influencing the accuracy, from which the total inaccuracy (total uncertainty) is then derived.

Uncertainty of the voltage measurement

First and foremost, measuring a temperature with thermocouples is not based on an actual temperature measurement, but a voltage measurement with subsequent conversion into a temperature. The accuracy of the voltage measurement is therefore the basis for the accuracy of the temperature determination. Since a change of 1 °C at the sensor causes a change in the single-digit μV range, depending on the thermocouple type, even a small uncertainty of the voltage measurement has a large influence on the final result.

Uncertainty of the temperature conversion

The conversion of the measured voltage into a temperature is carried out during evaluation either by means of value tables from the characteristic voltage/temperature curve of a thermocouple type or by approximation based on a polynomial. Due to the non-linearity of the characteristic voltage/temperature curve, both options are only approximations of the actual values, so that the conversion results in a further (small) uncertainty component from the transformation.

Uncertainty of the cold junction evaluation

Cold junction compensation in thermocouple measuring devices must be carried out at the transition from the thermocouple to the copper contacts of the electronics. However, in many cases the temperature at this point cannot be measured directly for mechanical reasons. In this case the temperature of the cold junction has to be approximated at a distance of a few millimeters or through an average value of the housing temperatures. Since the exact value cannot be determined in this way, this results in further uncertainty.

Uncertainty of the sensor

The three factors influencing the uncertainty referred to above relate to the uncertainties in the evaluation of the thermocouples. The accuracy of the thermocouple itself is another factor and must also be taken into account.

Since temperature measurement with thermocouples is actually a voltage measurement and the thermocouples have a non-linear characteristic voltage/temperature curve, it is not possible to simply add up the individual temperature uncertainties to obtain the total uncertainty. To calculate the total uncertainty, all temperature values must be converted into the corresponding voltage value of the respective thermocouple type. When the temperatures are added together an error occurs, as described in the example in the chapter on "Determination of the absolute temperature".

The following diagram shows an example of an analysis of the uncertainties associated with the evaluation of a thermocouple for an EL331x thermocouple terminal with internal cold junction compensation and conversion of the voltage into a temperature via a second degree polynomial. The diagram does not take into account the uncertainty of the thermocouple itself, which is an additional factor!

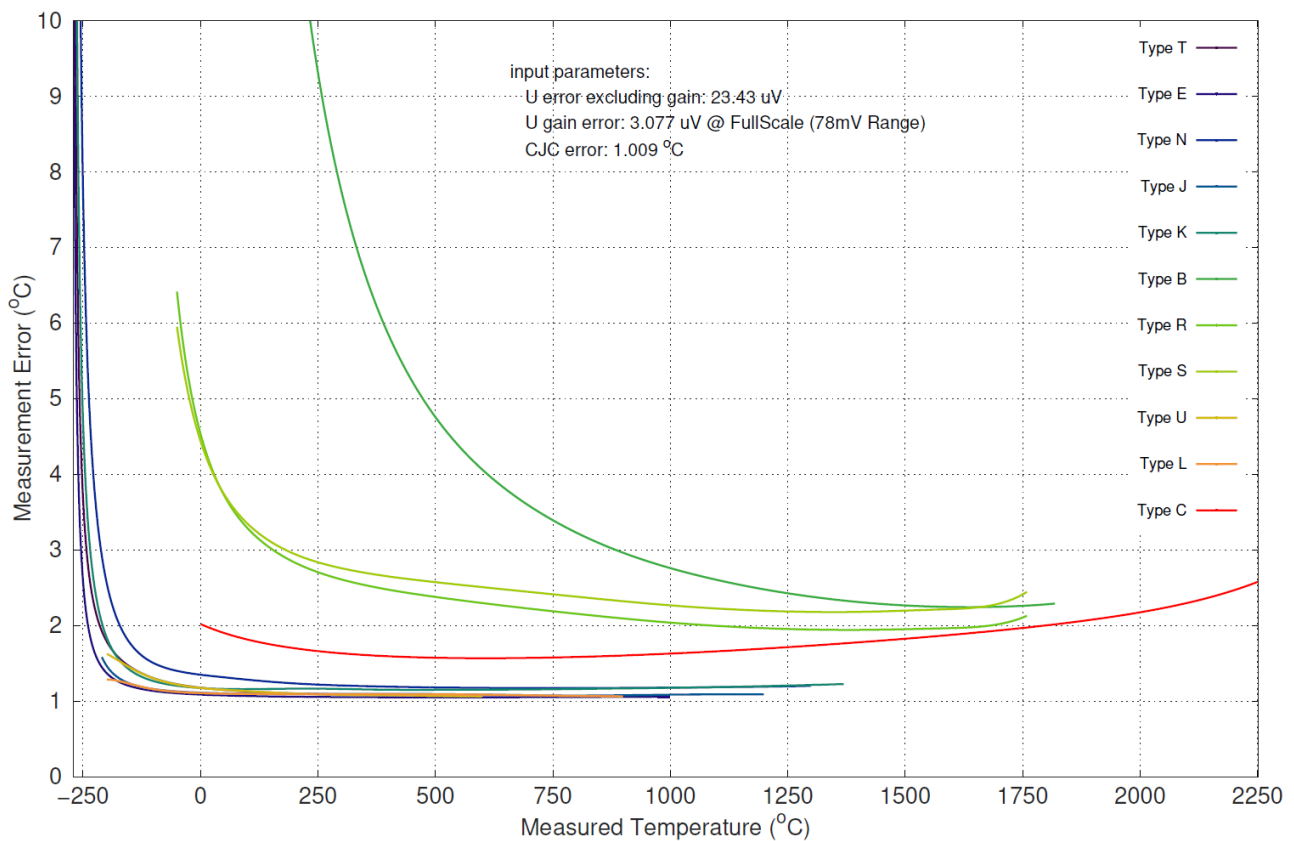


Fig. 5: Example of a thermocouple evaluation uncertainty analysis with an EL331x thermocouple terminal

It is clear from the diagram that the uncertainty of the measured temperature depends on the temperature to be measured. Especially in the lower temperature range, where there is a strong non-linearity of voltage and temperature, the uncertainty of the temperature measurement increases significantly.

Beckhoff offers several products for the evaluation of thermocouples, including

- EL331x-0000: EtherCAT terminal, 1/2/4/8 channel analog input, temperature, thermocouple, 16 bit
- EL3314-0002: EtherCAT terminal, 4 channel analog input, temperature, thermocouple, 24 bit, electrically isolated
- EL3314-0010: EtherCAT terminal, 4 channel analog input, temperature, thermocouple, 24 bit, high-precision
- EL3314-0030: EtherCAT terminal, 4 channel analog input, temperature, thermocouple, 24 bit, high-precision, external calibrated
- EL3314-0090: EtherCAT terminal, 4 channel analog input, temperature, thermocouple, 16 bit, TwinSAFE SC
- ELM370x-xxxx: EtherCAT terminal, 2/4 channel analog input, multi-functional, 24 bit, 10 ksp/s
- ELM334x-xxxx: EtherCAT measurement technology series, thermocouple input, mini thermocouple connector
- EP3314-0002: EtherCAT Box, 4 channel analog input, temperature, thermocouple, 16 bit, M12
- EPP3314-0002: EtherCAT P Box, 4 channel analog input, temperature, thermocouple, 16 bit, M12
- KL331x: bus terminal, 1/2/4 channel analog input, temperature, thermocouple, 16 bit
- EJ3318: EtherCAT plug-in module, 8 channel analog input, temperature, thermocouple, 16 bit

The current overview can be found at www.beckhoff.com

4.2 Basic principles of RTD technology

● General term: "device"



This chapter is used in the documentation of several Beckhoff products. It is therefore written in general terms and uses the generic term "device" for the different device types such as terminal (EL/ELM/KL/ES series...), box (IP/EP/EPP series...), module (EJ/FM series...).

Resistance sensors, also called resistance thermometers or RTD sensors (**R**esistance **T**emperature **D**etector), are electrical components that change their electrical resistance due to their material temperature. Due to this effect, RTD sensors provide a very reliable and accurate temperature measurement and are used in many different applications as part of a temperature measurement. RTD sensors are passive components as they have no amplifier effect or control function and measure temperature via an absolute temperature measurement.

The change in the resistance value as a function of temperature is described for each sensor by a material-dependent, non-linear characteristic or curve. The measured resistance value is subsequently converted into a temperature via such characteristic curves. This can be done either by automatic processing or manual conversion.

4.2.1 Types of RTDs/resistance thermometers

For the sake of understanding, the temperature-dependent change in resistance can be approximated as a linear equation for restricted temperature ranges:

$$\Delta R = k(T) \cdot \Delta T$$

Resistance thermometers are divided into PTC and NTC sensors:

- PTC: factor k is positive, with increasing temperature the electrical resistance increases.
- NTC: factor is negative, as the temperature drops, the electrical resistance increases.

Resistance thermometers exist in the various accuracy classes AA, A, B and C, each of which has its own limit deviations and validity ranges, with class AA having the highest measuring accuracy. The various accuracy classes, including the temperature-related tolerances, can be seen in the following table.

Accuracy class	Temperature tolerance [°C]
AA	$\pm (0.1 + 0.0017 \cdot T)$
A	$\pm (0.15 + 0.002 \cdot T)$
B	$\pm (0.3 + 0.005 \cdot T)$
C	$\pm (0.6 + 0.01 \cdot T)$

The accuracy class of a sensor, should be selected based on the desired target accuracy of the measurement. Resistance thermometers can be made of different temperature sensitive materials. The choice of material and the dimensioning of the sensor determine the possible resistance value and also the temperature range for which the sensor is suitable. Thus, resistance thermometers can be specially designed for different temperature and resistance ranges. KTY resistance sensors, for example, are used as a low-cost alternative to platinum sensors. However, due to the wide tolerance range of 1% - 5%, KTY sensors are more commonly used in applications that do not require precise measurement. Resistance thermometers made of nickel are also suitable for detecting smaller temperature differences. Ni sensors, due to their higher sensitivity than platinum sensors, achieve a greater relative change in resistance for the same temperature difference.

For classification in the following table typical materials and PTC/NTC properties:

NTC	PTC
Many semiconductors	Many metals
Various ceramics	Various ceramics
Some metallic alloys	Pt100, Pt1000...
NTC20, NTC100...	Ni100, Ni1000...
	KTY...

NTC	PTC
	FeT

The user must check whether a sensor is suitable for the intended measuring purposes and measuring devices. Factors to consider here include:

- Temperature range: is the sensor suitable for the intended temperature measuring range?
- Resistance measuring range: can the sensor resistance be measured in the intended temperature measuring range?
- Characteristic curve: how can the sensor resistance be converted into a temperature value? (if this is not done automatically via the measuring device, a vendor-specific sensor characteristic curve or table is required)
- Sensitivity/slope: how large is the change in resistance for an available change in temperature (ideally, the largest possible resistance range) - and how large is the digital sensitivity of the measuring device in digits/ Ω .
- Noise: both sensor and measuring device introduce a noise component into the measurement, which becomes visible as temperature noise depending on sensor and measuring device sensitivity.
- Velocity: how often is the sensor resistance measured?

● Sensor exchange

i Please note that 1:1 exchangeability is not always guaranteed, especially in the case of manufacturer-specified sensors. If necessary the new sensor must be recalibrated in the system.

● Resistance measurement

i ✓ To determine the resistance, it is common to let a small measuring current I in the mA range ($I < 5 \text{ mA}$) flow through the sensor and measure the resulting voltage. Three effects must be taken into consideration when doing this:

a) The measuring current can lead to self-heating of the sensor. However, this usually has only a minimal effect on the measuring accuracy. But this can play a significant role in high-precision measurements; see the comments in the following section:
["Self-heating of RTD sensors" \[► 56\]](#).

⇒ Special sensors tend to be used for cryogenic applications.

b) The sensor supply lines also have a resistance and add a (usually) constant additional resistance to the measurement. Compensation can be made by

- 3- or 4-wire connection of the sensor,
- manual consideration of the known line resistance in the calculation, or
- use of a sensor with higher nominal resistance - then the line effects are less significant.

c) Insulation faults or thermovoltages can affect the measurement.

4.2.2 Structure of resistance sensors

Two different common designs of RTD sensors exist, each having its advantages and disadvantages. As a rule, RTD sensors are inserted in a protective and non-conductive housing, depending on the application, so that external influences cannot affect the measurement result and a stable sensor design is ensured.

- **Thin-film RTD sensors**

A thin layer of the temperature-sensitive material (e.g. platinum) is applied to a non-conductive substrate (often ceramic). The length of the temperature-sensitive layer sets the nominal resistance of the sensor. The measurement layer is then sealed to protect it from external influences (usually with a layer of glass or epoxy resin).

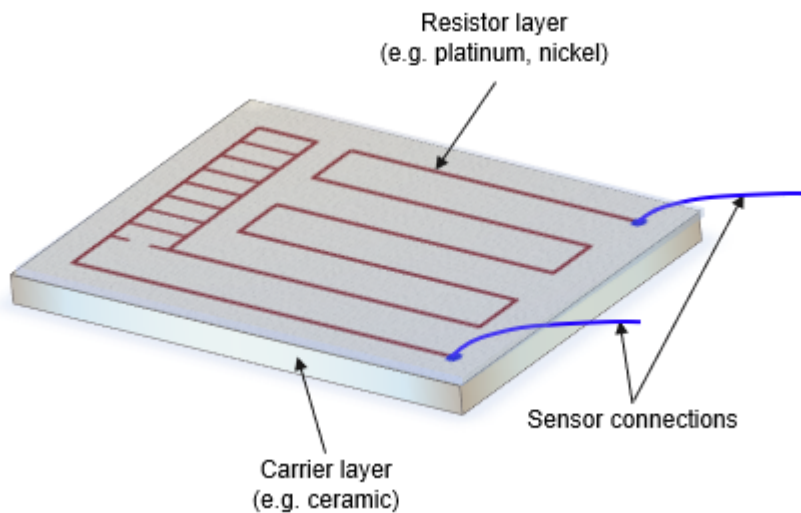


Fig. 6: Thin-film RTD sensor

Thin-film sensors are cost-effective due to their simple design, which requires less temperature-sensitive material, and can be manufactured in more customized shapes. However, the resistance value R_0 at $T=0\text{ °C}$ cannot be set as accurately as wired RTD sensors, so thin-film sensors generally have greater uncertainty. In addition, due to their small size, they are more affected by self-heating of the sensor and therefore tend to be used at low temperatures.

- **Wired RTD Sensors:**

A measuring wire, consisting of the temperature-sensitive material, is shortened according to the desired nominal resistance and then wound. The measuring wire is wound around or embedded/melted into a non-conductive rod as a core and enclosed by a non-conductive tube. Depending on the application, glass, ceramics, etc. are used as the non-conductive material. The most common design is shown in the figure below:

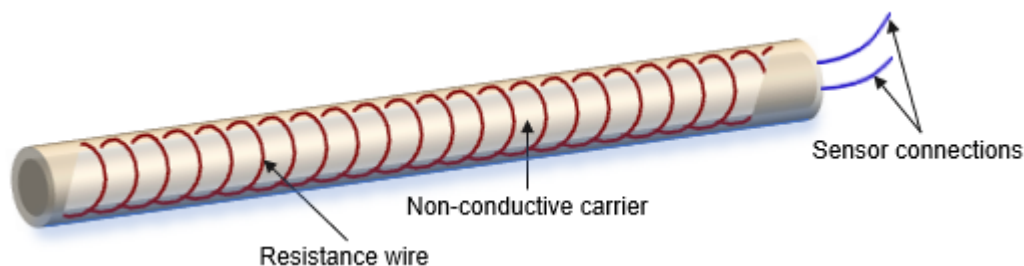


Fig. 7: Wired RTD sensor with measuring wire

4.2.3 Measuring principle of RTD temperature measurement

Since an RTD sensor changes its internal resistance in a known ratio as a function of temperature, only the resistance of the sensor needs to be measured for a temperature measurement. There are various possibilities for this, which can be divided into direct and indirect resistance measurements.

- **Indirect resistance measurement:**

In an indirect resistance measurement, the current and the voltage are measured simultaneously, so that the resistance value can then be calculated using Ohm's law. Here, a distinction is made between a current and a voltage correct measurement.

- **Current correct measurement**

In the context of a current correct measurement, the current is tapped via the resistance immediately before or after the resistance. The parallel-connected voltmeter thus measures not only the voltage across the resistance, but also the voltage that drops across the ammeter, so that the voltage measurement is distorted.

- **Voltage correct measurement**

In the context of a voltage correct measurement, the voltage that drops across the resistance is measured. In this case, however, the ammeter is connected before the voltmeter and the resistance, thus the current is also measured via the voltmeter. Consequently, the current measurement is distorted. Depending on the selected measuring circuit, the voltage dropping across the ammeter or the current flowing through the voltmeter must be taken into account.

- **Direct resistance measurement:**

A direct resistance measurement, also called a comparative or ratiometric measurement, involves a comparative measurement between the unknown and a known reference resistance. Both resistances are connected in series and are connected to a constant current or voltage source (see following figure).

Then either the voltage or the current of both resistances is calculated so that the unknown resistance can be determined. The reference resistance used here depends on the size of the resistances to be measured.

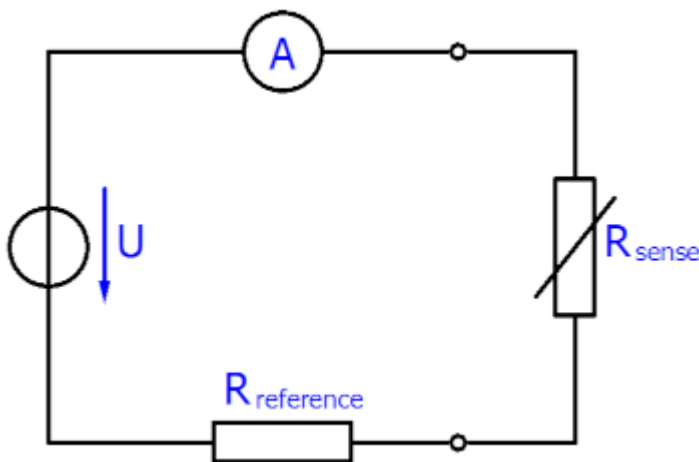


Fig. 8: Circuit for direct resistance measurement

4.2.4 Characteristic curve

The linear approximation is valid only for a small measuring range. In a larger measuring range (several 10 ... 100 k Ω are common), the characteristic curves for resistance calculation are defined with the help of exponential functions, since the change of the resistance value depending on the temperature is not linear and depends on the selected sensor. For the determination or exact conversion of the resistance value into a temperature value, these special characteristic equations are required.

The characteristic curves differ significantly, depending on the sensor selected, so there is no general PTC or NTC sensor, but many different resistance sensors with special characteristics that belong to the PTC or NTC family.

Typical characteristic equations are:

- For platinum/Pt sensors (PTC) according to e.g. IEC 60751 or ASTM-E1137 (so-called Callendar-VanDusen equation):

- Measuring range -200 °C ... 0 °C:

$$R(T) = R_0(1 + AT + BT^2 + C(T - 100 \text{ °C})T^3)$$

- Measuring range 0 °C ... 850 °C:

$$R(T) = R_0(1 + AT + BT^2)$$

- For NTC (semiconductor thermistors)

- Steinhart-Hart:

$$\frac{1}{T} = a + b \ln(R) + c \ln^3(R)$$

- B-parameter equation:

$$R_T = R(T) = A \cdot e^{\frac{B}{T}} = R_{T_0} \cdot e^{B\left(\frac{1}{T} - \frac{1}{T_0}\right)}$$

- The 6th order equation for Ni sensors according to DIN 43760 (withdrawn), e.g. for 6180 ppm/K

The various factors A, B, C, R_0 and T_0 are to be specified by the sensor manufacturer or can be determined by measuring the resistance at known temperatures. The parameter R_0 indicates the resistance in Ω of the platinum sensor at $T = 0 \text{ °C}$. The sensor designations are based on these characteristics, e.g. for Pt100 $R_0 = 100 \text{ }\Omega$ at $T = 0 \text{ °C}$.

The B-parameter equation is a simplified version of the Steinhart-Hart equation. The B parameter itself is only constant in a small range, e.g. between 25 °C ... 50 °C or 25 °C ... 85 °C. This is designated B25/50 or B25/85. The accuracy of the equation strongly depends on the B parameter. The larger the measuring range, the lower the accuracy. If a larger measuring range required, it is preferable to use the Steinhart-Hart equation.

For illustration purposes, typical characteristic curves for NTC and PTC sensors are shown in the following figure:

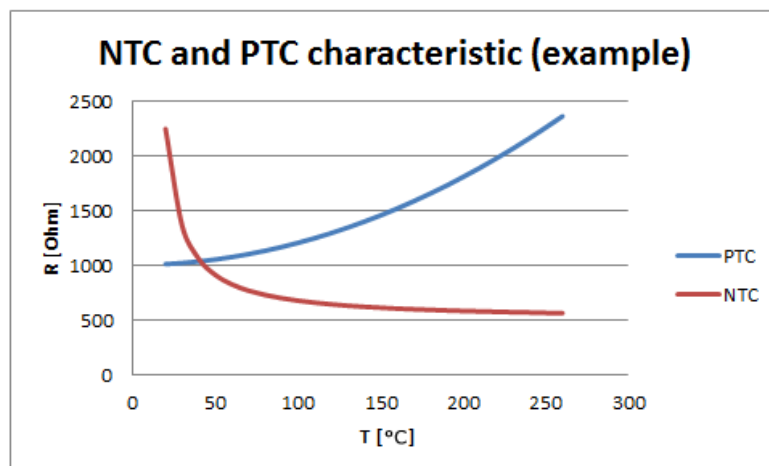


Fig. 9: Examples for temperature dependent resistance values

In principle, a sensor manufacturer can of course also publish the characteristic curve of his sensor informally as a table of values, as is done, for example, with KT/KTY sensors.

So there is no general NTC or PTC sensor, but these are designations for sensor families with a specific behavior.

4.2.5 Overview of common resistance sensors

The following overview shows some common resistance sensors which are suitable for temperature measurement. See also the following chapter.

Type	Temperature measuring range	Resistance range [Ω], approx.	Temperature coefficient [Ω/K], @ approx. 100 °C	Material / element type	Nominal resistance	
Pt100	-250 ... 850 °C	~18 Ω ... ~390 Ω	0.38 Ω/K	Platinum	100 Ω (T = 0 °C)	
Pt200		~30 Ω ... ~750 Ω	0.76 Ω/K		200 Ω (T = 0 °C)	
Pt500		~90 Ω ... ~1850 Ω	1.9 Ω/K		500 Ω (T = 0 °C)	
Pt1000		~185 Ω ... ~3800 Ω	3.8 Ω/K		1000 Ω (T = 0 °C)	
Ni100	-60 ... 250 °C	~70 Ω ... ~230 Ω	0.7 Ω/K	Nickel	100 Ω (T = 0 °C)	
Ni120		~65 Ω ... ~380 Ω	0.9 Ω/K		120 Ω (T = 0 °C)	
Ni1000		~700 Ω ... ~2000 Ω	7 Ω/K		1000 Ω (T = 0 °C)	
Ni1000TK5000		~700 Ω ... ~2000 Ω	5.6 Ω/K		1000 Ω (T = 0 °C) 1500 Ω (T = 100 °C)	
KT100/110/130/210/230 KTY10/11/13/16/19 KTY81/82-110,120,150 KTY81-121 KTY81-122 KTY81-151 KTY81-151 KTY81/82-210,220,250 KTY81-221 KTY81-222 KTY81-251 KTY81-252	-55 ... 150 °C	~500 ... ~2200 Ω	Temperature-dependent and to be obtained from the sensor manufacturer	Silicon	~2000 Ω (T = 25 °C) ~1000 Ω (T = 25 °C)	
KTY83-110,120,150 KTY83-121 KTY83-122 KTY83-151 KTY83-152	-55 ... 175 °C	~500 ... ~2500 Ω			Silicon	~1000 Ω (T = 25 °C)
KTY84-130,150 KTY84-151	-40 ... 300 °C	~350 ... ~2500 Ω			Silicon	~1000 Ω (T = 100 °C)
KTY21/23-6 KTY1x-5 KTY1x-7 KTY21/23-5 KTY21/23-7	-55 ... 150 °C	~500 ... ~4000 Ω			Silicon	~1000 Ω (T = 25 °C)

Type	Temperature measuring range	Resistance range [Ω], approx.	Temperature coefficient [Ω/K]	Material / element type	Nominal resistance
NTC2K ²⁾	-55 ... 150 °C ¹⁾	~75 Ω ... 150 k Ω	@-40 ... +10 °C: 1200 Ω/K @+10 ... +30 °C: 110 Ω/K @+30 ... 130 °C: 16 Ω/K	Different Semiconductors	2200 Ω (T = 25 °C)
NTC3K ²⁾		~100 Ω ... 205 k Ω	@-40 ... +10 °C: 1600 Ω/K @+10 ... +30 °C: 140 Ω/K @+30 ... 130 °C: 41 Ω/K		3000 Ω (T = 25 °C)
NTC5K ²⁾		~150 Ω ... 330 k Ω	@-40 ... +10 °C: 2600 Ω/K @+10 ... +30 °C: 240 Ω/K @+30 ... 130 °C: 68 Ω/K		5000 Ω (T = 25 °C)
NTC10K ²⁾³⁾		~300 Ω ... 690 k Ω	@-40 ... +10 °C: 5500 Ω/K @+10 ... +30 °C: 470 Ω/K @+30 ... 130 °C: 71 Ω/K		10000 Ω (T = 25 °C)
NTC20K ²⁾³⁾		~500 Ω ... 1.2 M Ω	@-40 ... +10 °C: 10 k Ω/K @+10 ... +30 °C: 930 Ω/K @+30 ... 130 °C: 140 Ω/K		20000 Ω (T = 25 °C)
NTC100K ²⁾		~3 k Ω ... 3.3 M Ω	@-40 ... +10 °C: 32 k Ω/K @+10 ... +30 °C: 4.7 k Ω/K @+30 ... 130 °C: 700 Ω/K		

¹⁾ The values may vary depending on the sensor manufacturer and the intended application.

²⁾ The temperature coefficient of the NTC is extremely temperature-dependent, the values given are only orientation values!

³⁾ Other variants of this type also exist, which differ in the characteristic values!

This informative diagram shows that an extremely wide resistance range is covered, especially with NTC sensors:

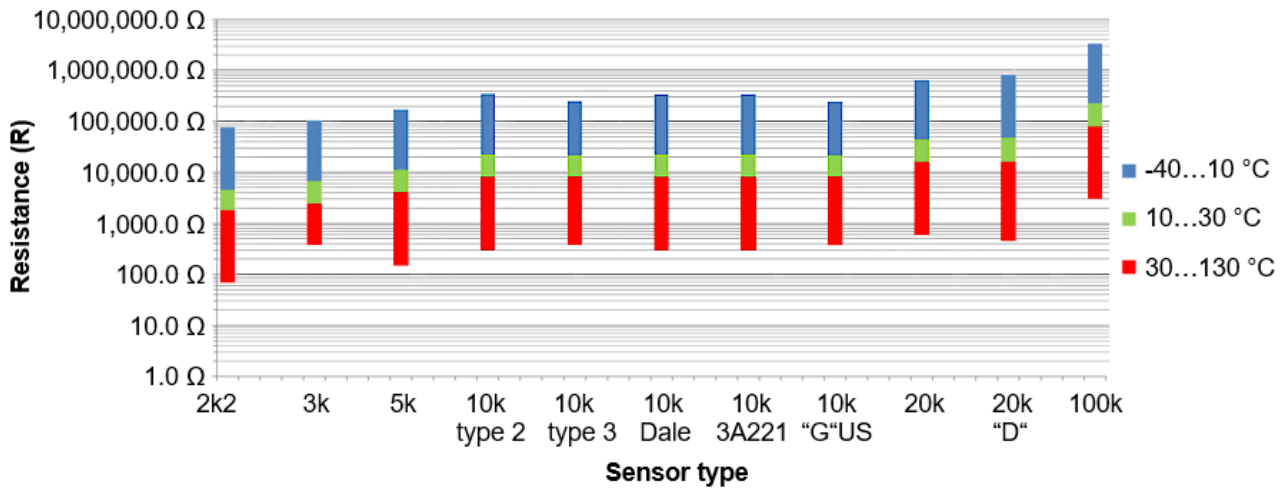


Fig. 10: Operating ranges of some NTC resistors

4.2.6 Connection techniques and supply line resistance compensation

Inevitably, when using RTD sensors, they can only be measured via supply lines. The supply lines to the sensor each have a (temperature-dependent!) internal resistance, which influences and falsifies the measurement. In addition, insulation faults or thermovoltages, for example due to uneven temperature distributions, can also influence the measurement. These must be checked by the user and taken into account depending on the application. In addition, RTD sensors react to the self-heating that occurs, so that this also influences the measurement result. Various connection techniques and special sensor data help to compensate for the supply line resistances, and the sensor self-heating can also be calculated with the aid of special sensor data. Possible connection techniques are two-wire, three-wire and four-wire. The individual advantages and disadvantages of the respective connection technology are attached to the explanation of the connection technologies. Direct resistance measurement with reference resistor is assumed.

- **Two-wire technique**

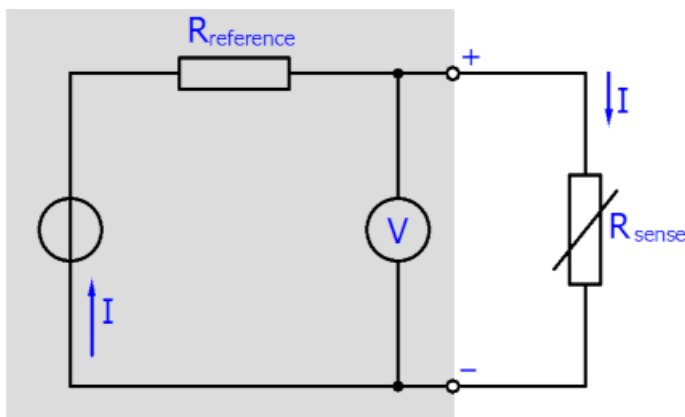


Fig. 11: Connection RTD sensor two-wire technique

- The sensor is connected without additional wires.
- This connection technology requires little connection material and is used for simple RTD temperature measurements
- Recommended for short supply lines or simple measurements only
- Transition resistance values of the terminal contacts affect the measurement. An adjustment by the user with the signal connection plugged in can increase the measuring accuracy again, but must be repeated regularly.
- For the compensation of the supply line resistances, the fixed supply line resistance can be determined by a measurement or an adjustment and then subtracted from the measurement result, another connection technique can be selected or a sensor with a high nominal resistance can be selected

Example of supply line compensation with the two-wire technique

Given is a 50 m long supply line made of copper with a line cross-section of 0.5 mm². The resistivity of copper is equal to 0.0175 Ω mm² m⁻¹ at room temperature.

Determination of the total resistance of the supply line:

$$R_{L_{tot}} = 0.0175 \, \Omega \, \text{mm}^2 \, \text{m}^{-1} \cdot (2 \cdot 50 \, \text{m} / 0.5 \, \text{mm}^2) = 3.5 \, \Omega$$

A Pt100 sensor has an average resistance change of $\approx 0.39 \, \Omega/\text{K}$. With a line resistance of $R_{L_{tot}} = 3.5 \, \Omega$, this results in a static temperature deviation of $3.5 \, \Omega / (0.39 \, \Omega/^\circ\text{C}) = 8.97 \, ^\circ\text{C}$ if this is not taken into account. The calculated 3.5 Ω can be subtracted from the measured value after the measurement (before the $R \rightarrow T$ transformation), so that the supply line resistances do not influence the measurement result (at least at this moment).

A change in the resistivity of the supply lines due to aging or temperature change will not be noticed in this case! For an exact calculation of the supply line resistances, these factors must be taken into account. For example, the temperature dependence of copper lines is not insignificant at $\sim 4000 \, \text{ppm/K}$ (0.4%/K) in 24/7 operation.

- **Three-wire technique**

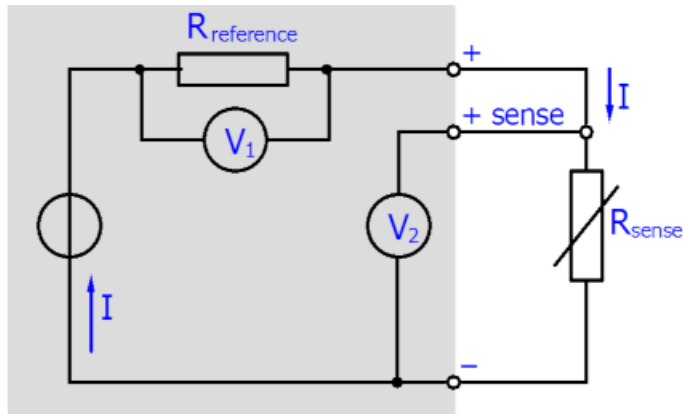


Fig. 12: Connection RTD sensor three-wire technique

- The sensor is connected with an additional wire, so that another measuring circuit is created.
- This measuring circuit is used to determine the resistance of the supply lines excluding the connected sensor, so that the supply line resistance can be determined directly and subtracted from the measured value
- Line "+" and "-" must have the same electrical properties here
- This connection technology theoretically offers more accurate temperature measurement at only slightly higher installation costs.
- Due to the cost reduction compared to the four-wire technique and a nevertheless more accurate measurement result compared to the two-wire technique, the three-wire technique is the most common industrial connection technology for resistance sensors.
- Transition resistances of the terminal contacts influence the measuring process (an adjustment by the user with the signal connection plugged in can increase the measuring accuracy again)
- **Four-wire technique**

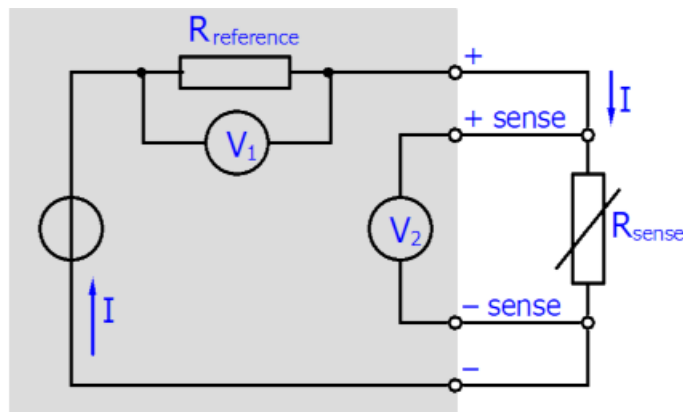


Fig. 13: Connection RTD sensor four-wire technique

- The sensor is equipped with two additional sense lines so that the current conduction and voltage measurement run over separate wires.
- The wires for currentless voltage measurement are thus not subject to voltage drop.
- This connection technique is recommended within the scope of exact temperature measurements, since the output measured value is line neutral.
- Especially for resistance measurements of very small resistances (range about $< 10 \Omega$) the use of the four-wire technique is required (also to be considered is the relative measurement deviation with respect to the FSV - the use of measuring terminals with smaller resistance measuring ranges is recommended).
- With the help of the four-wire technique, the influence of the supply lines can be completely and permanently compensated.
- A high level of cabling is required for four-wire technique.

- However, the adverse effect of thermovoltages may still occur.

4.2.7 Self-heating of RTD sensors

The measuring current through the sensor resistance inevitably and intentionally leads to a voltage drop across it. Thus, power is dissipated by the sensor, heating it and falsifying the measurement. The dissipation of heat to the environment via the air or another surrounding medium, the housing, as well as the object to be measured via surface contact (e.g. by means of adhesive layer), can be a complex process. It is advisable to roughly check whether the self-heating reaches a level that is relevant for the required measuring accuracy. Depending on the sensor, this can be the case with target accuracies of <100 mK.

Some sample values are used below to illustrate the effect; the method is to be adapted to the specific application if necessary.

About the sensor:

- A sensor may have a specified self-heating coefficient of 0.5 mK/μW for example, depending on its surrounding medium.
- The power dissipation and the self-heating can be calculated via the measuring current and the voltage drop across the resistive element. Caution: this is a nonlinear calculation!

About the Beckhoff terminal/module:

- The Beckhoff measuring device generates a measuring current through the RTD sensor (this can be done via an internal voltage source or a current source).
- One possible measurement method, implemented for example in EL32xx, could be the comparative measurement with a known reference resistance, shown here for the following considerations in the 2-wire connection for simplification:

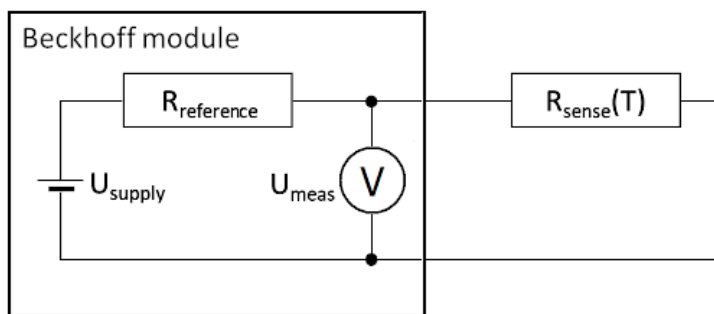


Fig. 14: Comparison measurement with a known reference resistance

- If U_{supply} , $R_{\text{reference}}$ and U_{meas} are known, then R_{sense} and thus the temperature T of the module can be calculated in the firmware.
- On the basis of the values given in the device documentation, the effect of the measurement amount on the R/RTD sensor can be calculated.

An example in numbers is shown below:

- The objective is to find out in which sensor and in which measuring range of the ELM3704 the least heat develops at a target temperature T .
- A sensor Pt100 or Pt1000 is used and measured from 0 100°C, the resistance range would thus be in the range 100...138 Ω or 1000...1385 Ω.

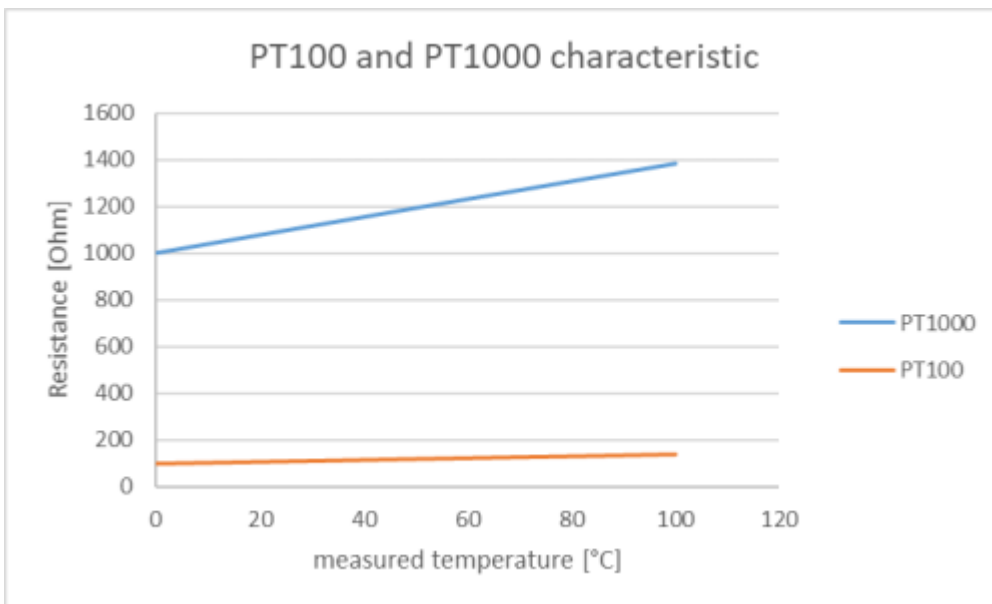


Fig. 15: Diagram of resistance values at measured temperature; Pt100, Pt1000 sensor

- The ELM3704 has the following properties (these are only guide values, the values given in the ELM370x documentation are valid):
 - measuring range 5 kΩ, $R_{reference} = 5\text{ k}\Omega$, $U_{supply} = 2.5\text{ V}$
 - measuring range 2 kΩ, $R_{reference} = 5\text{ k}\Omega$, $U_{supply} = 2.5\text{ V}$
 - measuring range 500 Ω, $R_{reference} = 5\text{ k}\Omega$, $U_{supply} = 4.5\text{ V}$
 - measuring range 200 Ω, $R_{reference} = 5\text{ k}\Omega$, $U_{supply} = 4.5\text{ V}$
 - measuring range 50 Ω, $R_{reference} = 5\text{ k}\Omega$, $U_{supply} = 4.5\text{ V}$
- $R_{reference}$ and R_{sense} are in series, so the measuring current and thus the power at the sensor in relation to R or T in the possible five measuring ranges of the ELM3704 are simple to calculate:

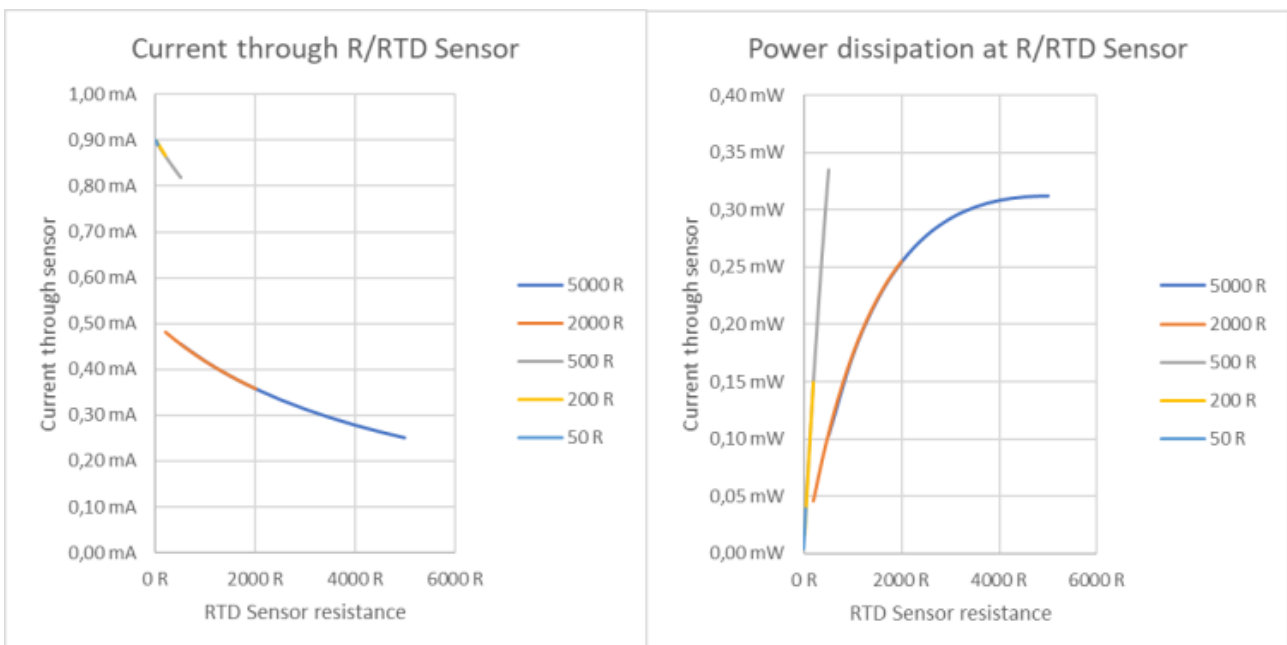


Fig. 16: Diagram of measuring current or power dissipation for the different measuring ranges

- Hence, at $T = 0\text{ °C}$ and thus $R_{Pt100} = 100\text{ }\Omega$ or $R_{Pt1000} = 1000\text{ }\Omega$, the Pt100 with 0.08 mW transforms only half as much power as the Pt1000 with 0.17 mW. As consequence, a lower electrical power dissipation thus also causes a lower self-heating.
- Nevertheless, the above sensor would heat itself by $0.17\text{ mW} \cdot 0.5\text{ mK}/\mu\text{W} = 85\text{ mK}$.

If self-heating becomes relevant to the process under consideration, consider:

- whether the sensor can be changed,
- whether the thermal connection of the sensor can be improved,
- whether a continuous measurement is necessary or whether the measuring current of the Beckhoff module can be temporarily switched off from the controller, e.g. 1 second measuring, 10 seconds cooling and
- if the effect is numerically tangible and can thus be subsequently calculated in the controller from the temperature value.

However, this consideration focuses solely on the issue of self-heating.

To establish whether the sensor and the measuring range are suitable overall, they must also be checked with respect to other aspects such as noise, measurement uncertainty in the measuring range and the sensitivity of the sensor $k = \Delta R / \Delta T_{\text{ambient}}$.

4.2.8 Effect of chained sensitivity

Also relevant for the use of RTD sensors is the occurring concatenated accuracy (measurement uncertainty) and sensitivity (smallest readable temperature change) from sensor and used measuring device (Beckhoff RTD analog input) in an intended temperature range. So the following are concatenated (connected in series)

- the measurement uncertainty $\pm[^\circ\text{C}]$ and sensitivity $[\Omega/^\circ\text{C}]$ of the sensor and
- the measurement uncertainty $\pm[\Omega]$ and sensitivity $[\Omega/\text{digit}]$ of the measuring device

Example:

- For a given temperature measuring range ΔT different RTD sensors are available, which have different resistance values and sensitivities in the intended temperature range. One of them is to be chosen.
- Various Beckhoff RTD measuring devices (terminals, box, module) are available for the resulting resistance range $\Delta\Omega$ of the sensor, which also have different sensitivities and measurement uncertainties.

Thus, the total sensitivity and the total measurement uncertainty of the sensor + measuring device configuration may vary depending on the selected measuring terminal and sensor. Via the technical data of the sensor and the measuring terminals used, the values of the overall configuration and thus the optimum combination can be determined.

● Measurement uncertainty calculation



The mathematics behind combined measurement uncertainties can become very complex, in this example the simple linear approach is chosen as the worst case.

Example sensitivity:

- A Pt1000 sensor is used at a measuring temperature of $100\text{ }^\circ\text{C}$.
- The Pt1000 sensor has a sensitivity of $3.78\text{ }\Omega/\text{K}$ and a resistance value of $1385.1\text{ }\Omega$ at this temperature point.
- The sensor is used with an ELM3502 for data collection. This has a resolution of 8388607 digits over $2000\text{ }\Omega$ and thus $238.42\text{ }\mu\Omega/\text{digit}$.
- The theoretical **total sensitivity** of the configuration is thus:
 $238.42\text{ }\mu\Omega/\text{digit} / 3.78\text{ }\Omega/\text{K} = 0.063\text{ mK}/\text{digit}$.
 Due to the signal noise of the device and sensor, this value is practically only achieved with very strong filtering!

Continuation to the measurement uncertainty:

- The measurement uncertainty of the terminal in the $2\text{ k}\Omega$ measuring range is $\pm 120\text{ ppm}^1$ at an ambient temperature of $23\text{ }^\circ\text{C}$, i.e. $\pm 0.24\text{ }\Omega$.
- Converted to Pt1000 temperature, the measurement uncertainty would be $\pm 0.24\text{ }\Omega / 3.78\text{ }\Omega/\text{K} = \pm 0.063\text{ K}$ or $\pm 63.49\text{ mK}$.
- If the Pt1000 sensor under consideration is a sensor of accuracy class A, it has a temperature tolerance of $\pm(0.15 + 0.002 \cdot T)$. At a measuring temperature of $100\text{ }^\circ\text{C}$, the possible deviation (measurement uncertainty) would thus be $\pm(0.15 + 0.002 \cdot 100\text{ }^\circ\text{C}) = \pm 0.35\text{ }^\circ\text{C}$.
- The **total uncertainty** is therefore $\pm 0.063\text{ }^\circ\text{C} + \pm 0.35\text{ }^\circ\text{C} = \pm 0.41\text{ }^\circ\text{C}$.

*) Example value, please observe device specification

4.2.9 Overview implemented RTD transformations

Some Beckhoff IO devices (IP20 terminals, plug-in modules, box-modules) support the evaluation of resistance sensors for temperature measurement (RTD) as Pt100, Pt1000, NTC1K etc.

The following are the characteristic curves partially implemented there depending on the device. The table values given are the basis for the evaluation in the device.

- Pt, Ni, KTY: the table values are stored in the device accordingly; intermediate values are interpolated. For KL terminals the temperature is calculated deviating from this via an approximation polynomial.
- NTC: the table values were used for determination of the Steinhart-Hart coefficients and by these coefficients the terminal determines the temperature.

Version 2020-12

Pt-RTD

Values in Ω	Pt100	Pt1000	Pt500	Pt200
[°C] (ITS-90)	-200...+850°C	-200...+850°C	-200...+850°C	-200...+850°C
-200	18.520	185.200	92.600	37.040
-190	22.825	228.250	114.125	45.650
-180	27.096	270.960	135.480	54.192
-170	31.335	313.350	156.675	62.670
-160	35.543	355.430	177.715	71.086
-150	39.723	397.230	198.615	79.446
-140	43.876	438.760	219.380	87.752
-130	48.005	480.050	240.025	96.010
-120	52.110	521.100	260.550	104.220
-110	56.193	561.930	280.965	112.386
-100	60.256	602.560	301.280	120.512
-90	64.300	643.000	321.500	128.600
-80	68.325	683.250	341.625	136.650
-70	72.335	723.350	361.675	144.670
-60	76.328	763.280	381.640	152.656
-50	80.306	803.060	401.530	160.612
-40	84.271	842.710	421.355	168.542
-30	88.222	882.220	441.110	176.444
-20	92.160	921.600	460.800	184.320
-10	96.086	960.860	480.430	192.172
0	100.000	1,000.000	500.000	200.000
10	103.903	1,039.030	519.515	207.806
20	107.794	1,077.940	538.970	215.588
30	111.673	1,116.730	558.365	223.346
40	115.541	1,155.410	577.705	231.082
50	119.397	1,193.970	596.985	238.794
60	123.242	1,232.420	616.210	246.484
70	127.075	1,270.750	635.375	254.150
80	130.897	1,308.970	654.485	261.794
90	134.707	1,347.070	673.535	269.414
100	138.506	1,385.060	692.530	277.012
110	142.293	1,422.930	711.465	284.586
120	146.068	1,460.680	730.340	292.136
130	149.832	1,498.320	749.160	299.664
140	153.584	1,535.840	767.920	307.168
150	157.325	1,573.250	786.625	314.650
160	161.054	1,610.540	805.270	322.108
170	164.772	1,647.720	823.860	329.544
180	168.478	1,684.780	842.390	336.956
190	172.173	1,721.730	860.865	344.346
200	175.856	1,758.560	879.280	351.712

Values in Ω	Pt100	Pt1000	Pt500	Pt200
[°C] (ITS-90)	-200...+850°C	-200...+850°C	-200...+850°C	-200...+850°C
210	179.528	1,795.280	897.640	359.056
220	183.188	1,831.880	915.940	366.376
230	186.836	1,868.360	934.180	373.672
240	190.473	1,904.730	952.365	380.946
250	194.098	1,940.980	970.490	388.196
260	197.712	1,977.120	988.560	395.424
270	201.314	2,013.140	1,006.570	402.628
280	204.905	2,049.050	1,024.525	409.810
290	208.484	2,084.840	1,042.420	416.968
300	212.052	2,120.520	1,060.260	424.104

Values in Ω	Pt100	Pt1000	Pt500	Pt200
[°C] (ITS-90)	-200...+850°C	-200...+850°C	-200...+850°C	-200...+850°C
310	215.608	2,156.080	1,078.040	431.216
320	219.152	2,191.520	1,095.760	438.304
330	222.685	2,226.850	1,113.425	445.370
340	226.206	2,262.060	1,131.030	452.412
350	229.716	2,297.160	1,148.580	459.432
360	233.214	2,332.140	1,166.070	466.428
370	236.701	2,367.010	1,183.505	473.402
380	240.176	2,401.760	1,200.880	480.352
390	243.640	2,436.400	1,218.200	487.280
400	247.092	2,470.920	1,235.460	494.184
410	250.533	2,505.330	1,252.665	501.066
420	253.962	2,539.620	1,269.810	507.924
430	257.379	2,573.790	1,286.895	514.758
440	260.785	2,607.850	1,303.925	521.570
450	264.179	2,641.790	1,320.895	528.358
460	267.562	2,675.620	1,337.810	535.124
470	270.933	2,709.330	1,354.665	541.866
480	274.293	2,742.930	1,371.465	548.586
490	277.641	2,776.410	1,388.205	555.282
500	280.978	2,809.780	1,404.890	561.956
510	284.303	2,843.030	1,421.515	568.606
520	287.616	2,876.160	1,438.080	575.232
530	290.918	2,909.180	1,454.590	581.836
540	294.208	2,942.080	1,471.040	588.416
550	297.487	2,974.870	1,487.435	594.974
560	300.754	3,007.540	1,503.770	601.508
570	304.010	3,040.100	1,520.050	608.020
580	307.254	3,072.540	1,536.270	614.508
590	310.487	3,104.870	1,552.435	620.974
600	313.708	3,137.080	1,568.540	627.416
610	316.918	3,169.180	1,584.590	633.836
620	320.116	3,201.160	1,600.580	640.232
630	323.302	3,233.020	1,616.510	646.604
640	326.477	3,264.770	1,632.385	652.954
650	329.640	3,296.400	1,648.200	659.280
660	332.792	3,327.920	1,663.960	665.584
670	335.932	3,359.320	1,679.660	671.864
680	339.061	3,390.610	1,695.305	678.122
690	342.178	3,421.780	1,710.890	684.356
700	345.284	3,452.840	1,726.420	690.568
710	348.378	3,483.780	1,741.890	696.756
720	351.460	3,514.600	1,757.300	702.920
730	354.531	3,545.310	1,772.655	709.062
740	357.590	3,575.900	1,787.950	715.180
750	360.638	3,606.380	1,803.190	721.276
760	363.674	3,636.740	1,818.370	727.348
770	366.699	3,666.990	1,833.495	733.398
780	369.712	3,697.120	1,848.560	739.424
790	372.714	3,727.140	1,863.570	745.428

Ni-RTD

Values in Ω	Ni100	Ni120	Ni1000	Ni1000 TK5000
α according to DIN43760	typ. 6180 pmm/K	typ. 6720 pmm/K	typ. 6180 pmm/K	typ. 5000 pmm/K
[°C] (ITS-90)	-60..50°C	-60..320°C	-60..250°C	-30..160°C
-60	69.52	80.943	695.200	

Values in Ω	Ni100	Ni120	Ni1000	Ni1000 TK5000
α according to DIN43760	typ. 6180 pmm/K	typ. 6720 pmm/K	typ. 6180 pmm/K	typ. 5000 pmm/K
[°C] (ITS-90)	-60..50°C	-60..320°C	-60..250°C	-30..160°C
-50	74.255	87.011	742.550	
-40	79.131	93.251	791.310	
-30	84.146	99.667	841.460	871.690
-20	89.296	106.261	892.960	913.480
-10	94.582	113.038	945.820	956.240
0	100	120.000	1,000.000	1,000.000
10	105.552	127.151	1,055.520	1,044.790
20	111.236	134.494	1,112.360	1,090.650
30	117.056	142.033	1,170.560	1,137.620
40	123.011	149.772	1,230.110	1,185.710
50	129.105	157.712	1,291.050	1,234.950
60	135.34	165.859	1,353.400	1,285.450
70	141.721	174.214	1,417.210	1,337.150
80	148.25	182.783	1,482.500	1,390.120
90	154.934	191.567	1,549.340	1,444.390
100	161.779	200.572	1,617.790	1,500.000
110	168.789	209.798	1,687.890	1,556.980
120	175.972	219.251	1,759.720	1,615.370
130	183.335	228.934	1,833.350	1,675.190
140	190.887	238.850	1,908.870	1,736.470
150	198.635	249.002	1,986.350	1,799.270
160	206.589	259.394	2,065.890	1,863.600
170	214.758	270.029	2,147.580	
180	223.153	280.911	2,231.530	
190	231.783	292.042	2,317.830	
200	240.66	303.427	2,406.600	
210	249.795	315.069	2,497.950	
220	259.2	326.971	2,592.000	
230	268.887	339.136	2,688.870	
240	278.868	351.569	2,788.680	
250	289.156	364.271	2,891.560	
260		377.247		
270		390.501		
280		404.035		
290		417.853		
300		431.958		
310		446.354		
320		461.044		

KT/KTY-RTD

Values in Ω	KT100..	KTY81/82-110...	KTY81-121	KTY81-122	KTY81-151	KTY81-152
[°C] (ITS-90)	-50..150°C	-50..150°C	-50..150°C	-50..150°C	-50..150°C	-50..150°C
-50	518	515	510	520	502	528
-40	570	567	562	573	553	582
-30	625	624	617	630	608	639
-20	685	684	677	690	667	701
-10	748	747	740	755	729	766
0	815	815	807	823	794	835
10	886	886	877	895	864	908
20	961	961	951	971	937	985
30	1,040	1,040	1,029	1,050	1,014	1,066
40	1,123	1,122	1,111	1,134	1,094	1,150
50	1,209	1,209	1,196	1,221	1,178	1,239
60	1,300	1,299	1,286	1,312	1,266	1,331

Values in Ω	KT100..	KTY81/82-110...	KTY81-121	KTY81-122	KTY81-151	KTY81-152
[°C] (ITS-90)	-50..150°C	-50..150°C	-50..150°C	-50..150°C	-50..150°C	-50..150°C
70	1,394	1,392	1,378	1,406	1,357	1,427
80	1,492	1,490	1,475	1,505	1,453	1,527
90	1,594	1,591	1,575	1,607	1,551	1,631
100	1,700	1,696	1,679	1,713	1,654	1,738
110	1,810	1,805	1,786	1,823	1,759	1,850
120	1,923	1,915	1,896	1,934	1,867	1,963
130	2,041	2,023	2,003	2,044	1,973	2,074
140	2,128	2,124	2,103	2,146	2,071	2,178
150	2,235	2,211	2,189	2,233	2,156	2,266

NTC-RTD

Values in Ω	NTC1K8	NTC1K8_TK	NTC2K2	NTC3K	NTC5K	NTC10k Carel	NTC10K
	R0=4940	R0=5200	R0=7373	R0=9822	R0=16325	R0=27280	R0=32650
[°C] (ITS-90)	-40..130°C	-30..150°C	-50..130°C	-30..80°C	-30..150°C	-40..110°C	-30..150°C
-50			154,464	205,800	333,914		6,678,300
-40	35,480		77,081	102,690	167,836	186,796	335,670
-30	20,659	24,500	40,330	53,730	88,342	110,881	176,680
-20	12,443	14,000	22,032	29,346	48,487	67,683	96,970
-10	7,730	8,400	12,519	16,674	27,649	42,431	55,300
0	4,940	5,200	7,373	9,822	16,325	27,280	32,650
10	3,241	3,330	4,487	5,976	9,952	17,961	19,900
20	2,177	2,200	2,814	3,750	6,247	12,092	12,490
25	1,800	1,800	2,252	3,000	5,000	10,000	10,000
30	1,496	1,480	1,814	2,417	4,028	8,312	8,060
40	1,049	1,040	1,199	1,598	2,662	5,826	5,320
50	750	740	812	1,081	1,801	4,159	3,600
60	545	540	561	747	1,244	3,020	2,490
70	403	402	396	527	876	2,228	1,750
80	303	306	284	378	628	1,668	1,260
90	230	240	207		458	1,266	920
100	178	187	154		339	974	680
110	139	149	116		255	758	510
120	110	118	88		194		390
130	87	95	68		150		300
140	71	77			117		230
150		64			92		180

4.3 Basic principles of strain gauge technology

General term: "device"

i This chapter is used in the documentation of several Beckhoff products. It is therefore written in general terms and uses the generic term "device" for the different device types such as terminal (EL/ELM/KL/ES series...), box (IP/EP/EPP series...), module (EJ/FM series...).

Basic information on the technological field of strain gauges (SG)/ load cells as metrological instruments is to be given below. The information is of general nature; it is up to the user to check the extent to which it applies to his application.

- Strain gauges serve either to directly measure the static (0 to a few Hz) or dynamic (up to several kHz) elongations, compressions or torsions of a body by being directly fixed to it, or to measure various forces or movements as part of a sensor (e.g. load cells/force transducers, displacement sensor, vibration sensors). The evaluated quantity is the change of the strain gauge property (e.g. electrical resistance).
- In the case of the optical strain gauge (e.g. Bragg grating), an application of force causes a proportional change in the optical characteristics of a fiber used as a sensor. Light with a certain wavelength is fed into the sensor. Depending upon the deformation of the grating, which is laser-cut into the sensor, due to the mechanical load, part of the light is reflected and evaluated using a suitable measuring transducer (interrogator).

The commonest principle in the industrial environment is the electrical strain gauge. There are many common terms for this type of sensor: load cell, weighbridge, etc.

Structure of electrical strain gauges

A strain gauge consists of a carrier material (e.g. a stretchable plastic film) with an applied metal film from which a structure of deformable thin film electrical resistor is worked in very different geometrical forms, depending on the requirements.

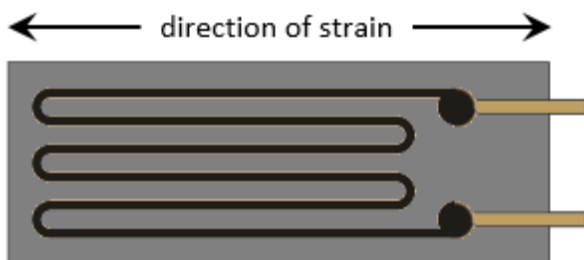


Fig. 17: Schematic view of a strain gauge

This utilizes a behavior whereby, for example in the case of strain, the length of a metallic resistance network increases and its diameter decreases, as a result of which its electrical resistance increases measurable:

$$\Delta R/R = k \cdot \varepsilon.$$

$\varepsilon = \Delta l/l$ thereby corresponds to the relative elongation; the strain sensitivity is called the k-factor. This also gives rise to the typical track layout of the conductive material within the strain gauge: the resistor track or course is laid in a meandering pattern in order to expose the longest possible length to the strain and to increase the selectivity of the force direction effect simultaneously.

Example:

The elongation $\varepsilon = 0.1\%$ of a strain gauge with k-factor 2 causes an increase in the resistance of 0.2%. Typical resistive materials are constantan ($k \approx 2$) or platinum tungsten (92PT, 8W with $k \approx 4$). In the case of semiconductor strain gauges a silicon structure is glued to a carrier material. The conductivity is changed primarily by deformation of the crystal lattice (piezo-resistive effect); k-factors of up to 200 can be achieved.

Measurement of signals

The change in resistance of an individual strain gauge can be determined in principle by resistance measurement (current/voltage measurement) using a 2/3/4-wire measurement technique.

Usually 1/2/4 strain gauges are arranged in a Wheatstone bridge (-> quarter/half/full bridge); the nominal resistance/impedance R_0 of all strain gauges (and the auxiliary resistors used if necessary) is usually equivalent to $R_1 = R_2 = R_3 = R_4 = R_0$. Typical values in the non-loaded state so are $R_0 = 120 \Omega$, 350Ω , 700Ω or $1 \text{ k}\Omega$.

The full bridge possesses the best characteristics such as increased linearity in the feeding of current/voltage, up to four times the sensitivity of the quarter-bridge as well as systematic compensation of disturbing influences such as temperature drift and creeping. In order to achieve high sensitivity, the four individual strain gauges are arranged on the object to be measured (the carrier) in such a way, that two are elongated and two are compressed in each case.

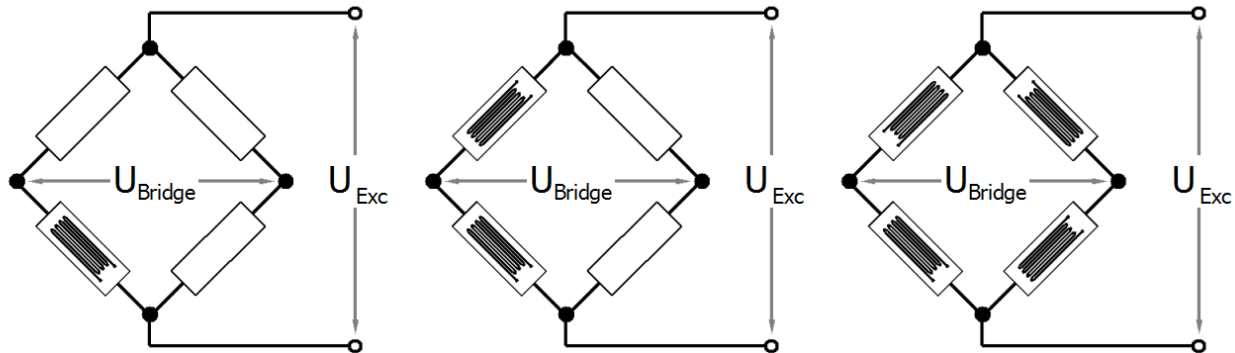


Fig. 18: quarter, half, and full bridge

At this point, the three most important voltages in the bridge environment are defined:

- U_{Exc} :
 - this is the feed voltage of the bridge as it comes from the measuring device or from an external source,
 - usually in the range $1 \dots 12 \text{ V DC}$,
 - it is fed to the bridge via supply line. Since current flows there, a voltage drop always occurs across the supply line; therefore, the bridge effectively only sees a voltage $< U_{Exc}$,
 - other terms: U_V , U_S , excitation, supply.
- U_{Sense} :
 - this is the bridge supply voltage as the measuring device "sees" it,
 - usually in the range $1 \dots 12 \text{ V DC}$,
 - without an extra sense supply line (e.g. 6-wire operation of the full bridge) it is equal to U_{Exc} in the measuring device,
 - if the bridge is operated **with** a sense line (full bridge: 6-wire operation, half bridge: 5-wire operation, quarter-bridge: 3/4-wire operation), U_{Sense} returns to the measuring device from the bridge virtually current-free and the measuring device knows the "true" U_{Exc} of the bridge,
 - other terms: U_{Ref} , reference, RemoteSense, feedback, compensation.
- U_{Bridge} :
 - this is the very small differential bridge voltage "generated" by the load in the bridge, which is to be measured by the measuring device,
 - it returns to the measuring device from the bridge virtually current-free and is mostly in the range $1 \dots 50 \text{ mV}$, depending on the magnitude of U_{Exc} , the load and the bridge sensitivity,
 - other terms: U_D , $U_{Differential}$, signal, AI.

The measuring bridges can be operated with constant current, constant voltage, or also with AC voltage using the carrier frequency method.

i Measuring procedure

The Beckhoff EL/KL335x terminals and the product group measurement technology ELM35/37xx, EPP35xx only support excitation with constant voltage. If excitation with AC is required, please contact Beckhoff sales.

Full bridge strain gauge at constant voltage (ratiometric measurement)

Since the relative resistance change $\Delta R/R$ is low in relation to the nominal resistance R_0 , a simplified equation is given for the strain gauge in the Wheatstone bridge arrangement:

$$U_D / U_V = \frac{1}{4} \cdot (\Delta R_1 - \Delta R_2 + \Delta R_3 - \Delta R_4) / R_0$$

$\Delta R/R$ usually has a positive sign in the case of elongation and a minus sign in the case of compression.

A suitable measuring instrument measures the bridge supply voltage U_{Exc} (or U_V) and the resulting bridge voltage U_{Bridge} (or U_D), and forms the quotients from both voltages, i.e. the ratio. After further calculation and scaling the measured value is output, e.g. in form of the effective mass in kg. Due to the division of U_{Bridge} and U_{Exc} the measurement is in principle independent of changes in the supply voltage.

If the voltages U_{Bridge} and U_{Exc} are measured simultaneously, i.e. at the same moment, and placed in relation to each other, this is referred to as a ratiometric measurement.

The advantage of this is that (with simultaneous measurement!) brief changes in the supply voltage (e.g. EMC effects) or a generally inaccurate or temporal unstable supply voltage likewise have no effect on the measurement.

A change in U_V by e.g. 1 % creates the same percentage change in U_D according to the above equation. Due to the simultaneous measurement of U_D and U_V the error cancels itself out completely during the division.

4-wire vs. 6-wire connection

With a constant voltage supply, the magnitude of the current can be quite considerable, e.g. $12 \text{ V} / 350 \text{ } \Omega \approx 34.3 \text{ mA}$. This leads not only to dissipated heat, wherein the specification of the strain gauge employed must not be exceeded, but possibly also to measuring errors in the case of inadequate wiring due to line losses not being taken into account or compensated.

In principle a full bridge can be operated with a 4-conductor connection (two conductors for the supply U_{Exc} and two for the measurement of the bridge voltage U_{Bridge}).

If, for example, a 25 m copper cable (feed + return = 50 m) with a cross section q of 0.25 mm^2 is used from the sensor up to the evaluating measurement module, this results in a line resistance of

$$R_L = l / (\kappa \cdot q) = 50 \text{ m} / (58 \text{ S} \cdot \text{m/mm}^2 \cdot 0.25 \text{ mm}^2) = 3.5 \text{ } \Omega$$

If this value remains constant, then the error resulting from it can be calibrated out. However, assuming a realistic temperature change of, for example, 30° the line resistance R_L changes by

$$\Delta R_L = 30 \text{ K} \cdot 3.9 \cdot 10^{-3} \text{ 1/K} \cdot 3.5 \text{ } \Omega = 0.41 \text{ } \Omega$$

In relation to a measuring bridge with $350 \text{ } \Omega$ input impedance this means a measuring error of $> 0.1 \text{ } \%$.

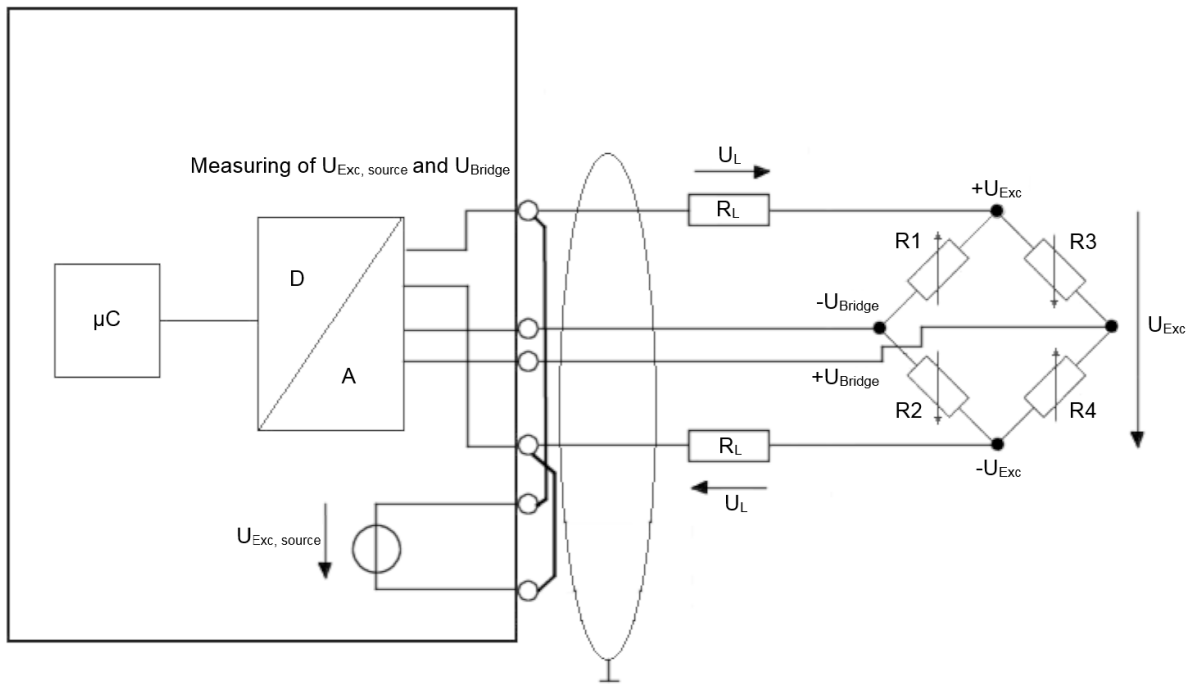


Fig. 19: 4-wire connection

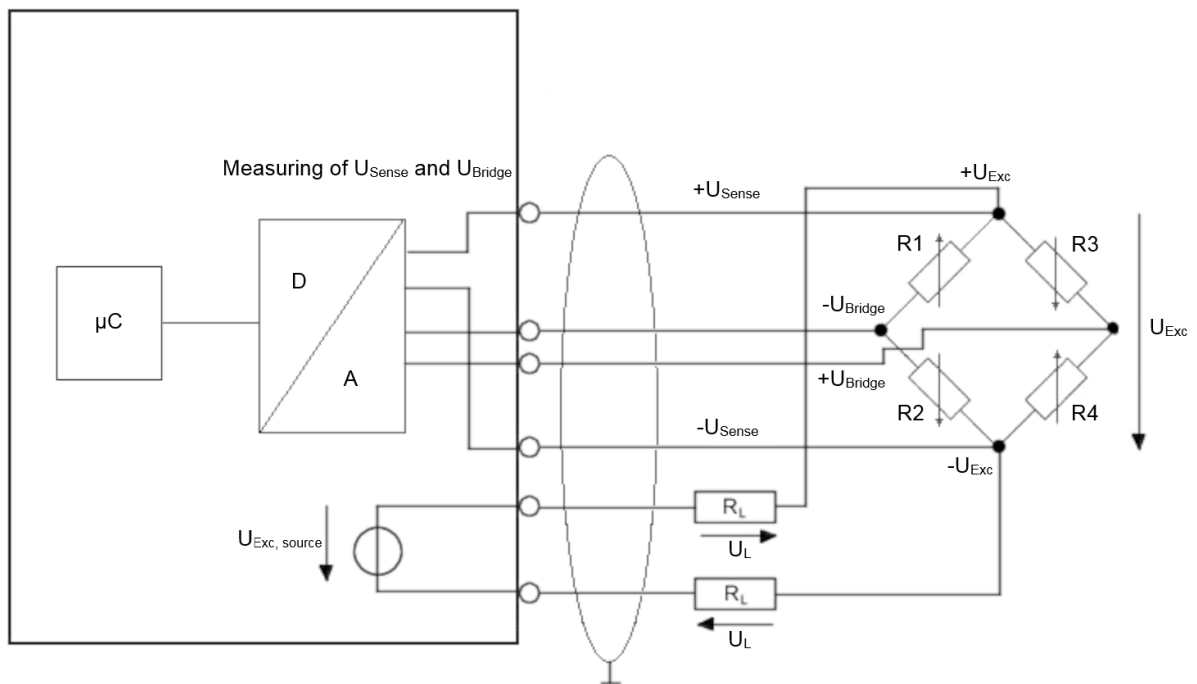


Fig. 20: 6-wire connection

This can be remedied by a 6-wire connection, in particular for precision applications.

The supply voltage U_{Exc} is thereby fed to the bridge (results in the pair of the current-carrying conductors, the feed line). The supply voltage U_{Exc} is only measured with high impedance as reference voltage U_{Sense} as the bridge voltage U_{Bridge} with two almost currentless return conductors each directly at the measuring bridge in the same way (often described as "Sense" input on measurement devices). Some measuring amplifiers then automatically increase the supply voltage thus far that the desired supply voltage is available at the bridge despite the potential difference on the supply line. In any case, the conductor-related errors can be compensated by the back measurement of U_{Sense} .

Since these are very small voltage levels of the order of mV and μ V, all conductors should be screened.

Structure of a load cell with a strain gauge

One application of the strain gauge is the construction of load cells.

This involves gluing strain gauges (full bridges as a rule) to an elastic mechanical carrier, e.g. a double-bending beam spring element, and additionally covered to protect against environmental influences.

The individual strain gauges are aligned for maximum output signals according to the load direction (two strain gauges in the elongation direction and two in the compression direction).



Fig. 21: Example of a load cell

The most important characteristic data of a load cell



Characteristic data

Please enquire to the sensor manufacturer regarding the exact characteristic data!

Nominal load E_{\max}

Maximum permissible load for normal operation, e.g. 10 kg

Nominal characteristic value mV/V

The nominal characteristic describes the sensitivity of the load cell at nominal load E_{\max} . This unit less value indicates the unbalance of the Wheatstone bridge, which, at supply voltage U_{Exc} , results in the output voltage U_{Bridge} .

An example: a nominal characteristic value 2 mV/V means that, with a supply of $U_{\text{Exc}} = 10 \text{ V}$ and at the full load E_{\max} of the load cell, the maximum output voltage is

$U_{\text{Bridge}} = 10 \text{ V} \cdot 2 \text{ mV/V} = 20 \text{ mV}$. The nominal characteristic value is always a nominal value – a manufacturer's test report is included with good load cells stating the characteristic value determined for the individual load cell, e.g. 2.0782 mV/V.

Accuracy class of a scale according to OIML R60

The accuracy class is indicated by a letter (A, B, C, D) and an additional digit, which encodes the **scale interval d with a maximum number n_{\max}** (1000), e.g. C4 means class C with a maximum of 4000 scale intervals. A division step is to be understood as the smallest possible/permissible unit with which weights can be differentiated. Smaller weight differences than the division unit can therefore not be clearly distinguished with the scale. The higher the quality of a weighing unit in terms of the components used and internal compensation elements, the finer its resolution.

The classes specify a maximum and minimum limit for **scale intervals d**:

- A: 50,000 – unlimited
- B: 5000 – 100,000
- C: 500 – 10,000
- D: 500 – 1000,

The scale interval $n_{\max} = 4000$ states that, with a load cell with a resolution of $E_{\min} = 1$ g, a calibratable set of scales can be built that has a maximum measuring range of $4000 \cdot E_{\min} = 4$ kg. Since E_{\min} is thereby a minimum specification, an 8 kg set of scales could be built – if the application allows – with the same load cell, wherein the calibratable resolution would then fall to $8 \text{ kg}/4000 = 2$ g. From another point of view the scale interval n_{\max} is a maximum specification; hence, the above load cell could be used to build a set of scales with a measuring range of 4 kg, but a resolution of only 2000 divisions = 2 g, if this is adequate for the respective application. Also the classes differ in certain error limits related to non-repeatability/creep/TC.

Accuracy class according to PTB

The European accuracy classes are defined in an almost identical way (source: PTB Braunschweig).

Class	Calibration value e	Minimum load E_{\min}	Maximum load E_{\max}	
			Minimum value	Maximum value
I Fine scales	$0.001 \text{ g} \leq e$	100 e	50000 e	-
II Precision scales	$0.001 \text{ g} \leq e \leq 0.05 \text{ g}$	20 e	100 e	100000 e
	$0.1 \text{ g} \leq e$	50 e	5000 e	100000 e
III Commercial scales	$0.1 \text{ g} \leq e \leq 2 \text{ g}$	20 e	100 e	10000 e
	$5 \text{ g} \leq e$	20 e	500 e	10000 e
IIII Coarse scales	$5 \text{ g} \leq e$	10 e	100 e	1000 e

It should be noted that a scale can usually only be used in a situation that is subject to calibration requirements with a considerably smaller scale interval than the data sheet indicates for an unregulated situation.

Minimum calibration value E_{\min}

This indicates the smallest mass that can be measured without the maximum permissible error of the load cell being exceeded [RevT].

This value is represented either by the equation $E_{\min} = E_{\max} / n$ (where n is an integer, e.g. 10000), or in % of E_{\max} (e.g. 0.01%).

This means that a load cell with $E_{\max} = 10$ kg has a maximum resolution of

$$E_{\min} = 10 \text{ kg} / 10000 = 1 \text{ g} \text{ or } E_{\min} = 10 \text{ kg} \cdot 0.01\% = 1 \text{ g}.$$

Resolution of the scale / strain gauge vs resolution of the electronic recording

As described above, scales have a scale interval, i.e. a number of resolvable steps, e.g. 6000d. A 12 kg scale could therefore resolve to 2 g, which is 0.016 % or 166 ppm of the full-scale value.

On the other hand, there is the question of what electrical analog acquisition is necessary for such a scale, if it is to be utilized to the full. The answer is found in the following steps:

- The resolution of the analog value acquisition must in any case be equal to the scale graduation, or preferably greater. 6000d is approximately $2^{12.5}$, so the analog value acquisition (ADC) must have at least 13 bits_{unsigned}, 14 bits signed if the analog input measures in bipolar mode (which is usually the case).
- However, 6000d means that the scale can unambiguously distinguish 6000 steps. This requirement must also be met by the analog value acquisition (weighing terminal). The measurement uncertainty of the weighing terminal is to be taken as the upper reference value for technically clearly distinguishable levels. So in this case it must be $< 166 \text{ ppm}_{\text{full-scale value}}$ for the 6000d scale to also meet a 6000d electronics.
- Ideally, the differential voltage U_{bridge} generated by the scale, e.g. 20 mV, should fully utilize the measuring range of the analog value acquisition to 100 %, i.e., up to the full-scale value (FSV)! Otherwise, this must be taken into account in the following calculation.
- It should be noted that the analog specification of the measurement uncertainty for Beckhoff analog products can vary depending on the terminal/box:
 - with measurement error/uncertainty over the operating temperature range of the device, e.g. $\pm 0.01\%_{\text{full-scale value}}$ at $T_{\text{ambient}} = 0 \dots 55 \text{ }^\circ\text{C}$,
 - or more precisely broken down in the extended analog characteristics: Basic accuracy @ $T_{\text{ambient}} = 23 \text{ }^\circ\text{C}$ and temperature coefficient of e.g. 10 ppm/K.
- If an even more precise consideration is required, the basic accuracy (measurement uncertainty at 23 °C) must be broken down further. The basic accuracy contains the four manufacturer-dependent elements: gain error, offset error, nonlinearity and repeatability.
 - The offset error can easily be eliminated by a zero compensation (tare).
 - Likewise, the gain error can be determined by adjustment with a calibration weight.
 - The unavoidable remaining parameters are nonlinearity and repeatability. If these are provided in the Beckhoff device specification, they therefore represent the lowest limit for the possible "division" of the analog value acquisition. If, for example, the *non-linearity over the whole measuring range*, $E_{\text{Lin}} = 50 \text{ ppm}$ and the *repeatability* (at 23°C), $E_{\text{Rep}} = 20 \text{ ppm}$, a scale with 14285d could be constructed from this (1/70 ppm).
 - Note: This assumes, of course, that the temperature influence is eliminated by air conditioning and the noise of the analog recording is eliminated by (digital) filtering.

Minimum application range or minimum measuring range in % of rated load

This is the minimum measuring range or the minimum measuring range interval, which a calibratable load cell or scale must cover.

Example:

Above load cell $E_{\text{max}} = 10 \text{ kg}$; minimum application range e.g. 40 % E_{max} .

The used measuring range of the load cell must be at least 4 kg. The minimum application range can lie in any range between E_{min} and E_{max} , e.g. between 2 kg and 6 kg if a tare mass of 2 kg already exists for structural reasons. A relationship between n_{max} and E_{min} is thereby likewise apparent: $4000 \cdot 1 \text{ g} = 4 \text{ kg}$.

There are other important characteristic values, which are for the most part self-explanatory and need not be discussed further here, such as nominal characteristic value tolerance, input/output resistance, recommended supply voltage, nominal temperature range etc.

Parallel connection of strain gauges

It is usual to distribute a load mechanically to several strain gauge load cells at the same time. Hence, for example, the 3-point bearing of a silo container on three load cells can be realized. Taking into account wind loads and loading dynamics, the total loading of the silo including the dead weight of the container can thus be measured. The mechanically parallel-connected load cells are usually also electrically connected in parallel and to one measuring transducer, e.g. the EL3356. To this end the following must be observed:

- It is highly recommended that the load cells used are adjusted in the nominal characteristic value with a low tolerance, i.e. that they all have an approximately equal nominal characteristic value of e.g. 2 mV/V $\pm 0.1\%$. If the load center and thus the load distribution among the load cells changes during successive weighings of the same weight, the final result remains the same. On the other hand, in the case of non-adjusted load cells with e.g. 2 mV/V $\pm 10\%$, a variable load distribution due to a change in the force application point or weight center point leads to correspondingly variable weighing results.
- The input impedance of the load cells (as a rule, a few 10 Ω higher than the initial or nominal weight) must be such that the current supply capability of the supply (can be integrated into the transducer electronics) is not overloaded and
- the nominal characteristic value [mV/V] remains unchanged in the calculation, the rated load of the load cells must be added accordingly.

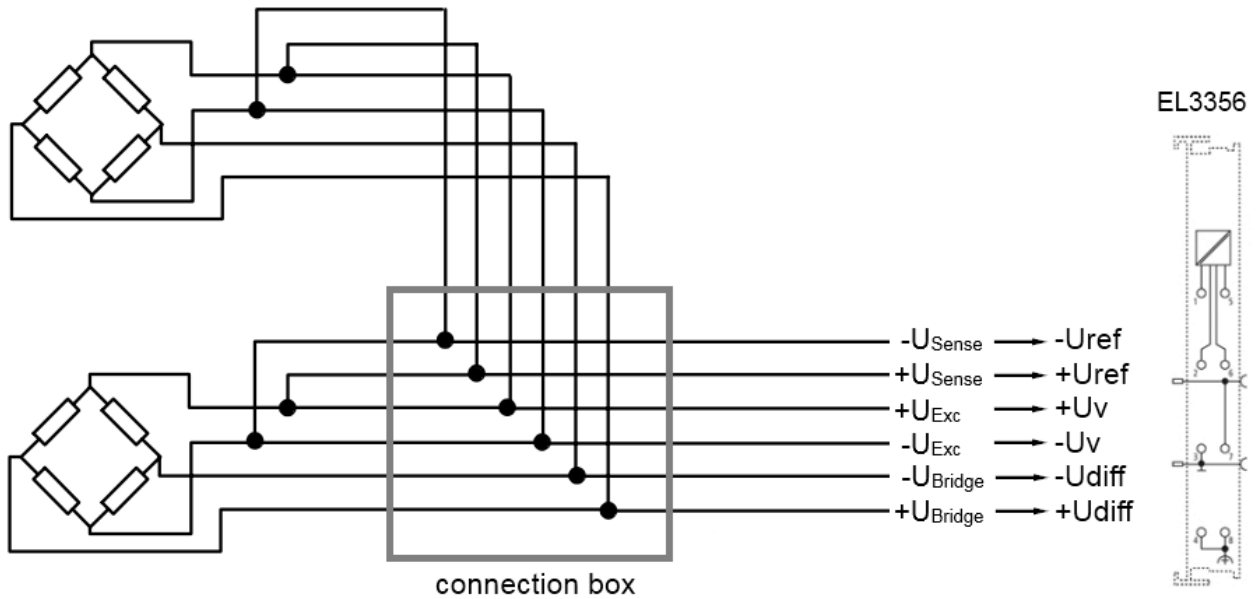


Fig. 22: Parallel strain gauge

Shunt calibration

Notes on shunt calibration

Note: Not all Beckhoff strain gauge/bridge measuring devices support shunt calibration.

Shunt calibration refers to a procedure in which a known resistor is temporarily connected parallel to a bridge resistor. This is possible with all bridge circuits (quarter/half/full bridge); example for full bridge:

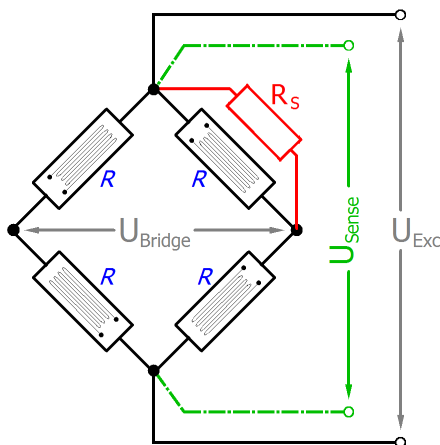


Fig. 23: Shunt calibration

This electrically simulates a load on the measuring bridge; depending on the situation, a measuring signal step change between 0.1 and a few mV/V occurs. The interesting thing is that the step change, which is dependent on all the elements involved, is predictable.

Shunt calibration is used, for example, to

- find wire breakages or wiring faults during commissioning,
- simplify the initial calibration of the measuring setup: if the sensor cannot be loaded, the gain of the electrical measurement can be checked through the known detuning. Data acquisition can be even more extensive if the shunt is installed upstream in the sensor or in the bridge, rather than in the measuring device (in this case the Beckhoff measuring terminal),
- detection of resistance changes (that change the gain) in cables, plugs, full/half/quarter bridge during operation,
- compensate for actual line resistances during commissioning without having to install an (expensive) compensating line. For this purpose, the determined detuning is compared with the theoretically expected detuning and a corresponding gain correction factor is calculated in the PLC or terminal (however, a technically better way with regard to line resistances would be to use compensating lines, i.e. 3-wire mode for quarter bridge, 5-wire mode for half bridge, 6-wire mode for full bridge).

Shunt calibration procedure

1. During commissioning, note the measured value at constant load, ideally without load.
2. Close the shunt and note the difference to the previous measured value. A signal step change in [mV/V] should occur which corresponds to the precalculated value.
3. During system operation the shunt calibration can be repeated regularly. The signal step change should not change significantly; if it does, it is an indication that electrically relevant components may have changed unintentionally.

Theoretically, the expected signal step change is based on the equation:

$$\frac{U_{IN}}{U_V} = \frac{R}{4 \cdot R_s}$$

is 0.875 mV/V for $R = 350 \Omega$ and $R_s = 100 \text{ k}\Omega$.

Formulas and information on shunt calibration can be found in high-quality technical literature (Keil, Hoffmann) and can in some cases be obtained from bridge manufacturers (Vishay, HBM). However, it should be noted that the actual bridge design in commercially available measuring bridges/strain gauges often goes beyond the fundamentals described in simple standard works with $R_1 \dots R_4 = R$. It is important to be aware of this, in order to be able to predict the signal step change [mV/V] during shunt calibration. Therefore, some aspects of actual measuring bridges are described below. Please note that the information is provided for general guidance only; for actual applications the user should discuss the finer details with the bridge manufacturer.

Input vs output impedance

Professionally manufactured measuring bridges/full bridges consist not only of the four bridge resistors R_1 , R_2 , R_3 , R_4 , but include a number of additional resistors and other sophisticated components, e.g. to compensate for temperature and non-linearity effects. The nominal or rated resistance of 120 or 350 Ω always refers to the output impedance (output resistance) of a bridge, i.e. the resistance that the measuring device sees at U_{Bridge} .

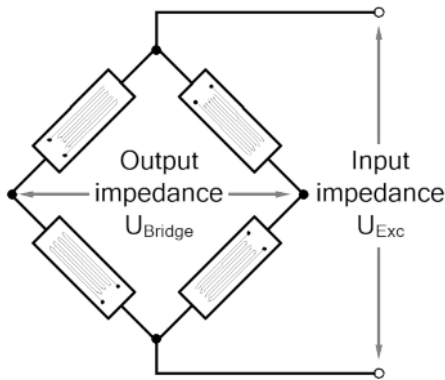


Fig. 24: Measuring bridge with 4 bridge resistors

Theoretically the input impedance (input resistance) is the same, although in practice it is up to 25% larger than the output impedance, since, for example, with $350\ \Omega$ bridges, $2\times$ approx. $32\ \Omega$ are often installed (for background on this see e.g. Stefan Keil, "Beanspruchungsermittlung mit Dehnmessstreifen", 1995, Chap. 5.3), which are also detected by the sensor:

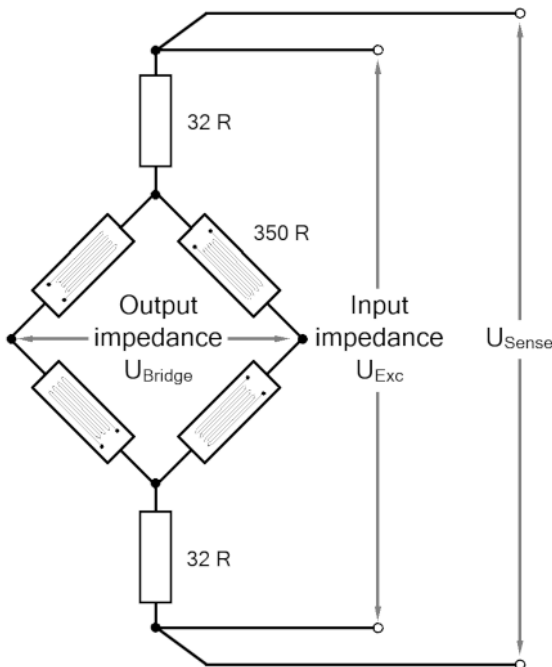


Fig. 25: Measuring bridge with 4 bridge resistors and 2 additional resistors

This is irrelevant in non-shunt mode, in which the load on the supply is actually reduced. However, in shunt mode this information is crucial if the signal step change is to be predicted correctly. In addition, bridge designs vary greatly across the world, depending on the manufacturer and price range; in some cases bridges are asymmetrical in terms of U_{Exc} .

Line resistances

The shunt bridges supply lines, which means the influence of their resistance must also be known or measured in order to be able to predict the signal step change. Formulas and information on resistances of cables, connectors and switches can be found in the specialist literature, manufacturer data sheets and internet sources. Values in the range of a few 10s to $100\ \text{m}\Omega$ are common for short lengths.

Step change prediction

Due to the different characteristics of bridges and environments, no comprehensive values or formulas for step change prediction in [mV/V] can be provided here. More meaningful is specific calculation according to the respective conditions, taking into account the components that are essential for the shunt calibration. Common simulation tools are available for this purpose; further information can be requested via measurement@beckhoff.com.

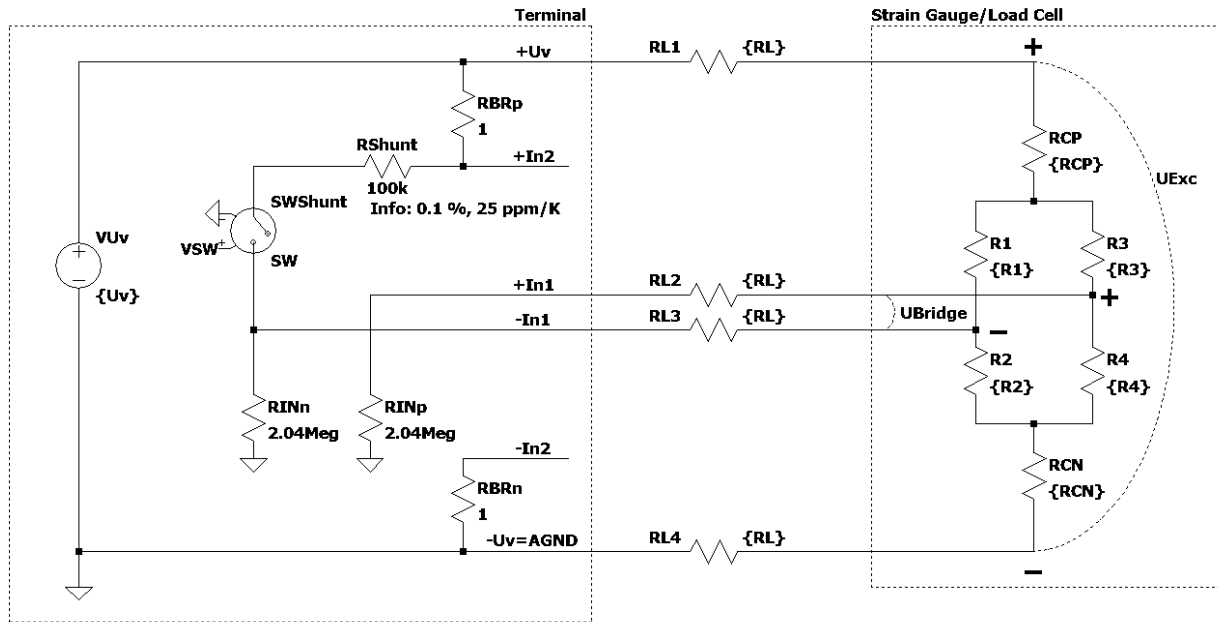


Fig. 26: Example 1 - Comprehensive consideration of the 4-wire connection for an ELM350x

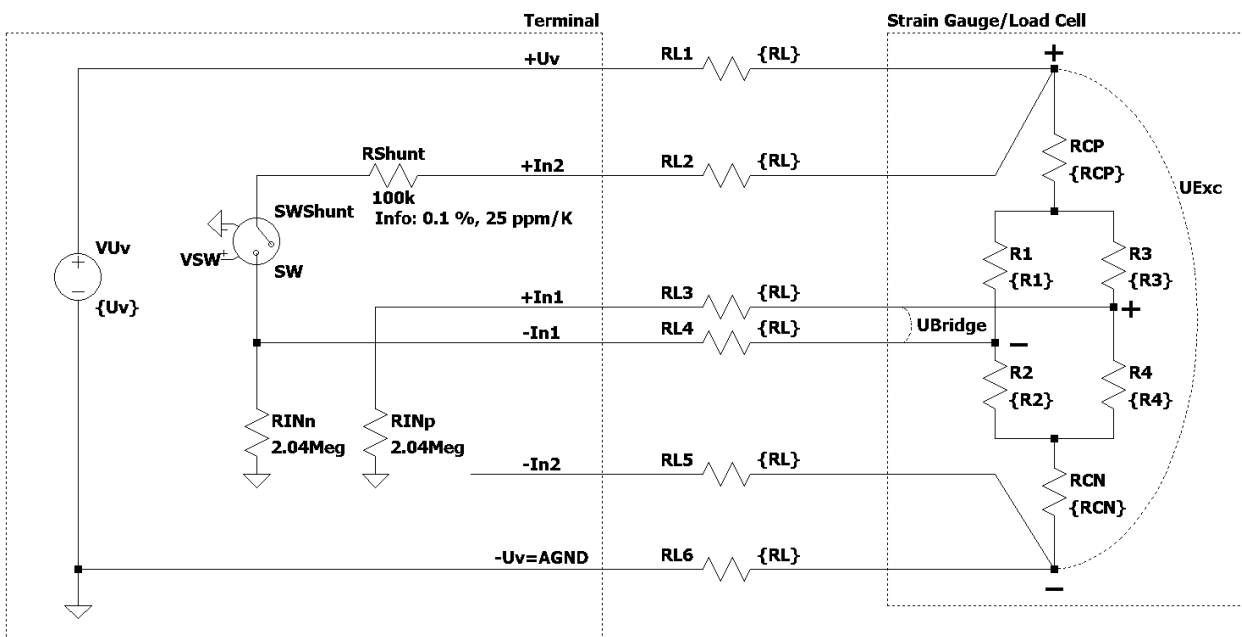


Fig. 27: Example 2 - Comprehensive consideration of the 6-wire connection for an ELM350x

Sources of error/disturbance variables

Inherent electrical noise of the load cell

Electrical conductors exhibit so-called thermal noise (thermal/Johnson noise), which is caused by irregular temperature-dependent movements of the electrons in the conductor material. The resolution of the bridge signal is already limited by this physical effect. The rms value e_n of the noise voltage can be calculated by:

$$e_n = \sqrt{4kTRB}$$

In the case of a load cell with $R_0 = 350 \Omega$ at an ambient temperature $T = 20 \text{ }^\circ\text{C}$ ($= 293\text{K}$) and a bandwidth of the measuring transducer of 50 Hz (and Boltzmann constant $k = 1.38 \cdot 10^{-23} \text{ J/K}$), the rms $e_n = 16.8 \text{ nV}$. The peak-peak noise e_{pp} is thus approx. $e_{pp} \approx 6.6 \cdot e_n = 111 \text{ nV}$ (thermal noise, 99.9 % interval of standard deviation).

Example:

For a bridge with 2 mV/V nominal characteristic value and supply of $U_{Exc} = 5 \text{ V}$, this results in an output voltage $U_{Bridge_max} = 5 \text{ V} \cdot 2 \text{ mV/V} = 10 \text{ mV}$ (for the nominal load) and therefore a maximum resolution of $10 \text{ mV} / 111 \text{ nV} = 90090$ digits. Converted into bit resolution: $\ln(90090)/\ln(2) \approx 16$ bits. Interpretation: a higher digital measuring resolution than 16 bits is thus inappropriate for such an analog signal in the first step. If a higher measuring resolution is used, then additional measures may need to be taken in the evaluation chain in order to gain a higher information content from the user- and noise superposition, e.g. hardware low-pass filter or software algorithms.

This resolution applies alone to the measuring bridge without any further interferences. The resolution of the measuring signal can be meaningfully increased by reducing the bandwidth of the measuring unit.

If the strain gauge is glued to a carrier (load cell) and wired up, both external electrical disturbances (e.g. thermovoltage at connection points) and mechanical vibrations in the vicinity (machines, drives, transformers and audible 50 Hz vibration due to magnetostriction etc.) can additionally impair the result of measurement.

Creep

Under a constant load, spring materials can further deform in the load direction. This process is reversible, but it generates a slowly changing measured value during the static measurement. In an ideal case the error can be compensated by constructive measures (geometry, adhesives).

Hysteresis

If even elongation and compression of the load cell take place, then the output voltage does not follow exactly the same curve, since the deformation of the strain gauge and the carrier runs different due to the adhesive and its layer thickness.

Temperature drift (inherent heating, ambient temperature)

Relatively large currents can flow in strain gauge applications. A full bridge with four 350 Ω resistors for example has a current consumption of $I = U_{Exc}/R_0 = 10 \text{ V} / 350 \Omega \approx 28.6 \text{ mA}$. The power dissipation of the whole full bridge is thus $P_{Exc} = U \cdot I = 10 \text{ V} \cdot 28.6 \text{ mA} = 286 \text{ mW}$. Depending on application (a cooling of the strain gauge takes place by heat dissipation into the carrier material) and carrier material a not insignificant error can arise that is termed apparent elongation. Therefore, the strain gauges on the sensor material are often counter-compensated by the manufacturer.

Inadequate circuit technology

As already shown, a full bridge may be able (due to the system) to fully compensate hysteresis, creep and temperature drift. Wiring-related measuring errors are avoided by the 6-conductor connection.

Measuring body and natural frequency

In the dynamic measurement of forces and weights, the setup and some of the properties of the transducer play an essential part in the attainable dynamics. The natural frequency of the complete system limits the dynamics of the application and is influenced by the spring constant of the measuring body and the coupled mass. The softer the measuring body ($=$ larger deformation under nominal load), the lower the natural frequency. In the case of measuring transducers with rigid measuring bodies, too, the coupled mass must always be included if the natural frequency is to be determined.

Load cells are technologically similar to force transducers, but have a softer structure and are usually manufactured at optimized cost. Consequently, the recommendation for the mechanical setup is:

- use a rigid measuring transducer and the lightest possible mounted parts,

- the natural frequency of the system should be at least 2-5 times higher than the measuring signal frequency (i.e. the dynamically moved test specimen from the application that is to be measured),
- Natural frequency specifications in data sheets apply only to the measuring transducer without mounted parts and are therefore not useable in the field. It is better to calculate with the nominal measuring path and masses of sensor plus mounted parts. The real natural frequency can be checked by means of a frequency analysis of the pulse response by FFT or manually by determining the period.

The natural frequency is to be calculated with:

$$f_0 = \frac{1}{2\pi} \cdot \sqrt{\frac{k}{m}} = \sqrt{\frac{F_{nom}}{4\pi^2 \cdot m \cdot s_{nom}}}$$

- f_0 = natural frequency of the complete setup [Hz]
- F_{nom} = nominal force [N] or calculated nominal force by nominal load of the transducer [kg] and gravity of earth [m/s²]
- s_{nom} = nominal measuring path of the transducer (deformation under nominal load) [m]
- m = sum of dead weight and coupled mass [kg]

With $F_{nom} = 450.5 \text{ N}$ (50 kg nominal load and 9.81 m/s^2 gravity), $s_{nom} = 0.18 \text{ mm}$, the resulting dependence on the mass, for example, is graphically:

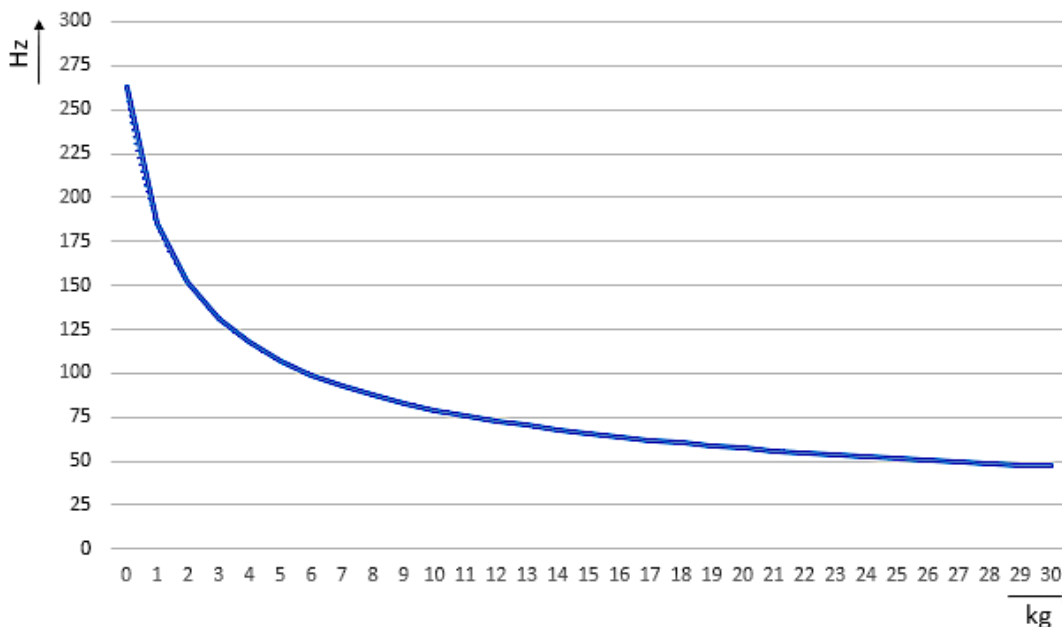


Fig. 28: Natural frequency as a function of the total mass

Recommendations for strain gauge measurement with Beckhoff modules

- Electrical connection:
 - Operation with an additional sense line for the bridge supply is recommended: Full bridge in 6-wire mode, half bridge in 5-wire mode, quarter bridge in 3/4-wire mode.
 - The use of full bridges instead of half or quarter bridges is generally recommended in order to achieve higher temperature stability and higher measuring accuracy.
- Selection of the feed voltage U_{Exc} :
 - A feed voltage of 5 V has proven to be useful in many cases.
 - In general it should be as high as possible within the permissible range according to the data sheet in order to achieve a large modulation of U_{Bridge} with the given nominal characteristic value [mV/V] and thus to maximize the electrical measuring range of the module (SNR increment).
 - However, it should be considered that the heating of the bridge in the load cell increases quadratically with U_{Exc} to a first approximation. With high feed voltages and insufficient heat dissipation from the sensor to the machine, this can lead to massive drift effects after switching on.

- If necessary, select a bridge with a higher nominal parameter [mV/V] or a higher internal resistance [Ω].
- Selection of the nominal load of the weighbridge:
 - It should be selected somewhat larger but as close as possible to the target load so that the mechanical and thus the electrical measuring range is utilized to the fullest extent possible.
 - The overload capacity of the load cell must be observed. Fast weighing procedures in particular can lead to excessive mechanical stresses; nevertheless, as stated above, the bridge should not be over-dimensioned (regarding E_{\max}).
 - The mechanical natural frequency of the load cell (in which the measuring bridge/strain gauge is installed!) or of the complete setup is to be considered in relation to the weighing procedures (number of product changes, product speed, product weights). If necessary, a significantly larger nominal load should be selected to the target load, because sensors with a higher nominal load have shorter nominal measuring paths and are thus mechanically more rigid. With a more rigid measuring body – usually the softest part of the entire setup – the natural frequency increases. As a result, the dynamics of the weighing procedure can be cleanly captured and measuring errors due to the natural oscillations of the weighing setup are avoided.
- Calibration/compensation of the bridge:
 - Regular zero compensation (tare) is recommended.
 - The tare effect should be observed in order to recognize a possibly damaged measuring bridge: the signal of a damaged measuring bridge drifts; it does not return to the original value after removal of the load.
 - For the compensation of a gain error, a compensation point close to the target load should be selected during commissioning and if possible during operation, especially if this lies well below the nominal load (measurements in the partial load range).
- Possible filtering of the measurement, dynamic effects:
 - In the case of fast sequential weighing procedures (several objects to be measured, e.g. products per second), it may be possible with adapted digital filters - despite an obviously “poor” measuring signal - to achieve a high measuring accuracy.
 - Overshoot effects can often be observed for example, the pickup device for measurement objects (products) actually always moves mechanically (even if only in the μm range).
 - The procedure of fast sequential weighing can also be dependent on the speed of which measurement objects (products) being moved over the weighting area; the filters for the measurement signal may then need to be dynamically adjusted.
 - The optimal signal analysis is supported by Beckhoff with various products: flexible filters in the EtherCAT modules, TwinCAT filter designer, TwinCAT filter library, TwinCAT Analytics and so on.

References

Some organizations are listed below that provide the specifications or documents for the technological field of weighing technology:

- **OIML** (ORGANISATION INTERNATIONALE DE MÉTROLOGIE LÉGALE) www.oiml.org
- PTB - Physikalisch-Technischen Bundesanstalt www.ptb.de
- Arbeitsgemeinschaft Mess- und Eichwesen: www.eichamt.de
- WELMEC - European cooperation in legal metrology www.welmec.org
- DKD - Deutscher Kalibrierdienst www.dkd.eu
- Fachgemeinschaft Waagen (AWA) im Verband Deutscher Maschinen- und Anlagenbau VDMA www.vdma.org

4.4 NAMUR basic information

General term: "device"

This chapter is used in the documentation of several Beckhoff products. It is therefore written in general terms and uses the generic term "device" for the different device types such as terminal (EL/ELM/KL/ES series...), box (IP/EP/EPP series...), module (EJ/FM series...).

The abbreviation of NAMUR, "User Association of Automation Technology in Process Industries" identifies an international association for users of automation technology that considers the interests related to standardization, devices and measurement control (or similar) of the Process Industries as its major task. In this role, the NAMUR releases the so called NE (proposed standards), each numbered continuously.

Information with regard to the implementation of this recommendation in Beckhoff products are specified in sections "Technical data" and "Process data" of this documentation.

Analog measured values

The analog output value of a sensor that can be measured among other things as a certain current value represents the measurement information (M).

By means of NAMUR NE43 a recommendation – irrespective of the sensor manufacturer – for standardized failure information (A) is defined in addition to the measurement information (e.g. malfunction of a measurement converter, error in connective wires, failure of an auxiliary energy etc.). The failure information states that there is an error in the measuring system. This concerns the analog output signal of sensors in a current loop and therefore in the form of a current value. A current value lying outside of the limits defined by NE43 is defined invalid as measurement information and then interpreted as failure information. The following diagram illustrates this:

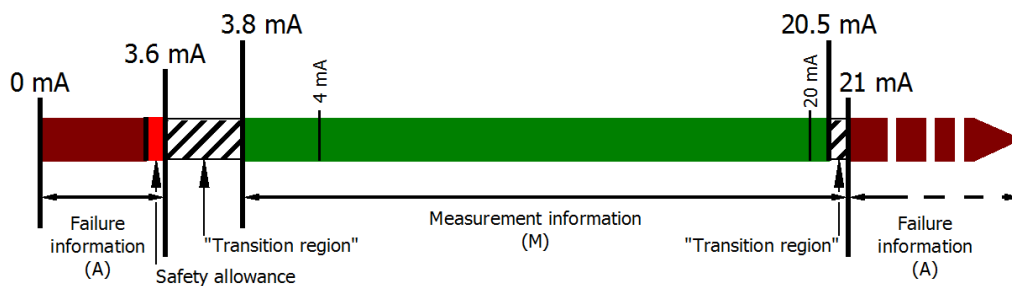


Fig. 29: Representation of the boundaries from NAMUR recommendation NE43, version from 03/02/2003

Boundaries from NAMUR recommendation NE43		
Failure information (A)	Measurement information (M)	Failure information (A)
$0 \text{ mA} \leq C_A \leq 3.6 \text{ mA}$	$3.8 \text{ mA} < C_M < 20.5 \text{ mA}$	$C_A \geq 21.0 \text{ mA}$

Digital measured values

The supply as well as the evaluation of the fed back current of the sensor via a 2-wire connection is done by a DC switching amplifier. This evaluates the analog current signal using prescribed limit and hysteresis values in transition junctions in accordance with the IEC / DIN EN 60947-5-6 (formerly NAMUR NA01) standard. The switching states will be passed through (if necessary, galvanic isolated) from the field side to the higher level control. Starting with a current loop, adherence to the limits defined by NAMUR is required in this case too for classification as valid measurement information. If these limits are exceeded there is generally an error, i.e. either a short circuit or an interruption of the 2-wire connection incl. the sensor.

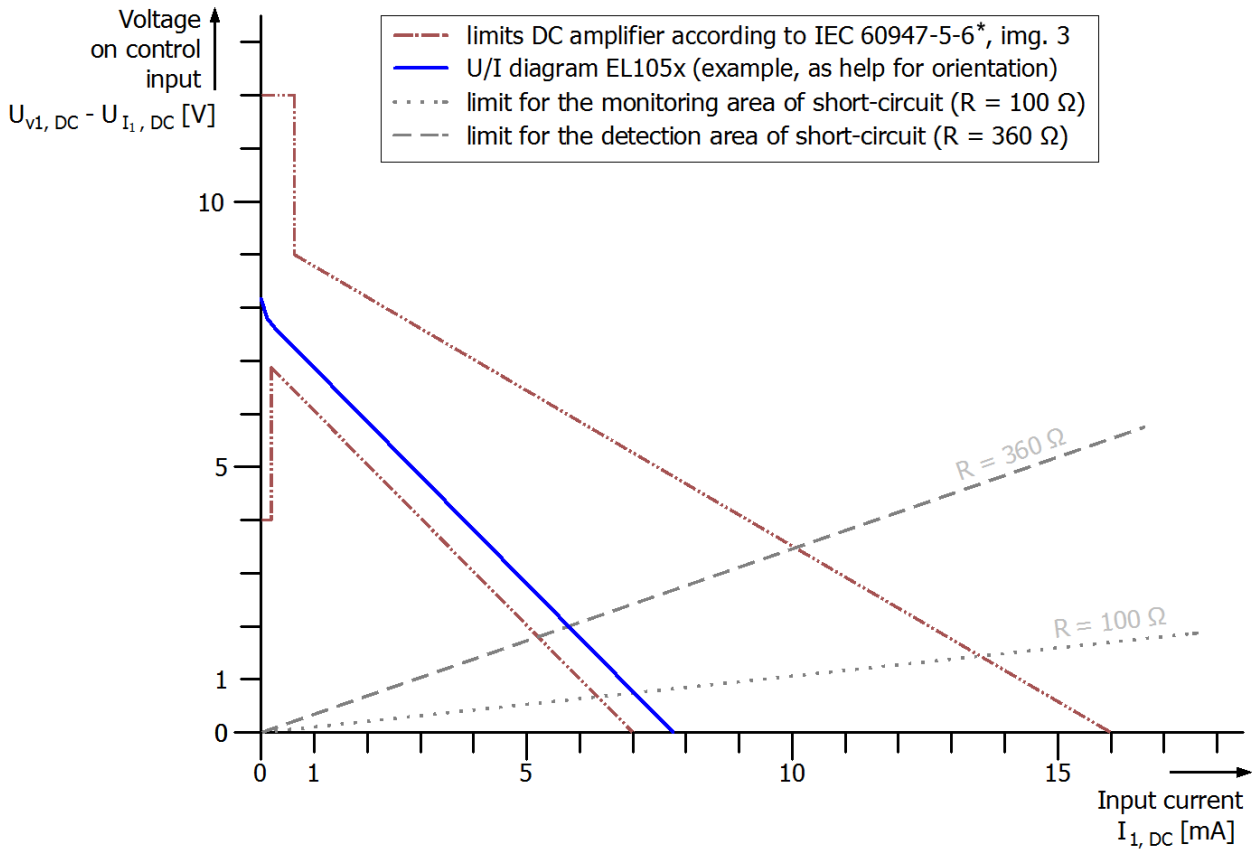


Fig. 30: Illustration of an exemplary U/I diagram incl. standard limits
 (*source of the standard limits: ÖVE/ÖNORM EN 60947-5-6, edition 2001-02-01)

4.5 Basic principles of IEPE technology

IEPE ("Integrated Electronics Piezo-Electric") is the standardized name for an analog electrical interface between piezoelectric sensors and electronic analysis equipment. Different manufacturers have developed their own brand names, such as ICP®, CCLD®, Isotron®, DeltaTron®, Piezotron®.

Application

Piezoelectric sensors are usually based on a quartz, in which an electrical charge is shifted under mechanical load. The charge can be detected as a voltage if the measurement is made with sufficiently high impedance. The measurement is a preferably static process, which must take place within a much smaller time interval than 10 seconds, since otherwise the charge difference is dissipated through external or internal derivatives. Such a sensor is therefore less suitable for static long-term loads, such as weighing a silo. Such sensors tend to be used for all kinds of predominantly higher frequency vibration measurements (unbalance detection, sound signals via microphones up to ultrasound, mechanical vibrations, foundation monitoring, etc.).

Over the decades, two electrical forms of interfaces to the evaluation unit have developed:

- Direct charge output
- IEPE output

Charge output

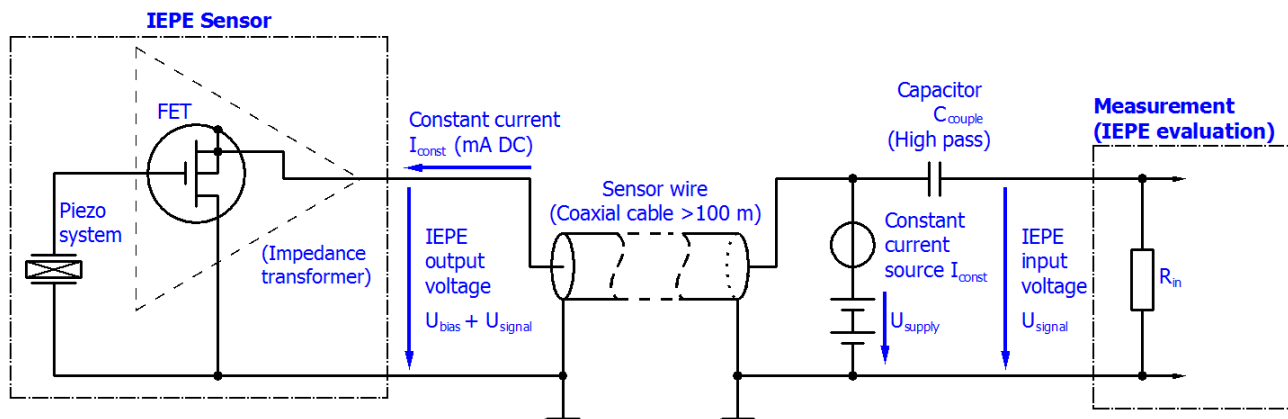
The sensor's output signal is provided by a very low change of charge (usually in the range of a little femto to pico coulomb) and tapped by a (possibly short) 2-wire cable. Thus a so called charge amplifier is an essential component of the measurement electronics.

Advantages: the sensor can be exposed to high temperatures over 150 °C; no power supply is required.

Disadvantages: very sensitive to external influences on the cable (line length, possible movement of the cable, type of cable and shielding, electromagnetic fields, etc.); elaborate receiving electronics and cable due to high source impedance.

IEPE output

Since the charging output interface is not generally accepted for industrial applications, a more robust transfer method was sought at an early stage. Thus, for IEPE integrates a field effect transistor (FET) directly at the output of the sensor.



If this sensor is supplied with constant current between 2 and 8 mA via the two-pole cable, the resulting bias voltage is usually approx. 8 to 15 V. If the piezo system is now directly or indirectly (e.g. by a diaphragm) loaded by a measure quantity e.g. force in form of pressure or acceleration, the FET changes its channel resistance caused by change of charge amount on its gate; according to this, a change of the gate source voltage. Because of the supply of I_{const} by a constant current source, the bias voltage changes correspondingly by the mechanical load of about few volts. Although the evaluation unit now usually has to provide the constant current supply but is able to deduce the measurement quantity by the back-measured voltage.

Advantages: robust system, which is suitable for operation in industrial conditions.

Disadvantages: upper temperature limit for the sensor 150 to 200 °C, smaller dynamic range.

Notes on constant current

- The higher the feed current, the more the vibration sensor heats up. This may cause a disadvantageous effect on e.g. the basic accuracy of the sensor. For this, note the information provided by the sensor manufacturer.
- The higher the feed current, the higher the maximum transferable signal frequency, since charge inflows and outflows can be balanced more quickly on the cable.
- The higher the supply current, the higher the resulting bias voltage. As a result, the transfer may become more robust against electromagnetic influence, but on the other hand that for large amplitudes the measurement quantity may enter the upper saturation faster.

Notes on the IEPE measuring device

- In some IEPE measuring devices the supply current can be switched off (0 mA), so that they can be used for voltage measurements, cf. for example Beckhoff ELM3604
- Since normally only AC signals are of interest in the vibration range, IEPE evaluations have an electrical high-pass with a cutoff frequency of approximately 10 Hz on the input side. Depending on the application e.g. the capturing of slow tower vibrations, the limit of this high-pass may be relevant, cf. for example the configurable high-pass of the ELM3604, which can be switched off.
- The bias voltage is suitable for detection of wire breakage or short circuit cases respectively, e.g. see also ELM3604 diagnostics options.

Notes on the IEPE sensor

- If IEPE sensors are mounted on high-voltage or frequency converter-controlled motors, an electrically insulated installation or an insulated sensor may be recommendable. In other cases, interference effects on the IEPE measurement have already been observed. This purely functional consideration must be weighed up by the plant installer against normative and electrical safety requirements.

Purposeful questions for the successful commissioning of an IEPE sensor

The following questions can be used to select the sensor and evaluation device (Beckhoff Terminal/Box) to suit the task:

1. The target frequency range of interest for the task must be specified
2. Is a small-scale or widely distributed system planned?
Especially in the 2nd case it can be useful to select so called isolated sensors to avoid hum/ground loops and signal noise
3. What amplitude accuracy is required?
The frequency behavior of a common IEPE sensor is characterized by significant amplitude errors at the bottom (< 1 kHz) as well as at the top (> 5 kHz)! See manufacturer's data. The appropriate sensor must then be selected from the target frequency range and the maximum permissible amplitude error (of the sensor). For example, with max. 5% amplitude error (corresponds to 5000 ppm, approx. -0.5 dB) a sensor in the range 2 ... 4400 Hz could be trustworthy, i.e. frequencies outside this range (which are transmitted!) must be filtered out on the device side.
4. Which mounting method to select (screwed, magnet, glued, ...).
The type of mounting has a considerable influence on the maximum frequency that can be transmitted! Resonances occur, see the instructions of the sensor manufacturers, also here the maximum permissible amplitude error on the system side must be applied.
For example, it could turn out that a sensor is only trustworthy up to 4 kHz, and frequencies above this would also have to be filtered out on the device side.
5. IEPE sensors are subject to a temperature dependency according to the data sheet!
6. What is the maximum acceleration expected? For this purpose, the required supply current must be determined as a function of the cable length.
7. The evaluation device should now be selected to match the key data determined above.
8. The appropriate sampling rate/oversampling, high-pass and low-pass filters must then be set in the configuration/commissioning.

4.6 Basics about signal isolators, barriers

Occasionally, analog signals cannot be fed directly from the sensor to the Beckhoff analog input terminal/ input module, in which case a special intermediary device must be added.

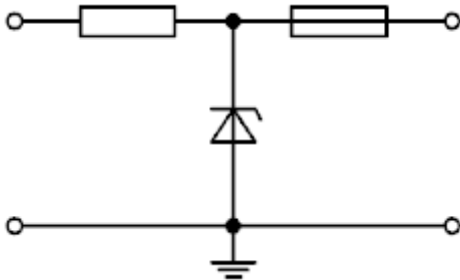


Reasons may include:

- The sensor may be installed in hazardous locations and protected according to the intrinsic safety ignition protection type (Ex i) while a Beckhoff ELX3xxx terminal is not yet available for the desired application.
- Separate electrical isolation between the sensor and the Beckhoff terminal/ module is required.
- The sensor has an electrical output signal for which Beckhoff does not yet offer a suitable input terminal or a suitable input module.

The type of intermediate device depends on the following criteria

- Electrical signal supplied by the sensor? voltage 10 V or μV , AC or DC, 20 mA or 1 A, resistance, ...
- The sensor must be powered in some way, e.g.
 - an IEPE sensor requires 2..8 mA constant current,
 - a resistor requires a measuring current,
 - an electronic sensor may need a 24V supply, or it may be fed via a 20 mA loop.
- What dynamic transmission quality for AC signals must the sensor provide via the intermediate device? Each intermediate device influences the analog signal, e.g. in terms of frequency-dependent attenuation, crosstalk, line resistance or bandwidth. This must be taken into account when an intermediate device is used in a metrological application.
- Is the device used for energy limitation in accordance with the intrinsic safety ignition protection type (Ex i)? In this case, a barrier with appropriate approval is required. Zener barriers are often used in such situations. They are made up of resistors, fuses and Zener diodes.



As already mentioned, these can influence the analog signal quality with respect to the above features, e.g. by temperature-dependent change of the internal resistance.
Terms: Zener barrier.

- Does it have to ensure electrical isolation of the analog signal?



Does electrical isolation of the analog signal have to be provided? Devices that electrically isolate the transmitted signal reconfigure the signal, so that in this case special attention must be paid to the signal influence. In this case the analog properties of the isolator and the Beckhoff analog terminal/ module are interlinked. The properties of the isolator are dominant, particularly when Beckhoff ELM measurement terminals, measurement modules or other high-quality analog devices are used. On the output side, they typically supply standard signals, such as 10 V or 20 mA. Compared with the use of external devices for electrical isolation, the use of Beckhoff input terminals/ input modules with

channel-based electrical isolation is advantageous.

Terms: signal isolator, signal converter, signal transducer, isolating amplifier, measuring amplifier, level transducer.

- Are both measures, i.e. explosion protection according to ignition protection type Ex i and electrical isolation necessary? In this case, so-called isolation barriers are used, which ensure energy limitation for intrinsic safety and also electrical isolation of the signal. Please refer to the notes on analog signal influence referred to above.

From a metrological point of view, signal-influencing intermediate devices should be avoided if possible.

5 Notes on analog data values

5.1 Notices on analog specifications

Beckhoff I/O devices (terminals, box modules, modules) with analog inputs and outputs are characterized by a number of technical characteristic data; refer to the technical data in the respective documents.

Some explanations are given below for the correct interpretation of these characteristic data.

Unless otherwise stated, the explanations apply accordingly to input and output signals.

5.1.1 Full scale value (FSV), output end value

An I/O device with analog input measures over a nominal measuring range, which is limited by an upper and a lower limit (start value and end value), which can usually already be taken from the device designation. The range between both limits is called measuring span and corresponds to the formula (end value - start value). Analogous to pointing devices this is the measuring scale (see IEC 61131) or also the dynamic range.

For analog I/O devices from Beckhoff, the full scale value (FSV) of the respective product (also: reference value) is selected as the largest limit of the nominal measuring range and is given a positive sign. This applies to both symmetrical and asymmetrical measuring spans.

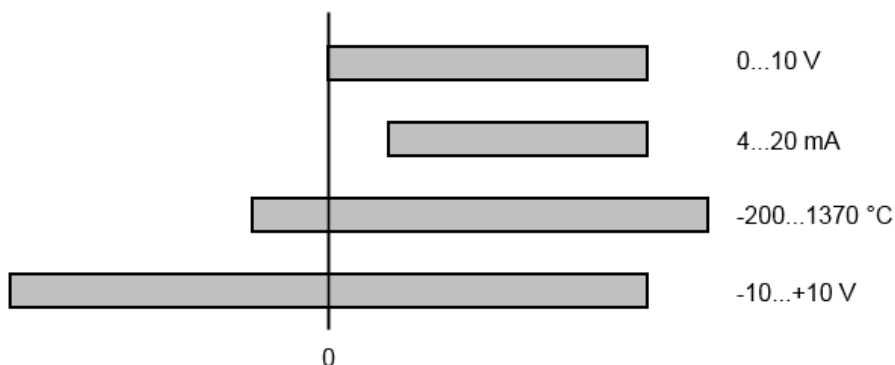


Fig. 31: Full scale value, measuring span

For the above **examples** this means:

- Measuring range 0...10 V: asymmetric unipolar, FSV = 10 V, measuring span = 10 V
- Measuring range 4...20 mA: asymmetric unipolar, FSV = 20 mA, measuring span = 16 mA
- Measuring range -200...1370 °C: asymmetric bipolar, FSV = 1370 °C, measuring span = 1570 °C
- Measuring range -10...+10 V: symmetric bipolar, FSV = 10 V, measuring span = 20 V

Depending on the functionality, an analog input channel may have a technical measuring range that exceeds the nominal measuring range, e.g. to gain more diagnostic information about the signal.

The case-by-case information in the device documentation on the behavior outside the nominal measuring range (measurement uncertainty, display value) must be observed.

The above thoughts are correspondingly applicable to analog output devices:

- The full scale value (FSV) becomes the output end value
- Here, too, there can be a (larger) technical output range in addition to the nominal output range

5.1.2 Measurement error/measurement deviation/measurement uncertainty, output uncertainty

● Analog output



The following information also applies analogously to the output end value of analog output devices.

The relative measuring error as a specification value of a Beckhoff analog device is specified in % of the nominal FSV (output end value) and calculated as the quotient of the numerically largest probable deviation from the true measured value (output value) with respect to the FSV (output end value):

$$\text{Measuring error} = \frac{\left| \text{max. deviation} \right|}{\text{full scale value}}$$

It should be noted here that the "true measured value" cannot be determined with infinite accuracy either, but can only be determined via reference devices with a higher expenditure of technology and measuring time and thus a significantly lower measurement uncertainty.

The value therefore describes the result window in which the measured value determined by the device under consideration (Beckhoff analog device) lies with a very high probability in relation to the "true value". Thus, colloquially, this is a "typical" value (typ.); this expresses that the vast statistical majority of values will be within the specification window, but in rare cases there may/will be deviations outside the window.

For this reason, the term "measurement uncertainty" has become established for this window, since "error" is now used to refer to known disturbance effects that can generally be systematically eliminated.

The uncertainty of measurement must always be considered in relation to potential environmental influences:

- invariable electrical channel properties such as temperature sensitivity,
- variable settings of the channel (noise via filters, sampling rate, ...).

Measurement uncertainty specifications without further operational limitation (also called "service error limit") can be assumed as a value "over everything": entire permissible operating temperature range, default setting, etc.

The window is always to be understood as a positive/negative span with "±", even if occasionally indicated as a "half" window without "±".

The maximum deviation can also be specified directly.

Example: measuring range 0...10 V (FSV = 10 V) and measurement uncertainty $< \pm 0.3\%_{\text{FSV}}$ → the expected maximum usual deviation is ± 30 mV in the permissible operating temperature range.

● Lower measurement uncertainty possible



If this specification also includes the temperature drift, a significantly lower measuring error can usually be assumed in case of a constant ambient temperature of the device and thermal stabilization after a user calibration.

5.1.3 Temperature coefficient tK [ppm/K]

An electronic circuit is usually temperature dependent to a greater or lesser degree. In analog measurement technology this means that when a measured value is determined by means of an electronic circuit, its deviation from the "true" value is reproducibly dependent on the ambient/operating temperature.

A manufacturer can alleviate this by using components of a higher quality or by software means.

The temperature coefficient, when indicated, specified by Beckhoff allows the user to calculate the expected measuring error outside the basic accuracy. The basic accuracy is usually specified for 23 °C ambient temperature, in special cases also at other temperature.

Due to the extensive uncertainty considerations that are incorporated in the determination of the basic accuracy, Beckhoff recommends a quadratic summation.

Example: Let the basic accuracy be $\pm 0.01\%$ typ. (full scale value), $tK = 20 \text{ ppm/K}$ typ at 23 °C.; the accuracy A35 at 35 °C is wanted, hence $\Delta T = 12 \text{ K}$:

$$G_{35} = \sqrt{(0.01\%)^2 + (12\text{K} \cdot 20 \frac{\text{ppm}}{\text{K}})^2} = 0.026\% \text{ full scale value, typ.}$$

Remarks: ppm $\triangleq 10^{-6}$ % $\triangleq 10^{-2}$

5.1.4 Long-term use

Analog devices (inputs, outputs) are subject to constant environmental influences during operation (temperature, temperature change, shock/vibration, irradiation, etc.) This can affect the function, in particular the analog accuracy (also: measurement or output uncertainty).

As industrial products, Beckhoff analog devices are designed for 24h/7d continuous operation.

The devices show that they generally comply with the accuracy specification, even in long-term use. However, as is usual for technical devices, an unlimited functional assurance (also applies to accuracy) cannot be given.

Beckhoff recommends checking the usability in relation to the application target within the scope of normal system maintenance, e.g. every 12-24 months.

5.1.5 Ground reference: single-ended/differential typification

For analog inputs Beckhoff makes a basic distinction between two types: *single-ended* (SE) and *differential* (DIFF), referring to the difference in electrical connection with regard to the potential difference.

The diagram shows two-channel versions of an SE module and a DIFF module as examples for all multi-channel versions.

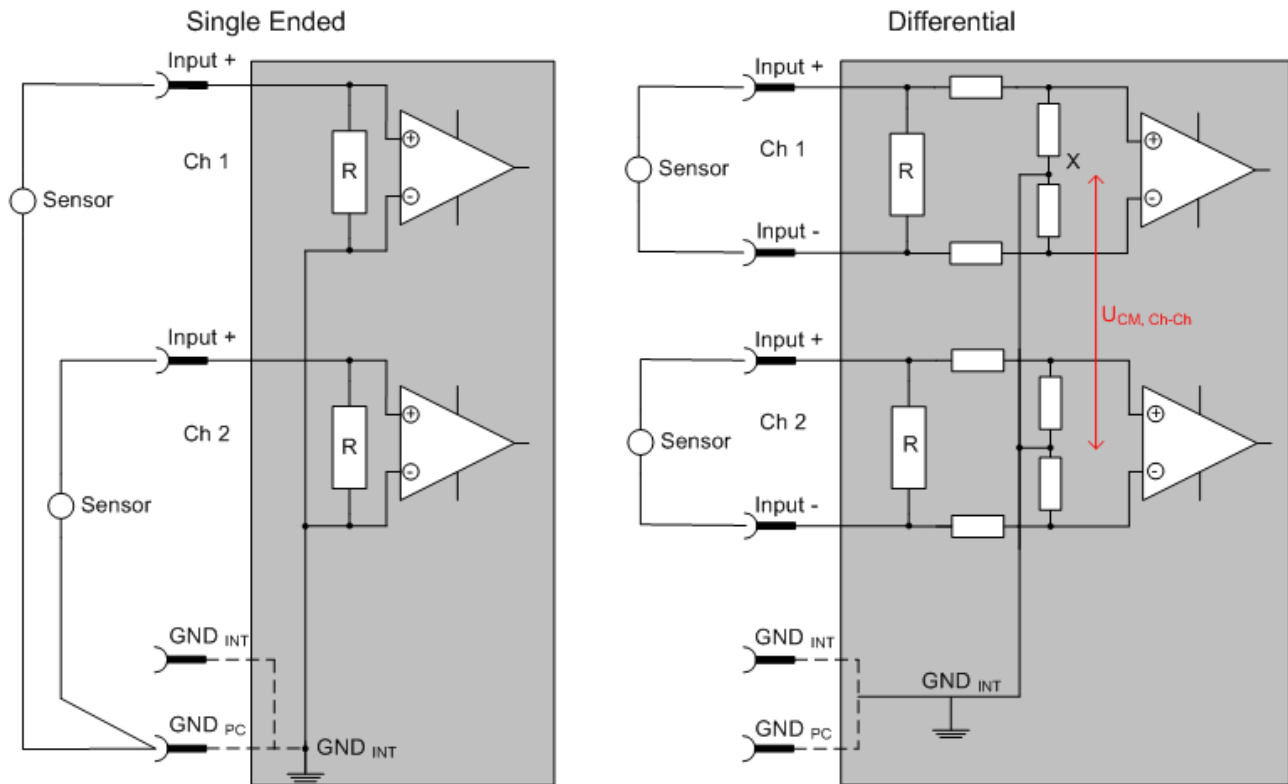


Fig. 32: SE and DIFF module as 2-channel version

Note: Dashed lines indicate that the respective connection may not necessarily be present in each SE or DIFF module. Electrical isolated channels are operating as differential type in general, hence there is no direct relation (voltaic) to ground within the module established at all. Indeed, specified information to recommended and maximum voltage levels have to be taken into account.

The basic rule

- Analog measurements always take the form of voltage measurements between two potential points. For voltage measurements a large R is used, in order to ensure a high impedance. For current measurements a small R is used as shunt. If the purpose is resistance measurement, corresponding considerations are applied.
 - Beckhoff generally refers to these two points as input+/signal potential and input-/reference potential.
 - For measurements between two potential points two potentials have to be supplied.
 - Regarding the terms “single-wire connection” or “three-wire connection”, please note the following for pure analog measurements: three- or four-wire connections can be used for sensor supply, but are not involved in the actual analog measurement, which always takes place between two potentials/wires. In particular this also applies to SE, even though the term suggests that only one wire is required.
- The term “electrical isolation” should be clarified in advance. Beckhoff I/O devices feature 1 to 8 or more analog channels; with regard to the channel connection a distinction is made in terms of:
 - how the channels WITHIN a module relate to each other, or
 - how the channels of SEVERAL modules relate to each other.

The property of electrical isolation indicates whether the channels are directly connected to each other.

- Beckhoff I/O devices always feature electrical isolation between the field/analog side and the bus/EtherCAT side. In other words, if two analog I/O devices are not connected via the power contacts (cable), they are effectively electrically isolated.
- If channels within a device are electrically isolated, or if a single-channel device has no power contacts, the channels are effectively always differential. See also explanatory notes below. Differential channels are not necessarily electrically isolated.
- Analog measuring channels are subject to technical limits, both in terms of the recommended operating range (continuous operation) and the destruction limit. Please refer to the respective device documentation for further details.

Explanation

• Differential (DIFF)

- Differential measurement is the most flexible concept. The user can freely choose both connection points, input+/signal potential and input-/reference potential, within the framework of the technical specification.
- A differential channel can also be operated as SE, if the reference potential of several sensors is linked. This interconnection may take place via the system GND.
- Since a differential channel is configured symmetrically internally (cf. Fig. SE and DIFF module as 2-channel variant), there will be a mid-potential (X) between the two supplied potentials that is the same as the internal ground/reference ground for this channel. If several DIFF channels are used in a module without electrical isolation, the technical property V_{CM} (common-mode voltage) indicates the degree to which the mean voltage of the channels may differ.
- The internal reference ground may be accessible as connection point at the device, in order to stabilize a defined GND potential in the device. In this case it is particularly important to pay attention to the quality of this potential (noiselessness, voltage stability). At this GND point a wire may be connected to make sure that $V_{CM,max}$ is not exceeded in the differential sensor cable. If differential channels are not electrically isolated, usually only one $V_{CM,max}$ is permitted. If the channels are electrically isolated this limit should not apply, and the channels voltages may differ up to the specified separation limit.
- Differential measurement in combination with correct sensor wiring has the special advantage that any interference affecting the sensor cable (ideally the feed and return line are arranged side by side, so that interference signals have the same effect on both wires) has very little effect on the measurement, since the potential of both lines varies jointly (hence the term common mode). In simple terms: Common-mode interference has the same effect on both wires in terms of amplitude and phasing.
- Nevertheless, the suppression of common-mode interference within a channel or between channels is subject to technical limits, which are specified in the technical data.
- Further helpfully information on this topic can be found on the documentation page *Configuration of 0/4..20 mA differential inputs* (see documentation for the EL30xx terminals, for example).

• Single-ended (SE)

- If the analog circuit is designed as SE, the input/reference wire is internally fixed to a certain potential that cannot be changed. This potential must be accessible from outside of the device on at least one point for connecting the reference potential, e.g. via the power contacts (cable).
- In other words, in situations with several channels SE offers users the option to avoid returning at least one of the two sensor cables to the device (in contrast to DIFF). Instead, the reference wire can be consolidated at the sensors, e.g. in the system GND.
- A disadvantage of this approach is that the separate feed and return line can result in voltage/current variations, which a SE channel may no longer be able to handle. See common-mode interference. A V_{CM} effect cannot occur, since the device channels are internally always 'hard-wired' through the input/reference potential.

Typification of the 2/3/4-wire connection of current sensors

Current transducers/sensors/field devices (referred to in the following simply as 'sensor') with the industrial 0/4-20 mA interface typically have internal transformation electronics for the physical measured variable (temperature, current, etc.) at the current control output. These internal electronics must be supplied with energy (voltage, current). The type of cable for this supply thus separates the sensors into *self-supplied* or *externally supplied* sensors:

Self-supplied sensors

- The sensor draws the energy for its own operation via the sensor/signal cable + and -. So that enough energy is always available for the sensor's own operation and open-circuit detection is possible, a lower limit of 4 mA has been specified for the 4-20 mA interface, i.e., the sensor allows a minimum current of 4 mA and a maximum current of 20 mA to pass.
- 2-wire connection see Fig. *2-wire connection*, cf. IEC60381-1
- Such current transducers generally represent a current sink and thus like to sit between + and – as a 'variable load'. See also the data of the sensor manufacturer.

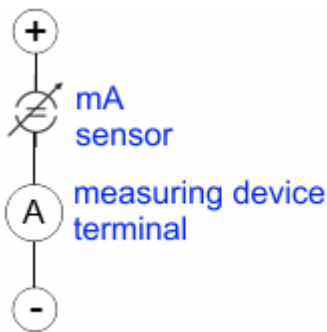


Fig. 33: 2-wire connection

Therefore, they are to be connected according to the Beckhoff terminology as follows:

preferably to **'single-ended' inputs** if the +Supply connections of the device are also to be used - connect to +Supply and Signal.

They can, however, also be connected to **'differential' inputs**, if the termination to GND is then manufactured on the application side – to be connected with the right polarity to +Signal and –Signal. It is important to refer to the information page *Configuration of 0/4...20 mA differential inputs* (see documentation for the EL30xx terminals, for example)!

Externally supplied sensors

- 3- and 4-wire connection see Fig. *Connection of externally supplied sensors*, cf. IEC60381-1
 - the sensor draws the energy/operating voltage for its own operation from two supply cables of its own. One or two further sensor cables are used for the signal transmission of the current loop:
 - 1 sensor cable: according to the Beckhoff terminology such sensors are to be connected to **'single-ended' inputs** in 3 cables with +/-/Signal lines and if necessary, FE/shield
 - 2 sensor cables: for sensors with 4-wire connection based on +supply/-supply/+signal/-signal, check whether +signal can be connected to +supply or –signal to –supply.
 - Yes: then you can connect accordingly to a Beckhoff **'single-ended' input**.
 - No: the Beckhoff **'differential' input** for +Signal and –Signal is to be selected; +Supply and –Supply are to be connected via additional cables.
- It is important to refer to the information page *Configuration of 0/4...20 mA differential inputs* (see documentation for the EL30xx terminals, for example)!

Note: expert organizations such as NAMUR demand a usable measuring range <4 mA/>20 mA for error detection and adjustment, see also NAMUR NE043.

The Beckhoff device documentation must be consulted in order to see whether the respective device supports such an extended signal range.

Usually there is an internal diode existing within unipolar terminals/ box modules (and related product groups), in this case the polarity/direction of current have to be observed.

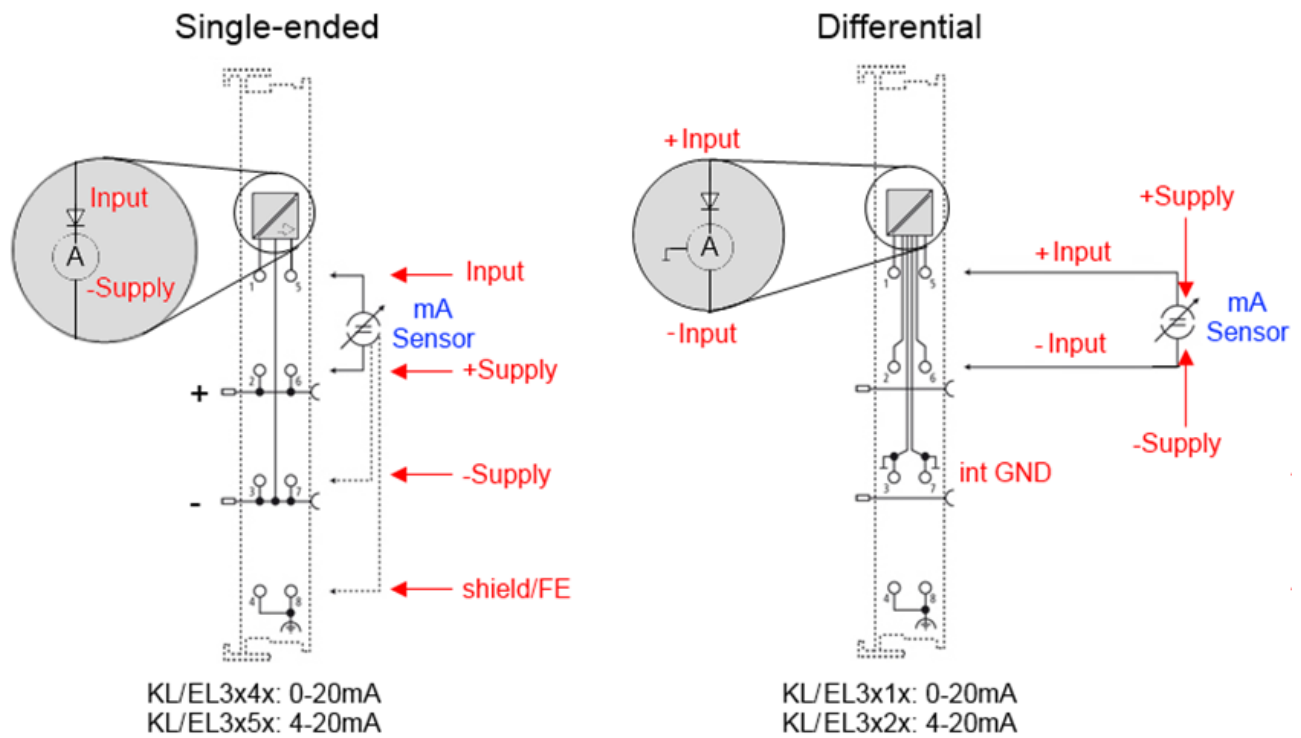


Fig. 34: Connection of externally supplied sensors

Classification of Beckhoff Terminals/ Box modules - Beckhoff 0/4-20 mA Terminals/ Box modules (and related product groups) are available as **differential** and **single-ended**:

Single-ended

EL3x4x: 0-20 mA, EL3x5x: 4-20 mA, same as KL and related product groups

Preferred current direction because of internal diode

Designed for the connection of externally-supplied sensors with a 3/4-wire connection.

Designed for the connection of self-supplied sensors with a 2-wire connection

Differential

EL3x1x: 0-20 mA, EL3x2x: 4-20 mA, same as KL and related product groups

Preferred current direction because of internal diode

The terminal/box is a passive differential current measuring device; passive means that the sensor is not supplied with power.

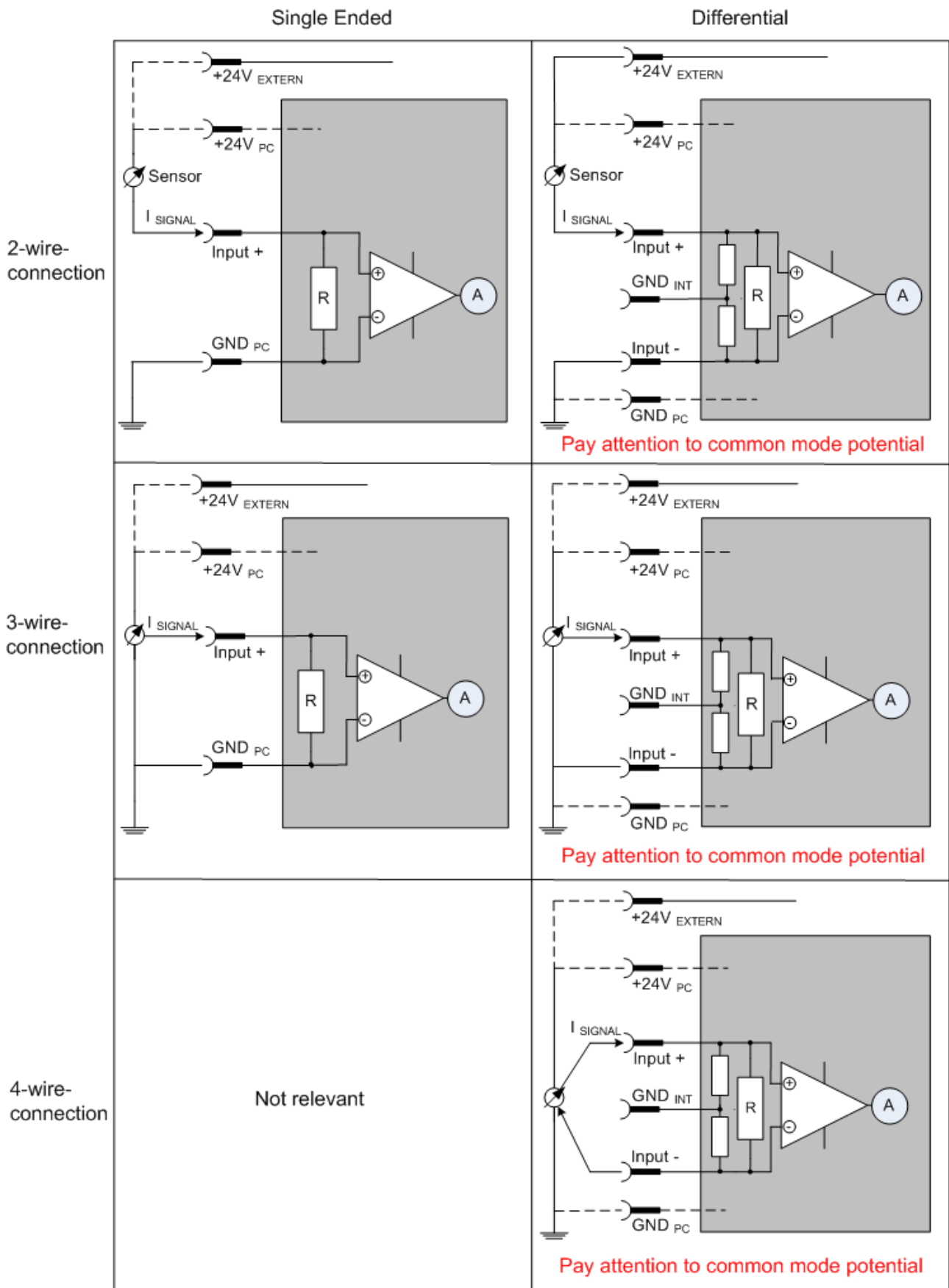


Fig. 35: 2-, 3- and 4-wire connection at single-ended and differential inputs

5.1.6 Common-mode voltage and reference ground (based on differential inputs)

Common-mode voltage (V_{cm}) is defined as the average value of the voltages of the individual connections/inputs and is measured/specified against reference ground.

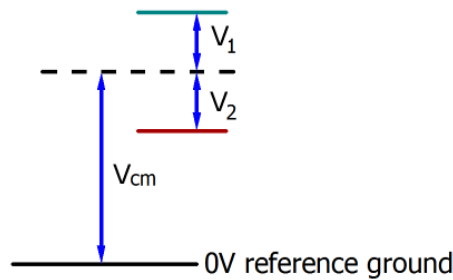


Fig. 36: Common-mode voltage (V_{cm})

The definition of the reference ground is important for the definition of the permitted common-mode voltage range and for measurement of the common-mode rejection ratio (CMRR) for differential inputs.

The reference ground is also the potential against which the input resistance and the input impedance for single-ended inputs or the common-mode resistance and the common-mode impedance for differential inputs is measured.

The reference ground is usually accessible at or near the I/O device. Locations for this can be terminal contacts, power contacts/power line or just a mounting rail.

Please refer to the documentation regarding positioning. The reference ground should be specified for the device under consideration.

For multi-channel I/O devices with resistive (= direct, ohmic, galvanic) or capacitive connection between the channels, the reference ground should preferably be the symmetry point of all channels, taking into account the connection resistances.

Reference ground samples for Beckhoff IO devices:

1. Internal AGND fed out: EL3102/EL3112, resistive connection between the channels
2. 0 V power contact: EL3104/EL3114, resistive connection between the channels and AGND; AGND connected to 0 V power contact with low-resistance
3. Earth or SGND (shield GND):
 - EL3174-0002: Channels have no resistive connection between each other, although they are capacitively coupled to SGND via leakage capacitors
 - EL3314: No internal ground fed out to the terminal points, although capacitive coupling to SGND

5.1.7 Dielectric strength

A distinction should be made between:

- Dielectric strength/current resistance (destruction limit): exceeding this limit can result in irreversible changes to the electronics, up to and including destruction.
 - against a specified reference ground
 - differential

Unless otherwise stated, the destruction limit refers to a permanent condition. Information on short-term tolerable overload can often only be given in individual or simple load cases, as general information usually requires a great deal of testing (How often does the case occur? How long is the recovery time afterwards? How high is the overload? Does it have a damaging effect, generate heat or something else?)

- Recommended operating voltage range/operating current range: If this is exceeded, operation in accordance with the specification can no longer be assumed; the value is also determined in this case
 - against a specified reference ground
 - differential

This value is always below the destruction limit.

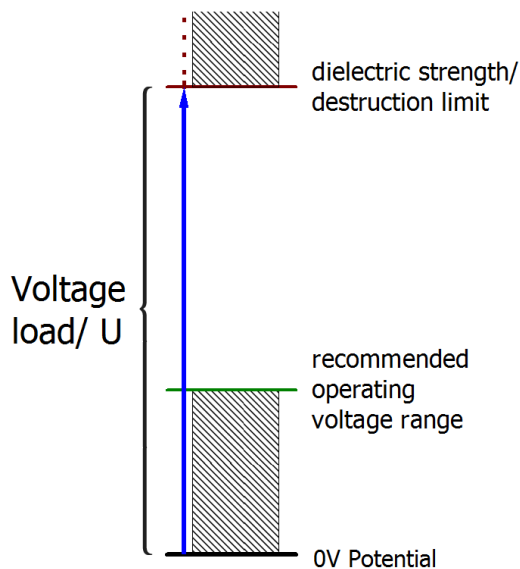


Fig. 37: Recommended operating voltage range

Special specification details can be provided in the device documentation, e.g. taking into account:

- Self-heating, ambient conditions
- Rated voltage
- Insulating strength
- Edge steepness of the applied voltage or holding periods
- Normative environment (e.g. PELV)

5.1.8 Temporal aspects of analog/digital or digital/analog conversion

● Analog output



The following information applies analogously to analog signal output via DAC (digital-to-analog converter).

The conversion of the constant electrical input signal to a value-discrete digital and machine-readable form takes place in the analog Beckhoff EL/KL/EP input modules with ADC (analog digital converter). Although different ADC technologies are common, from the user's point of view they all have one common feature: after the end of the conversion, a certain digital value is available for further processing in the controller. This digital value, the so-called analog process data, has a fixed temporal relationship with the “original parameter”, i.e. the electrical input value. Therefore, corresponding temporal characteristic data can be determined and specified for Beckhoff analogue input devices.

This process involves several functional components, which act more or less strongly in every AI (analog input) module:

- the electrical input circuit
- the analog/digital conversion
- the digital further processing
- the final provision of the process and diagnostic data for collection at the fieldbus (EtherCAT, K-bus, etc.)

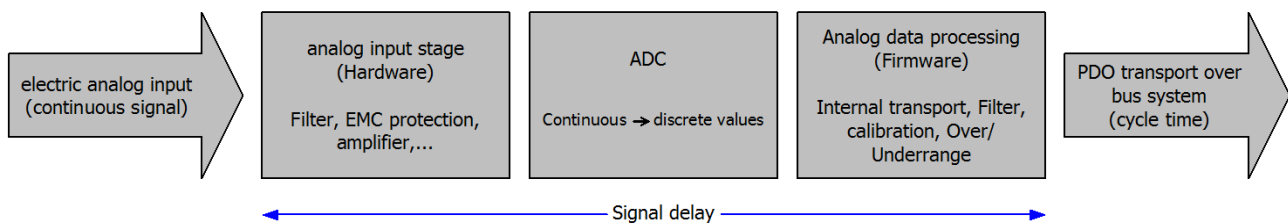


Fig. 38: Signal processing analog input

Two aspects are crucial from a user perspective:

- “How often do I receive new values?”, i.e. a sampling rate in terms of speed with regard to the device/channel
- What delay does the (whole) AD conversion of the device/channel cause?
So hardware and firmware parts in toto. For technological reasons, the signal characteristics must be considered to determine this specification: depending on the signal frequency, there may be different propagation times through the system.

This is the “external” view of the “Beckhoff AI channel” system – internally the signal delay in particular is composed of different components: hardware, amplifier, conversion itself, data transport and processing. Internally a higher sampling rate may be used (e.g. in the deltaSigma converters) than is offered “externally” from the user perspective. From a user perspective of the “Beckhoff AI channel” component this is usually irrelevant or is specified accordingly, if it is relevant for the function.

For Beckhoff AI devices the following specification parameters for the AI channel are available for the user from a temporal perspective:

1. Minimum conversion time [ms, µs]

This is the reciprocal value of the maximum **sampling rate** [Sps, samples per second]:

Specifies how often the analog channel provides a newly detected process data value for collection by the fieldbus. Whether the fieldbus (EtherCAT, K-bus) fetches the value with the same speed (i.e. synchronous), or more quickly (if the AI channel operates in slow FreeRun mode) or more slowly (e.g. with oversampling), is then a question of the fieldbus setting and which modes the AI device supports.

For EtherCAT devices the so-called toggle bit indicates (by toggling) for the diagnostic PDOs when a newly determined analog value is available.

Accordingly, a maximum conversion time, i.e. a smallest sampling rate supported by the AI device, can be specified.

Corresponds to IEC 61131-2 Chap. 7.10.2 2, "Sampling repeat time"

2. Typical signal delay

Corresponds to IEC 61131-2, Chapter 7.10.2 1, "Sampling duration". From this perspective it includes all internal hardware and firmware components, but not "external" delay components from the fieldbus or the controller (TwinCAT).

This delay is particularly relevant for absolute time considerations, if AI channels also provide a timestamp that corresponds to the amplitude value – which can be assumed to match the physically prevailing amplitude value at the time.

Due to the frequency-dependent runtime of a signal, a dedicated value can only be specified for a given signal. The value also depends on possibly changing filter settings of the channel.

A typical characterization in the device documentation can be:

2.1 Signal delay (step response)

Keyword settling time:

The square wave signal can be generated externally with a frequency generator (note impedance!).

The 90% limit is used as detection threshold.

The signal delay [ms, µs] is then the time interval between the (ideal) electrical square wave signal and the time when the analog process value has reached the 90% amplitude.

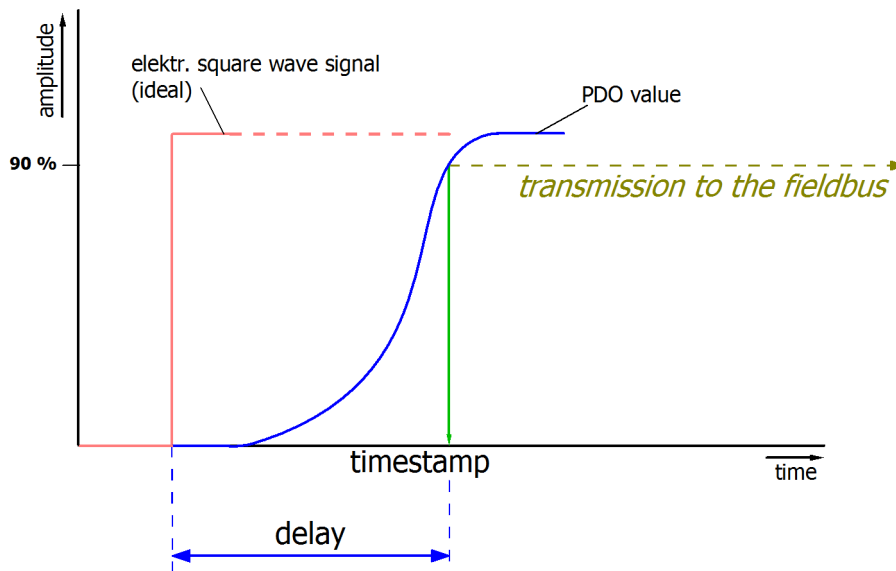


Fig. 39: Diagram Signal delay (step response)

2.2 Signal delay (linear)

Keyword group delay:

Describes the delay of a frequency-constant signal

Test signal can be generated externally with a frequency generator, e.g. as sawtooth or sine. Reference would then be a simultaneous square wave signal.

The signal delay [ms, µs] is then the time interval between the applied electrical signal of a certain amplitude and the moment when the analog process value reaches the same value.

For this purpose, the test frequency must be selected in a reasonable range; this can be, for example, 1/20 of the maximum sampling rate.

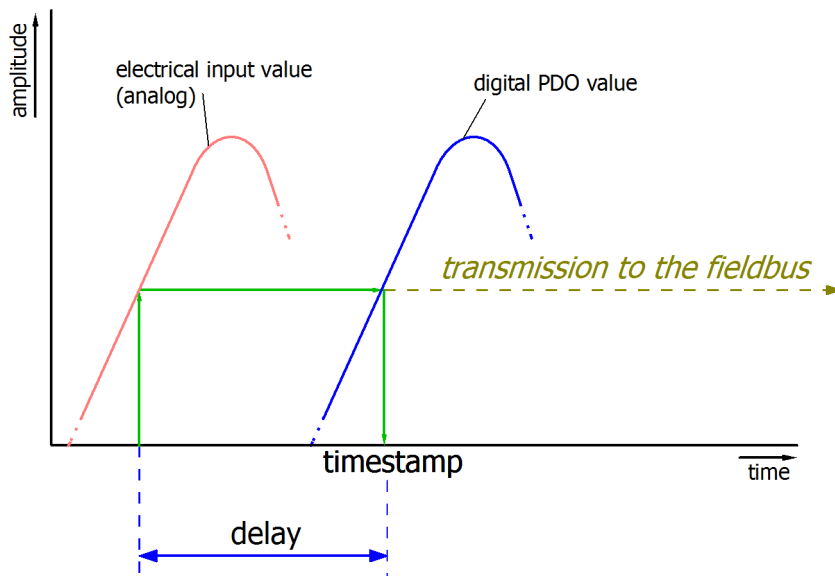


Fig. 40: Diagram Signal delay (linear)

3. Additional information

Additional information may be provided in the specification, e.g.

- actual sampling rate of the ADC (if different from the channel sampling rate)
- time correction values for runtimes with different filter settings
- etc.


5.1.9 Explanation of the term GND/Ground

I/O devices always have a reference potential somewhere. After all, the working voltage is only created by two points having different potentials – one of these points is then called the reference potential.


In the Beckhoff I/O area and in particular with the analog products, various reference potentials are used and named. These are defined, named and explained here.

Note: for historical reasons, different names are used with various Beckhoff I/O products. The following explanations place them on a uniform foundation.

SGND

- Also called: FE, Functional Earth, Shield GND, Shield.
- Use: Dissipation of interference and radiation, predominantly currentless.
- Symbol: .
- Notes and recommendations on SGND/FE can be found in the separate Analog Manual in the chapter "Notes regarding analog equipment - shielding and earth".
- SGND usually ends at the structural earth star point.
- In order to be usable for its intended purpose, SGND itself should be a low noise/noise-free "clean" current and voltage sink.


PE

- Also called: Protective Earth.
- Use: Protective measure to prevent the occurrence of hazardous touch voltages by dissipating these touch voltages and then tripping upstream protective devices. If installed correctly, the PE conductor is currentless, but according to specification it must be capable of conducting for the protection case.
- Symbol: .
- PE usually ends at the structural earth star point.
- For specifications and notes on PE, please refer to the relevant rules.

PGND, AGND

- Use: Reference ground or return line of analog or digital signals.
- Depending on use, nominally currentless as reference potential or conducting as return line.
- In the analog area, the so-called standard signals can be 0...10 V and 4...20 mA, measuring bridge signals and thermocouples can be in the range of a few mV and resistance measurement in any Ohm range, and voltages can be from μV to a few thousand Volts.
- In the digital area they can be, for example, 0/24 V, -5/+5 V etc.

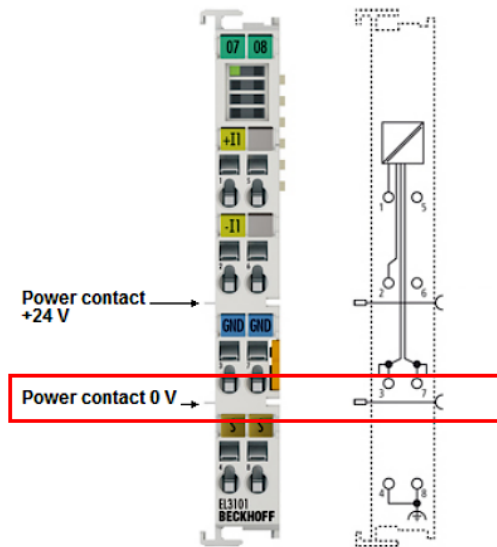
- Symbols:

preferred: .

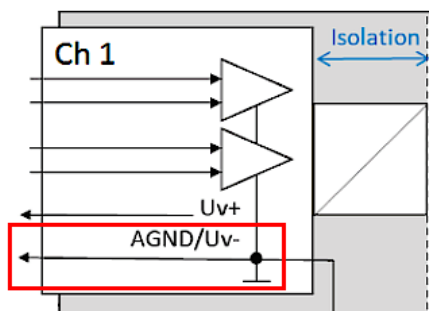
hardly used any more, but actually means earth potential: .

- There may be several PGND/AGND networks in a system that are electrically isolated from one another.
- If a device has several AGNDs, due to isolation by channel, these can be numbered: AGND1, AGND2, ...
- PGND
 - also called: GND_{PC} , 0 V, power contact 0 V, “-“ (opposite to this positive power contact: “+”).
 - Version: PGND is a structural description of the "negative" power contact rail of the Bus Terminal system.

- Can be connected to the device electronics, for example for supplying power to the device or as a signal feedback (see chapter [Ground reference: single-ended/differential typification \[► 89\]](#)). Refer to the respective device documentation.
- Example: PGND is not connected to the device electronics (the analog signal refers to a separate AGND):



- AGND
 - Also called: GND_{int} , GND, analog ground, GND_{analog} .
 - AGND electrically designates the device's analog reference ground.
 - AGND can, for example, be internally connected to PGND or to a connection point so that it can be connected externally to a desired potential. Electrical restrictions according to the device documentation must be observed, e.g. common mode limits.
 - AGND is usually a currentless reference potential. The action of interference on AGND must be avoided.
 - Example: AGND is fed out on the device plug:



5.1.10 Sampling type: Simultaneous vs. multiplexed

Analog inputs and outputs in Beckhoff devices can operate in two different ways in terms of time: "simultaneous sampling" or "multiplex sampling". This so-called sampling type has a decisive influence on the performance of such a device and must be taken into consideration when selecting a product, at least when it comes to very complex timing control tasks. Whether an analog device operates simultaneously or multiplexed can be taken from the respective device documentation.

This question is relevant for control tasks as well as for measurement tasks (DataRecording), if the timing of the analog value acquisition is sensitive.

Note: The terms "simultaneous" and "multiplex" have been used for a long time and in many contexts, so they have different meanings depending on the historical background and the subject area. In this chapter and in relation to I/O, the terms are used as Beckhoff understands them as an I/O manufacturer for the benefit of the user:

- If a test signal is applied electrically to all channels of a multi-channel device at the same time and the measurements are evaluated in software, e.g. in TwinCAT Scope, and if no significant offset/delay can be observed between the channels, then it is a **simultaneously sampling device** ¹⁾
- If an offset can be seen, it is a **multiplex sampling device**
- The easiest **test** to perform is with a square wave signal because an offset can then be easily observed. However, the rare special case could occur (especially if the test signal is generated from an EL2xxx/EL4xxx from the same IO line) that the square wave signal runs synchronously to the EtherCAT for several minutes and then no offset can be seen.

Absolutely safe is a test with a sinusoidal signal, but then it must be considered that measurement deviations (related to the amplitude) of the channels in the device are also represented as time offset!

Ideally, one should concentrate on the zero crossing.

- 1-channel devices are considered as simultaneous sampling by definition.

Explanation with the example "analog input": if a continuous analog signal is to be digitized and thus fed to the further programmatic processing, it is digitized by a so-called ADC (AnalogDigitalConverter), e.g. with 16 bit resolution:

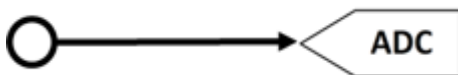


Fig. 41: Schematic representation of sampling with ADC converter

This represents an analog input channel that is functional in itself. It samples (measures) as often as desired, e.g. 1,000 times per second, and thus sends 1,000 measured values equidistant in time (= at equal time intervals) for further processing.

Often several channels are combined in one device, in this case the question arises about the sampling type: simultaneous or multiplex.

¹⁾ For experts: such a device could also be equipped with a multiplexing ADC, which works with sample-and-hold on all channels. Then technically multiplex is built in, but from the outside the device works simultaneously, because all channels are electrically read in at the same time.

Simultaneous

As in the 1-channel example, each channel can have its own ADC, shown here for 4 channels:

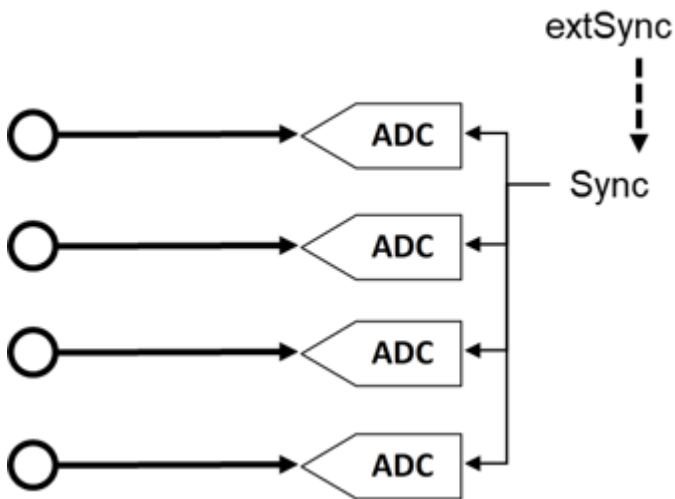


Fig. 42: Schematic representation simultaneous sampling with 4 ADC converters

These ADCs rarely run free in time and sample independently but are normal triggered in some way (the measurement is triggered) to achieve the most desired effect that the n channels sample simultaneously. This gives the analog input device the property that all (4) measurements are obtained at the same time. This gives a temporally consistent view of the machine situation and makes measurement evaluations in the controller very easy. If the ADC are triggered simultaneously by the sync signal, this is called simultaneous sampling.

A special added value arises when such devices are synchronized externally, e.g. via EtherCAT DistributedClocks, and then all analog channels of all devices of a plant operate simultaneously: either really simultaneously without offset among each other or with the same frequency but with constant, known and thus compensatable offset among each other.

As shown above, this requires extensive electronics with multiple identical structures. For this reason, parallel analog devices are usually always simultaneously sampling. Free-running or non-triggered, multiple ADCs are conceivable (and can then no longer be called "simultaneous"), but are rather uncommon.

Multiplex

Simultaneous sampling is often not required for simple automation tasks. This may be because the simplest analog electronics are to be used for cost reasons, or the control cycle time is relatively slow compared to the conversion time in the ADC. Then the advantages of the multiplex concept can be used: Instead of 4 ADC only one ADC is installed, for this a channel switch (from the device manufacturer) must be installed, which switches through the 4 input channels to the ADC quickly one after the other in the μs range. The switching process is performed by the device itself and is usually not accessible from the outside.

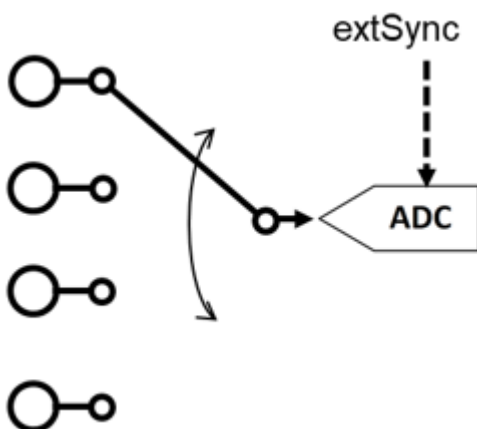


Fig. 43: Schematic representation of multiplex sampling with an ADC converter

This is therefore a time multiplex. As a rule the ADC samples equally clocked, the time intervals of the channels are therefore equal, whereby the start of channel 1 is usually done by the communication cycle (EtherCAT) or DistributedClocks. For further details please refer to the device documentation.

Advantage: cheaper electronics compared to simultaneous setup.

Disadvantage: the measured values are no longer acquired simultaneously, but one after the other.

Both circuits have their technical and economic justification, for time demanding automation tasks simultaneous circuits should always be chosen, because with them it is easier to keep the temporal overview.

For analog outputs the same explanations apply, they can also be equipped with multiple simultaneous DACs or output a multiplexed DAC to several outputs.

5.2 Notes regarding analog equipment - shielding and earth

Meticulous application of the term “earth” is required, particularly when it comes to reliable use of analog (measuring) signals. The conductive coupling of different potentials, such as earth potential and a housing potential or the earth points of analog devices, can have different aims:

1. Earthing as protective measure against the occurrence of dangerous touch voltages (PE)
2. Earthing for definition of a common signal potential, in order to ensure the function of analog measurements, for example
3. Earthing for discharging of interference or internally generated emissions (FE); keywords: interference immunity and interference emission


In each case the user should be clear which of the above aims is to be achieved through the respective measures. The respective reference earth can have different potential!


The observations, measures and effects described below primarily refer to 3. “FE/functional earth”, taking into account the requirements of 2. “Common reference potential”. Information and specifications relating to 1. “PE” can be found in the relevant guidelines, such as VDE0100, and is not part of this section on analog equipment. The focus and application area of the following notes is for the scope of analog signal transmission.

● The terms “protective earth” and “functional earth”



This section primarily deals with functional earth (FE,

symbol: ) as a functionally relevant regular part of an installation, in contrast to protective

earth (PE, symbol: ), which is intended to protect persons from excessive touch voltages.

● This document



This document provides general recommendations based on practical experience, without taking into account specific features of particular installations. These recommendations should be regarded as a collection of technical solution options. System manufacturers should check to what extent the measures described here are applicable to their system, and which of the suggested measures should be implemented. To this end, different measuring and testing techniques should be used. Any problems should be examined thoroughly, in order to ascertain the trigger and the fault location.

This document attempts to deal with a complex issue and does not claim to be exhaustive. We gladly accept suggestions or critical comments.

● Lightning protection



Lightning protection aspects are not considered.

● Potentially explosive areas



Special regulations and procedures may apply for potentially explosive atmospheres and supply lines for such areas, which are not covered by this documentation.

● Reference to individual documents



Special instructions and documentation relating to the devices used must be followed.

Recommended procedure in the event of a conspicuousness

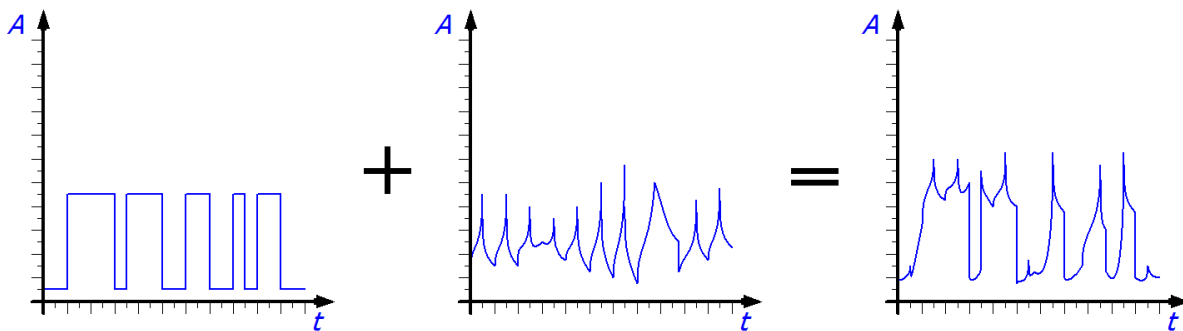
1. Use this document, other publicly available documents/standards and manufacturer documentation to familiarise yourself with the background and practical characteristics of EMC interference. Reflect on the mechanism of action between source of interference → transfer path → interference sink.
2. Use the specified diagnostic methods to isolate the interference sink, i.e. the location/device that does not work properly

3. Reflect on how the fault could have occurred, taking into account the background information from section 1.
4. Use the information and solution proposals provided to weigh up system-specific options or normative specifications/restrictions. We recommend to only change one component at a time, in order to verify the effectiveness of the respective measure.
5. At the same time, use the specified diagnostic methods to ascertain whether the source of interference or the transfer path has been found.

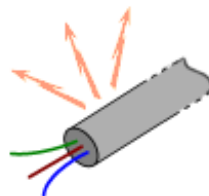
Functional chain: source of interference – coupling – interference sink

The undesirable effect of a source of interference on an interference sink via the coupling can be reduced or completely suppressed through the measures described below. A fault results in modification of a wanted signal. In the worst case, the recipient of the wanted signal is no longer able to interpret the information content, or its operation is disturbed due to the modified amplitude/frequency or even electrical damaged.

The fault can be transferred by wire or by radiation.

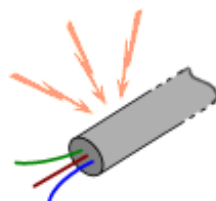


A device can simultaneously act as source of interference and as interference sink (depending on the effective direction).



A cable/device acts as **source of interference** through strong/weak interference effect (emissions, interference emission) due to (e.g.)

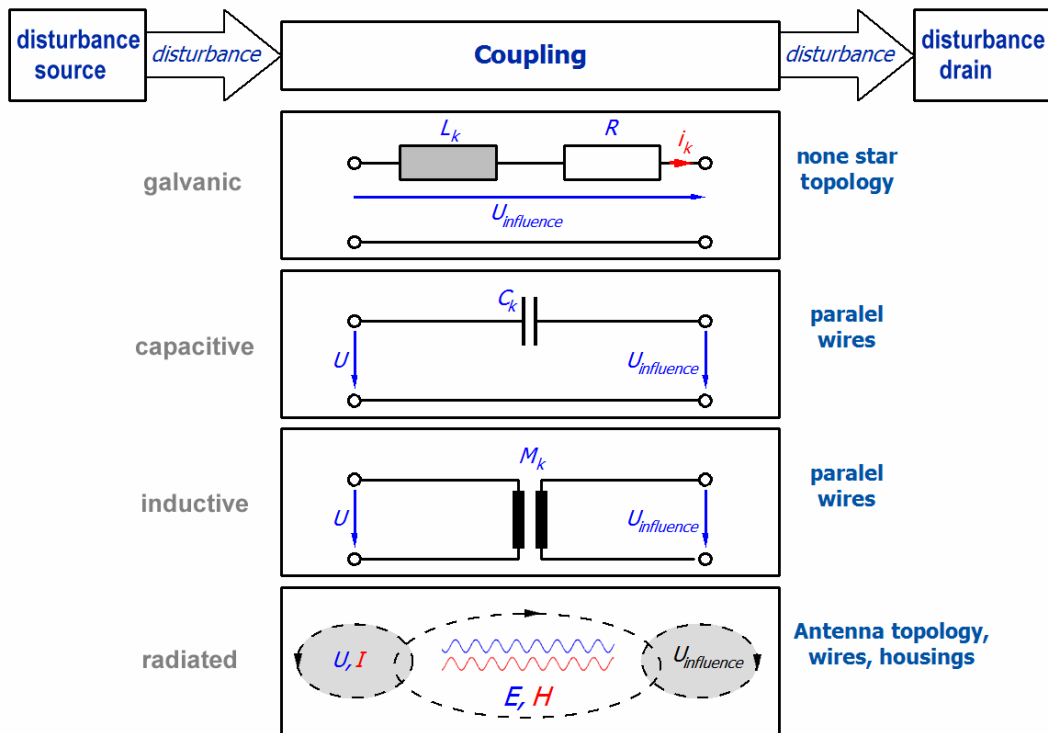
- strong/weak interference effect through emissions, i.e. interference emissions
- insufficient suppression through shielding, chokes, filters
- insufficient avoidance through discharge facilities, spark gaps, incorrectly dimensioned termination resistors



A cable/device acts as **interference sink** through strong/weak susceptibility to interference, i.e. inadequate immunity to interference due to (e.g.)

- missing or inadequately implemented protection components: shielding, compensating elements, discharge facilities, spark gaps

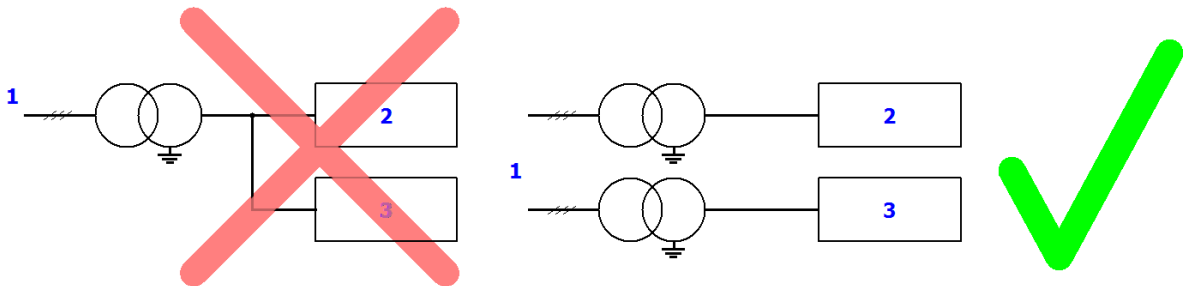
In general, the following mechanisms are available for coupling a fault with the wanted signal:



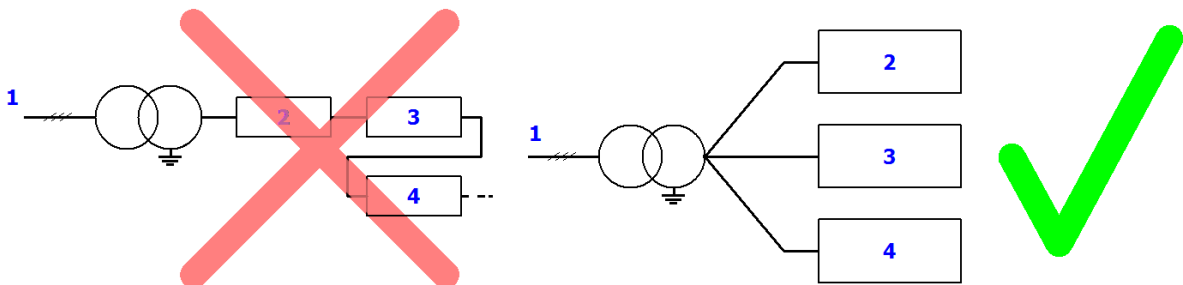
Shielding measures or interference generation prevention may be applied as remedial action.

Galvanic coupling – measures against transfer:

- Separation of different potentials, avoidance of equalising currents



- Star wiring, no ladder network



Capacitive coupling – measures against transfer:

- Spatial separation

- Full, close-meshed shielding of the signal cable without interruption or holes. Holes in the sense of this documentation are uncovered areas of the order of centimetres. Significant signal components can be emitted or unintentionally received from a hole with a size of 10 % of the wavelengths.
- Single-sided, low-impedance connection of the shielding to system earth

Inductive coupling – measures against transfer:

- spatial separation
- Shielding, see capacitive coupling
- Two-sided, low-impedance connection of the shielding to system earth
- Equidirectional, tight twisting (high twisting rate) of the analog signal cables with each other

Wireless coupling - measures:

- Short cable lengths
- Shielding, see capacitive coupling

Common signal potential, basic measures and notices

In some applications the reference potentials of different devices have to be linked, e.g. in order to be able to perform a measurement.

- Usually, no equalising currents should flow via such connections – for remedial measures see the following section.
- Buffer amplifiers may have to be used in some cases
- Potential-free connections on the device side may be suitable in some cases – note the permitted potential difference!

FE/shielding, basic measures and information

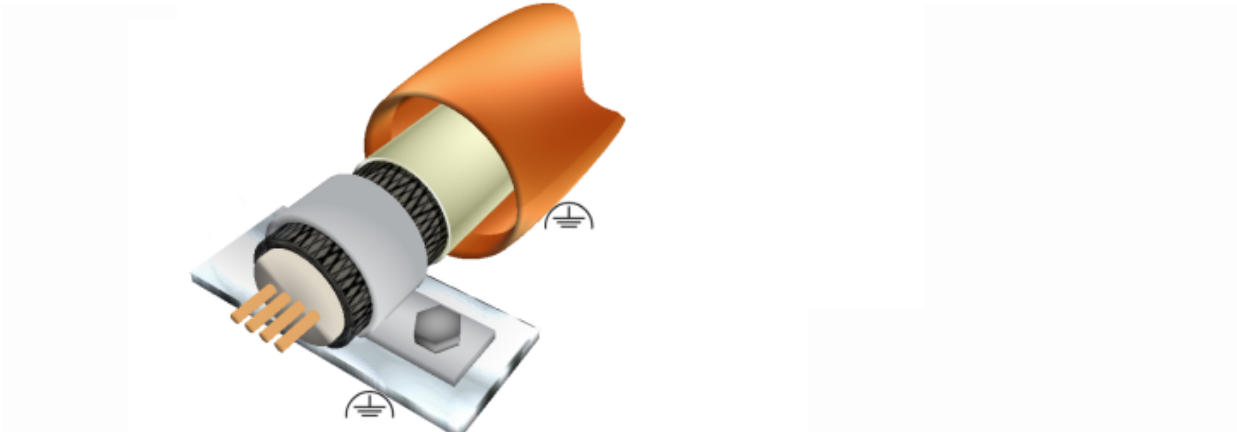
A list of exemplary measures, taking into account the information provided above, which may be considered in order to reduce interference, is provided below.

- Temporal effectiveness: the effectiveness of implemented measures may reduce over time and should therefore be checked regularly, particularly in the event of anomalies. Negative influencing factors include broken wire, oxidation at contact points, mechanical damage, change in earthing characteristics, change in environment (new interference sources?), etc.
- Selected reference potential
 - The reference potential used for discharge/earthing may itself be subject to interference, so that a connection to it may introduce more interference in the system than it discharges. In this case, a different, low-interference reference potential should be used.
 - To ensure good discharge, it may be helpful to install a separate FE earthing point in the building and use it for sensitive signals/shielding. Caution in the event of lightning strike: a lightning strike in the vicinity can result in large potential differences between buildings and earth, which can affect locally separated earthing equipment. Spark gaps may be able to prevent equipment damage. VDE guidelines must be followed!

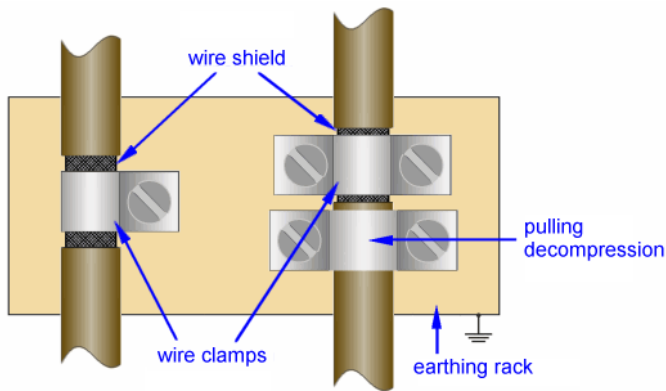
Wanted signal routing

- Cable routing
 - The cable connections should be as short as possible
 - The denser the cables can be laid over a metallic area/equipotential bonding, the less interference can be introduced, and the more interference is discharged capacitively via earth.
 - Analog signal cables that are susceptible to interference and load cables with strong interference potential:
 - parallel installation, with a distance of at least 20 cm from each other
 - avoid parallel installation
 - unshielded cables should be twisted, if possible

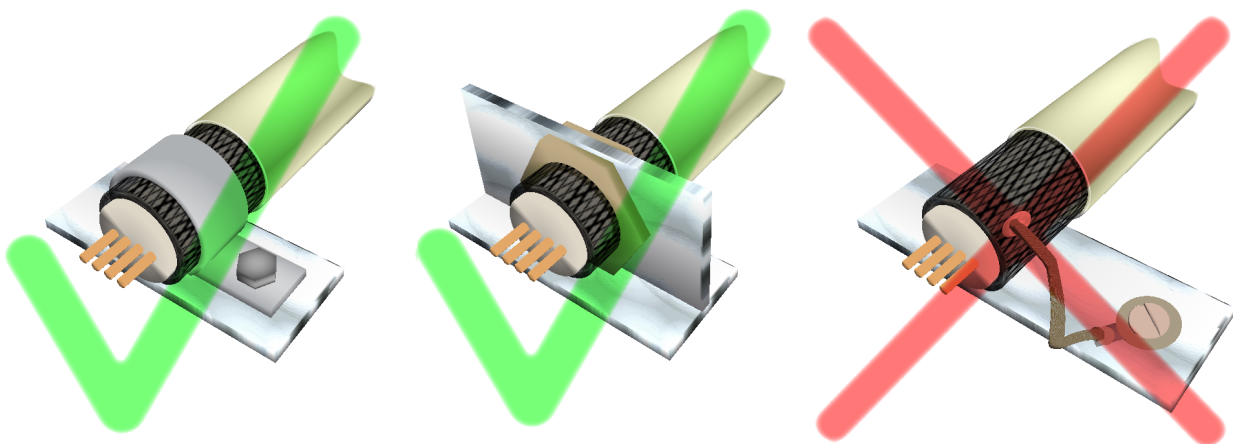
- provide shielding through metallic isolating strips
- Use wire end sleeves or cable sockets to connect flexible cables/strands. Tinning is no longer permitted.
- Unused wires/cables should be earthed on one side as a minimum.
- Shielding
 - Shielding must not be used to function as N or PE conductor. Functional earth intended for improving EMC (electromagnetic compatibility) must not be used as protective earth according to VDE 0100.
 - The shielding should not be used to carry discharge/fault currents.
 - Some connection technologies as coax requires signal ground and shield on the same conductor. This can be disadvantageous in specific environments. So it should be checked, if another connection method can be used that provides a separate shield as e.g. triax.
- Shield configuration
 - If braided screen is used, it should consist of tin-coated/nickel-plated copper. Aluminium braid may be suitable, provided the specific properties are taken into account.
 - For cables shielded with braid, the cover should be 60% to 95%.
 - In special cases magnetic shielding using magnetically conductive, highly permeable material may be required.
 - Cable shielding may consist of braid and/or electrically conductive foil. The use of foil on its own is inappropriate, since it can easily be interrupted.
 - Contacting of the electrically conductive foil alone for the purpose of shield coupling is not permitted; the braiding must be contacted. Amongst others, the contacting of the electrically conductive foil confects a too low galvanic coupling and is moreover mechanical less resistant.
 - Earthed metal tubes used for shrouding cable can offer additional shielding



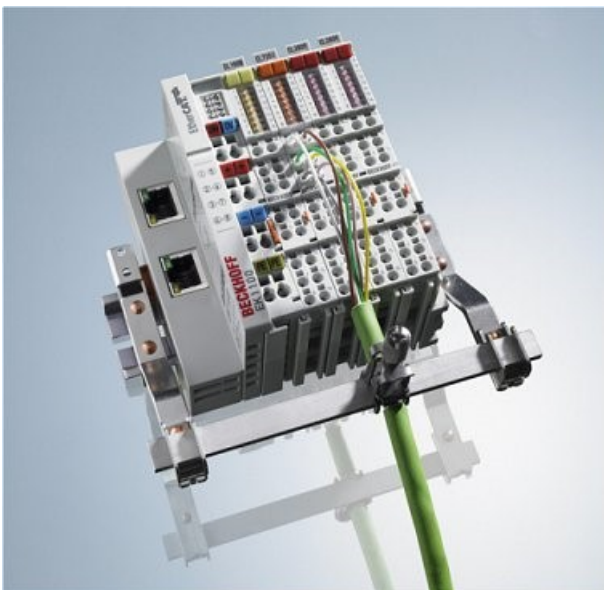
- Shield connection
 - For discharge purposes, a “good connection” should be aimed for, i.e.
 - low-impedance connection → cross-section as large as possible, fine-wired, perhaps earthing strap
 - short cables
 - large-area contact, perhaps EMC gasket
 - 360°, if possible
 - metallic conductive components without contaminants, lacquer, fat, oxide layer



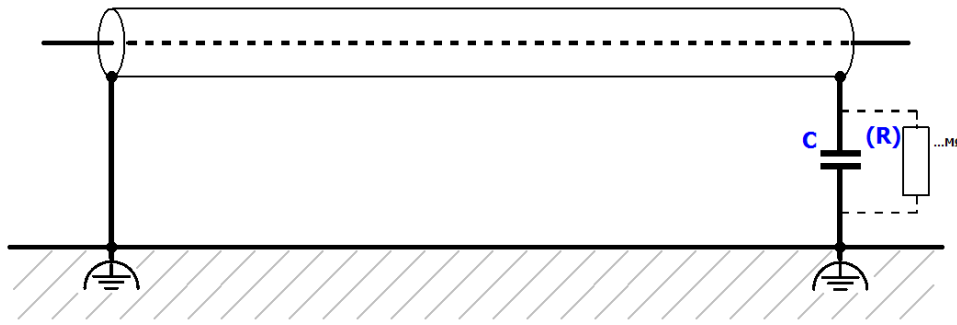
- Pig tails (braid twisted at the end or wire attached to the braid) significantly reduce the effectiveness of the shield coupling. It's strictly recommended not to use it – particularly with regard to increased immunity to interference requirements.



Beckhoff offers the ZB8500 shield connection system for this purpose. And also see section “Shielding concept”.



- Hum interference may occur if several cables that are connected on both sides run between two devices (“earth loop”). However, opening of the shield on one side can significantly reduce the shield effectiveness. A better solution is coupling of the respective shield on one side via a coupling capacitor ($C = 10.. 100\text{nF}$, bipolar). This provides separation for DC, while currents from HF influence can still be discharged.



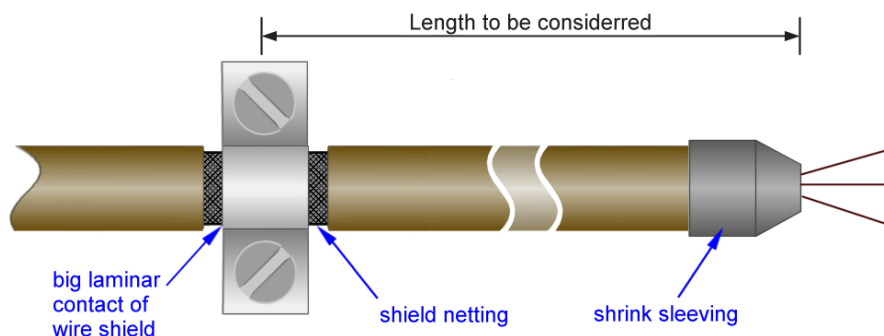
The coupling capacitor C must have adequate dielectric strength. In some situations it may be advisable to connect a resistance R in the MΩ range parallel to the capacitor.

⚠ CAUTION

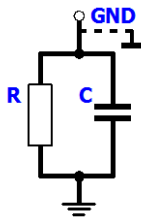
Potentially explosive atmospheres

Note special regulations for potentially explosive atmospheres!

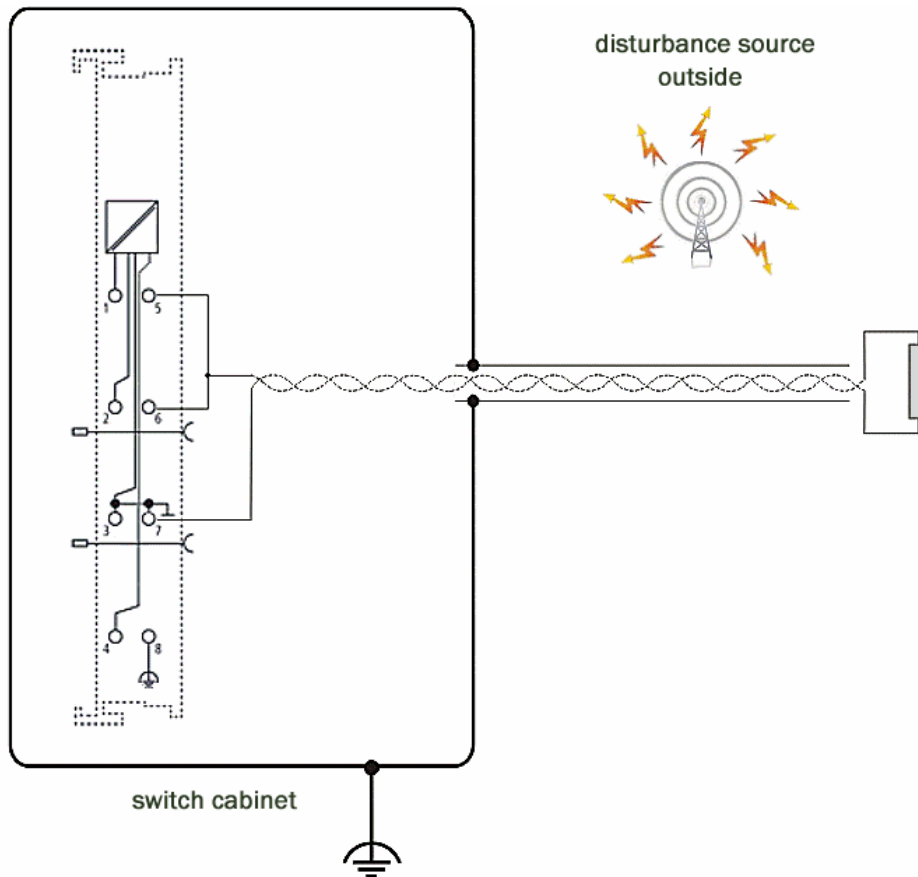
- If the shielded cable continues after the shield contact, the further free cable length under shielding should be no longer than a few segments of 10 cm. This also applies to cables within control cabinets.



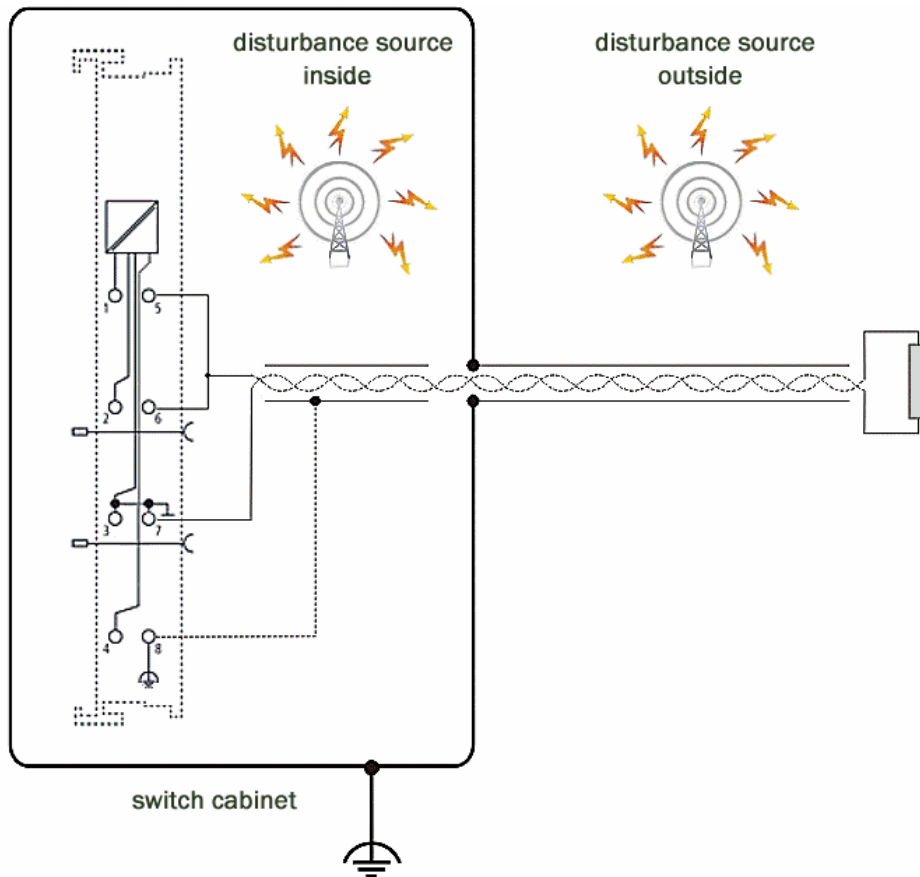
- Manufacturers sometimes equip devices with an RC combination between earth and PE. On the one hand this can achieve good discharge capacity for HF interference, on the other hand the device may not be damaged inadvertently through high leakage currents. Such an RC combination on the device side as connection between earth and PE counts as earth-free coupling.



- A high-resistance resistor prevents excessive leakage currents. The capacitor short-circuits high-frequency peaks with low impedance. A specified dielectric strength applies for the combination. Good interference protection can be achieved if a shielded cable is laid completely earth-free (only RC connection on both sides).
- If a shielded cable has a drain wire, connection of this conductor to the shield coupling only is inadequate. At the cable end the shield and the drain wire should be connected together at the designated shield point.
- Connection of the shielding with sources of interference - only expected outside the control cabinet
 - Apply the shielding at the control cabinet entry
 - Continuation of the shielding within the control cabinet may not be necessary

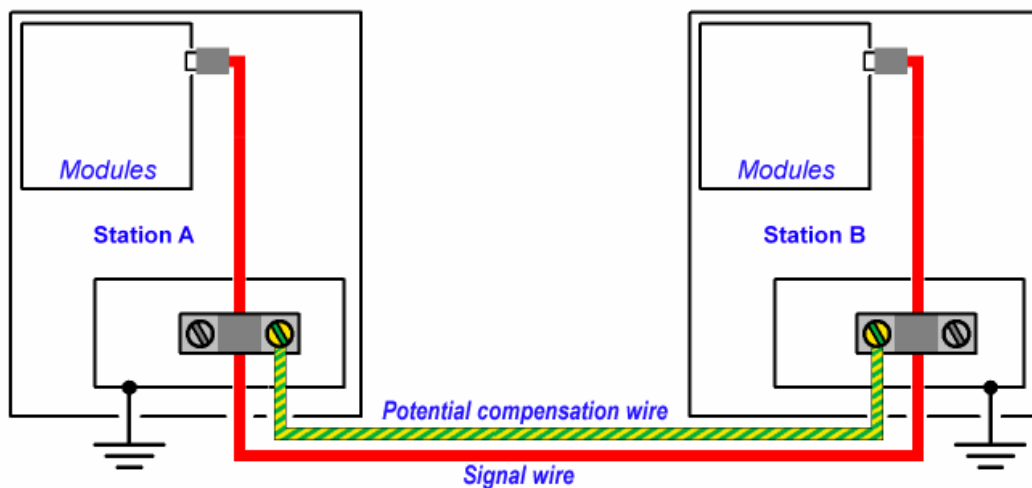


- Connection of the shielding with sources of interference - also expected inside the control cabinet
 - see: notices on control cabinet design
 - The shielding should be opened after the entry into the control cabinet, applied and then continued up to the terminal. At the device it should be contacted again (terminal contact or separate shield coupling).



Equalisation of potential difference

- If signal or communication lines are run over longer distances, the installation should be checked for potential differences. Example: ribbon conductors in a wind turbine tower. To prevent equalising currents in the shielding:
 - suitable equipotential bonding conductors can be provided
 - optical fibre can be used
 - buffer amplifiers can be used

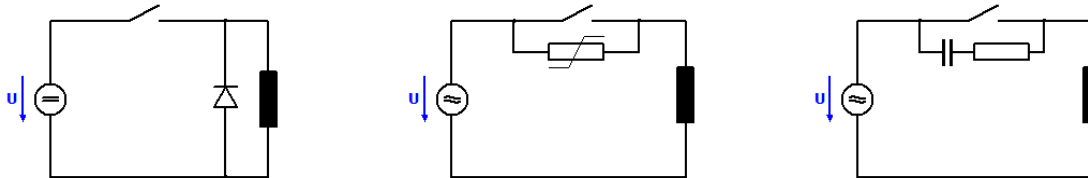


- The equipotential bonding conductor should be fine-wired, so that it has a large surface area to ensure effectiveness for high-frequency interference currents. In addition, compliance with the minimum diameters according to IEC 60364-5-54 is required
 - copper 6 mm²
 - aluminium 16 mm²
 - steel 50 mm²

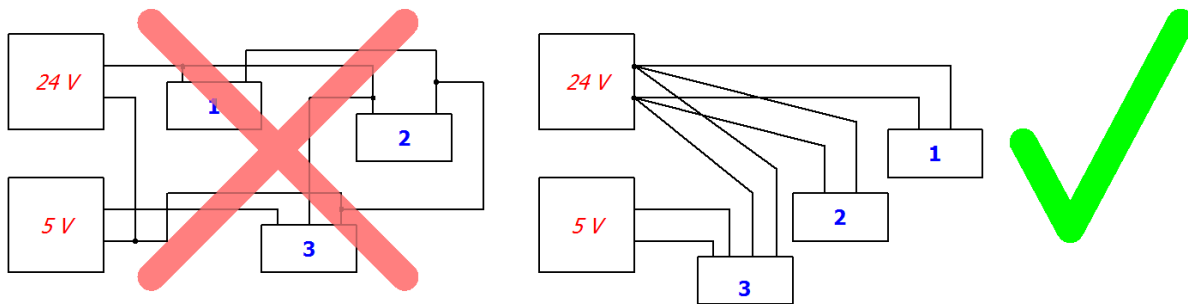
- The earthing system should have a star configuration.
- The PE connection replaces neither HF earthing nor the shielding, but is required for safety reasons.
- Lightning protection may have to be provided.
- Atmospheric influences can lead to significant potential shifts.

Additional safety measures

- For connected inductors and capacitors protective circuits/extinguishing equipment must be provided on the device side, in order to prevent voltage peaks as long the connected device does not already support such a performance.



- Filter components against interference emission should be used if necessary, e.g. in the form of current-compensating chokes or toroidal core ferrites
- Pick up the power supply for the measuring equipment in a star shape from the central supply source. Lay the feed and return wire together side by side



- Thermoelectric effects in the mV range could have a disturbing effect to analog signals and also
 - Avoid potential differences between different materials
 - Check the temperature or material, if necessary

Practice-oriented diagnostic methods for system examination

The following section lists some options for checking the effectiveness of shielding measures:

- Visual inspection
- Acoustic inspection (listen for voltage flash-overs)
- Voltage measurement with voltmeter between suspect system points
- Monitoring of voltages on shielding conductors with an oscilloscope that is suitable for high frequencies
- Current measurement of equalising currents on the shielding cable with a clamp-on ammeter. The current on the shielding should not exceed a few milliamps (True RMS).
- Continuity measurement of the shielding and checking for unacceptable shunt
- Temperature measurement of surge arresters; the contact point will warm up in the presence of high current passage and high contact resistance

5.3 Notes on analog aspects - dynamic signals

This chapter deals with the problem of measurement/acquisition of actual analog electrical signals from the industrial automation environment. Such signals are generated by sensors and measured by automation components. With this information, the (software-based) control system perceives the physical system reality and derives follow-up actions from it.

The signals are formed electrically and measured analogously as

- signals via industrial interfaces 10 V, 20 mA, ...
- signals from the sensor directly: voltage of a battery [V], bridge signal [mV/V], current measurement [A], resistance [Ω]...

Signals that do not have to be measured electrically but are already present virtually in the control system can also be analyzed with the tools listed below but are not the focus of this document.

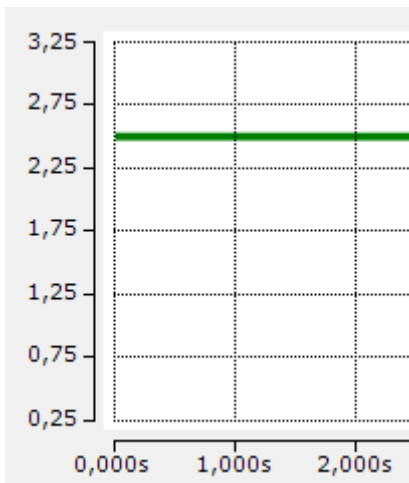
Introduction

This chapter deals with the usual "circumstances" of real analog sensor signals in industrial environments, which are considered "over time", in the course of which information is transmitted to the controller in the form of

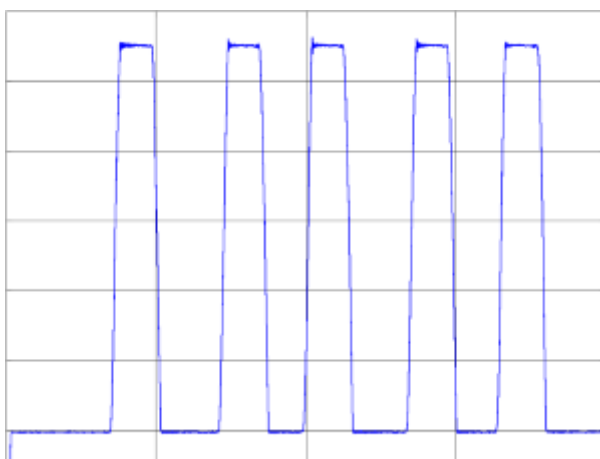
- amplitude or signal level, or "signal is present", "signal is not present"
- frequency or
- a mixture thereof

In practical terms and based on actual examples, this means

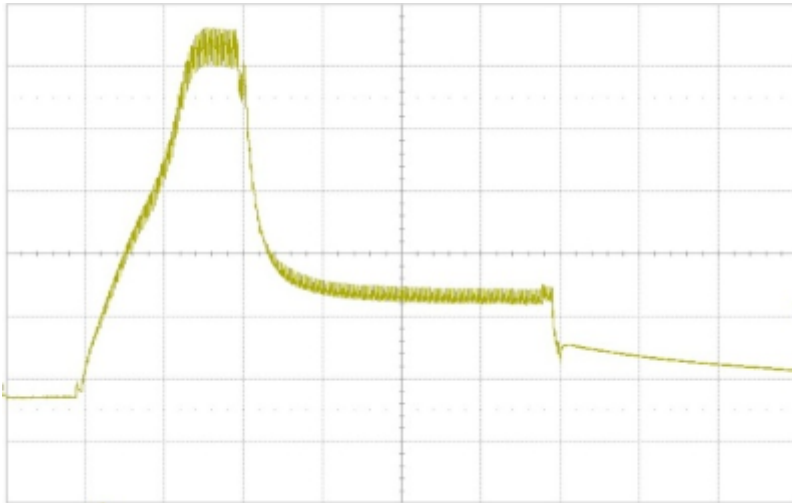
- the signals are "constant" → battery measurement (but only without load)



- or are constantly changing, unpredictable, e.g.:

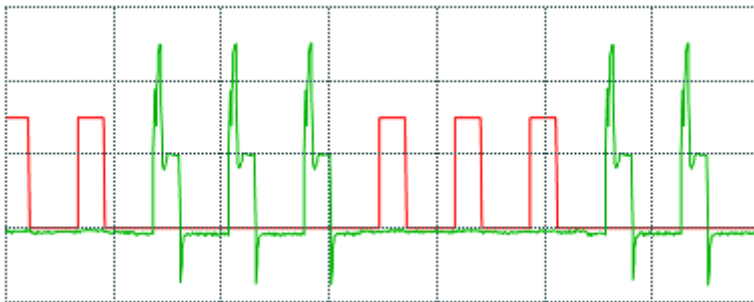


(continuous weighing process)



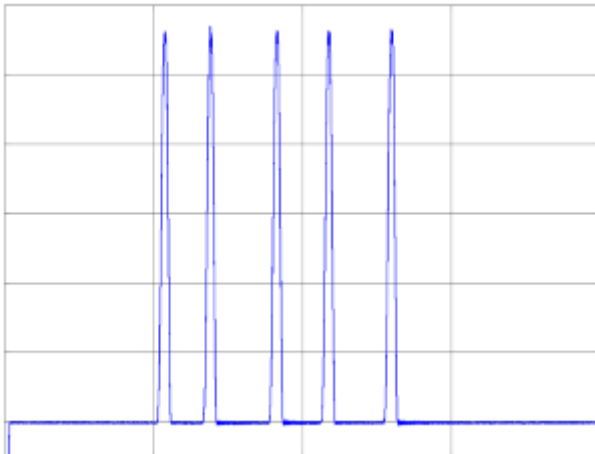
(excitation of a solenoid valve)

- In most cases they are not constantly cyclic "deterministic", like a 1 kHz sine wave from a frequency generator, but have pauses and change their frequency, i.e. they are "stochastic", e.g.:

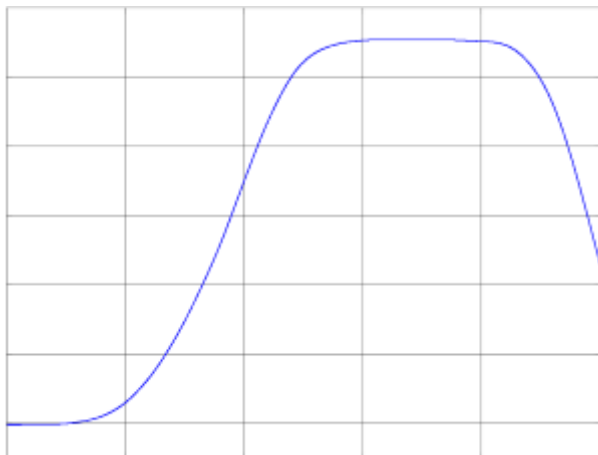


(excitation of a solenoid valve)

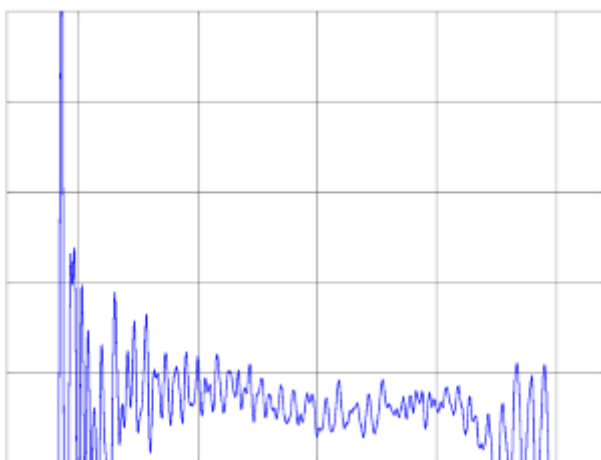
- Sometimes they are very steep-edged:



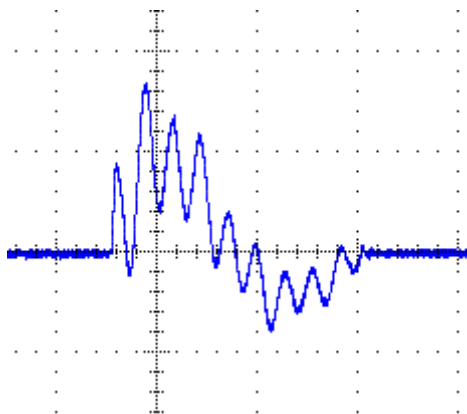
- Or not:



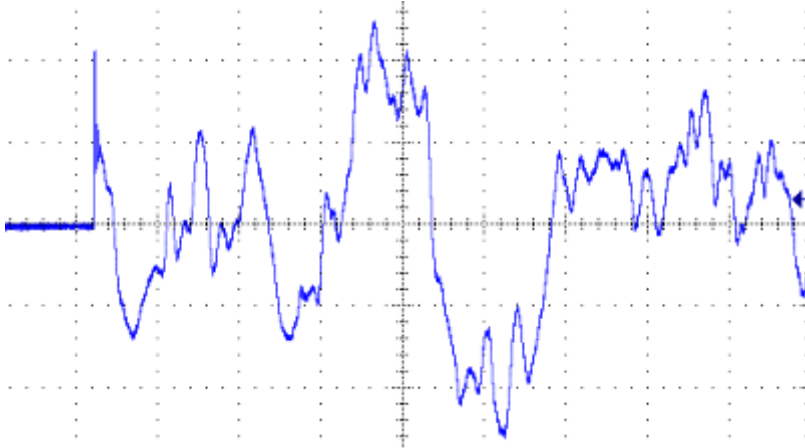
- They are never "ideal" but are subject to disturbance, interference and attenuation:



- They can be superimposed, apparently consisting of two superimposed sine signals:

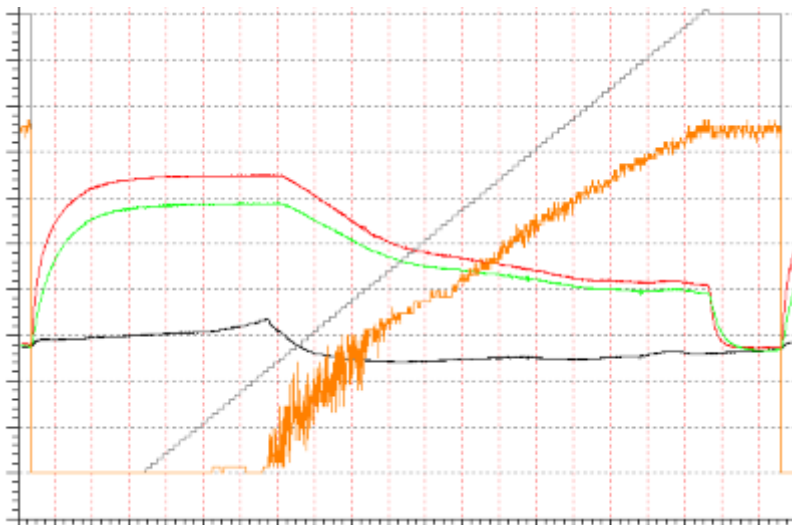


- If many frequencies are involved, this is indeed the case:

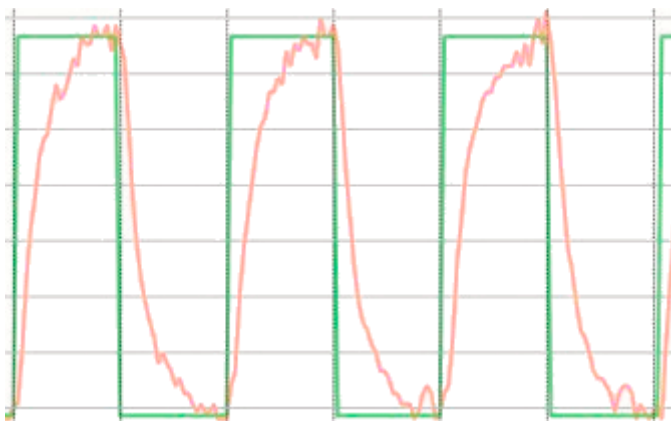


(the beginning of a song, measured at the loudspeaker)

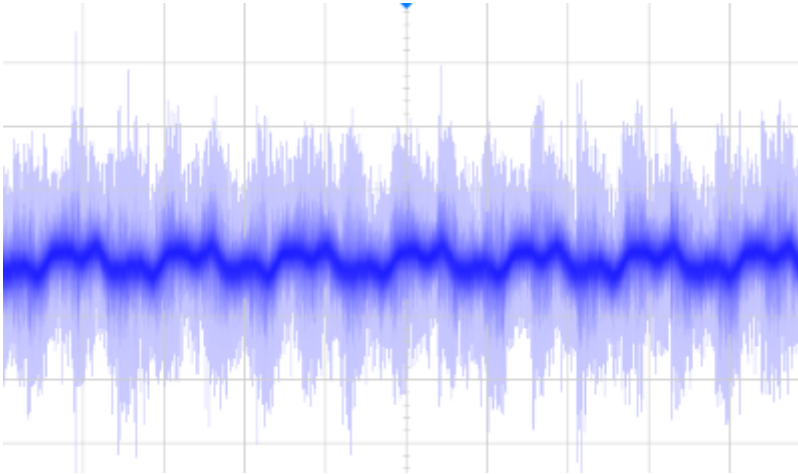
- They change over time, temperature, humidity, installation position, etc.:



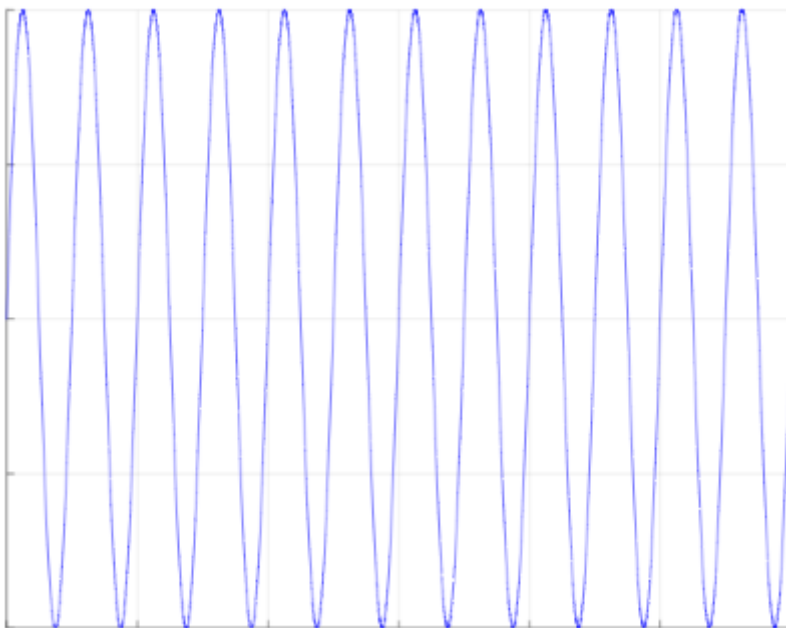
- And a desired square wave signal (green) quickly becomes something else (red) on the line:



- Sometimes all these factors interact, in which case the question arises: "what is the measured value"?



- In any case, they rarely look as ideal and cyclical as here:



NOTICE

The time axis is relative

In the above examples the x/time axis is intentionally not labeled. Whether a signal is fast/slow, flat/steep "only" depends on the evaluation against the set requirement and the measuring time: in a mechanical tensile test (tear test), the signal changes only slightly for a long time, until very steep signal changes in the μs range are suddenly observed at the break point

Although "real" industrial signals are not permanently uniformly ideal and sinusoidal, it is helpful to use the terms and tools of theoretical signal analysis to characterize effects and test the effectiveness of measures. Keywords such as "signal frequency", "edge steepness", "attenuation" and similar can then be applied to the real signal section by section.

This chapter therefore considers the extensive theoretical basis of signal theory (which can be studied via www.wikipedia.com and standard text books) through the eyes of the industrial automation engineer and focuses on

- signal parameters $\mu\text{V}..k\text{V}$, corresponding to Ampere, $\frac{\text{mV}}{\text{V}}$ etc.,
- signal frequencies 0 Hz to ~ 1 MHz,
- non-constant signals,

- that are not ideal.

Practical applications

Analog devices can measure as follows, in order of increasing complexity:

- Static electrical variables that do not change over a "short" time: DC voltage or DC current, generally one constant variable, "DC" for short (direct current). This is available e.g. as output voltage of a battery that is not under load.
Note: "short" is a subjective term that very much depends on the particular situation
- Dynamic electric variables that change over time: AC voltage or AC current, generally one alternating variable, "AC" for short (alternating current). It has a signal shape that repeats with a certain period. This is present, for example, in the German power supply system with a sinusoidal signal form of 50 Hz or appears in the form of "rapidly" changing measured variables on machines. The reciprocal value of the period value is the frequency f ; unit Hz. The maximum value is called amplitude among other things and can refer to the current or voltage value. For a first approach it can be regarded as a constantly repeating, periodic/deterministic signal.
- Mixed signals: These are a "mixed form" of several overlaid alternating variables. They take the form of a voltage or current signal containing several alternating variables with different frequencies and amplitudes, and may also contain a DC voltage, which is usually referred to as the "DC component" or "offset". Here too, the first approach should be based on constantly repeating, periodic/deterministic signals
- If the signals change in their frequency/amplitude, so-called non-deterministic/stochastic (random) signals, we finally encounter the real cable reality.
A particularly good example of a signal of this kind would be a "noise signal".

It should be noted that the "actual" signals that appear – the "real" signals – are more or less mixed signals, because electronic components are always "lossy" and usually distort a "pure" signal shape. Ideal signals are theoretical variables where no losses are taken into account. Therefore, a signal is specified as a real occurring mixed signal among other things by its maximum amplitude A and the lowest frequency that it contains, i.e. the base frequency.

In addition, the constancy of a frequency in real environments is usually not possible either due to physical conditions. As a rule, it is rather complicated to create an oscillation generating system that is subject to virtually no changes of frequency over time.

Below, we explain what fundamentally needs to be observed when measuring dynamic signals with analog devices.

Signal theory

The basic accuracies specified in the Beckhoff IO documentation apply in general to static (DC) signals unless stated otherwise. When determining the specification, a DC signal is applied and a measurement is only carried out when the entire measuring system has completely settled down and the measured value does not change within a "short" time. At attempt is made in the production calibration to minimize the residual deviation ΔG_{DC} .

On account of the losses and inertia of resistors, inductances and capacitances in the amplifiers of an electrical input circuit as well as the finite calculation times of digital signal processing blocks, settling requires a certain time (also referred to as settling time). Depending on the layout, this can take between a few nanoseconds and several seconds. Side note: If the thermal settling of the devices/cables also has to be taken into account, it can even take many minutes.

If, on the other hand, a dynamic, time-dependent (AC) signal is measured, the measuring system can never settle to a completely stationary state, because the signal is constantly changing and the rate of change of the AC signal is greater than the settling time of the system. This gives rise to an additional frequency-dependent deviation that is not covered by the DC specification ΔG_{DC} . For example, if the dynamic signal is a sine wave

$$S(t) = A \cdot \sin(2 \cdot f_{\text{signal}} \cdot f \cdot t),$$

with amplitude A , the additional deviation can be displayed as gain deviation ΔG_{AC} . In reality, this means that $A_{\text{measured}} \neq A_{\text{signal}}$, where not only attenuation $A_{\text{measured}} < A_{\text{signal}}$ is possible, but also inadvertently amplification $A_{\text{measured}} > A_{\text{signal}}$. The total gain deviation then results in

$$\Delta G_{\text{tot}} = \Delta G_{AC} + \Delta G_{DC} \text{ (frequency-dependent)}$$

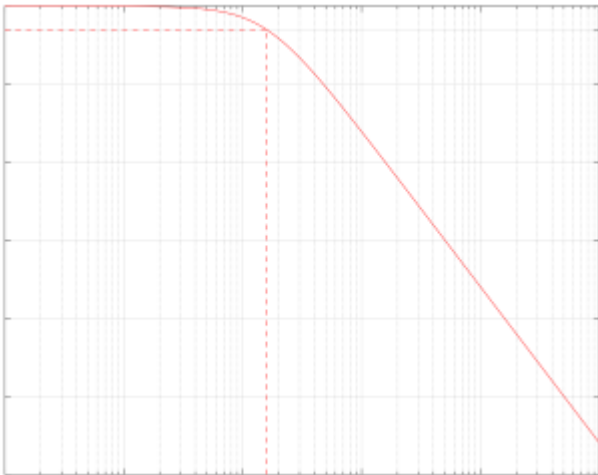
where ΔG_{AC} is the additional gain deviation due to the alternating signal.

Below, a real signal is examined whose signal composition (base frequency, noise, overlaid interferences) changes constantly; nevertheless, an ideal case is assumed with regard to its frequency, which is then constant ($f = \text{const.}$).

Note: since this method has its historical basis in signal transmission in the AC range, the corresponding terms are used: gain/amplification, dB, attenuation and so on. As described later, this often leads to common statements in logarithmic [dB] representation, which have to be converted for low-frequency [ppm] assessment.

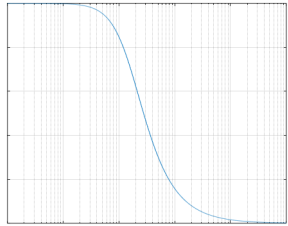
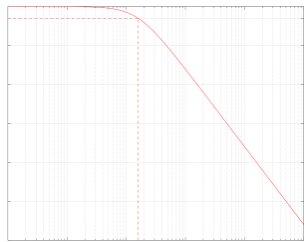
The frequency response in dB and ppm

This frequency-dependent deviation can be represented as a so-called frequency response. The frequency response describes the ratio of the output signal to the input signal with regard to the amplitude and the phase for a certain frequency range.



The phase shift is irrelevant in many applications and is therefore often not displayed. However, it should be borne in mind that not only the amplitude of the output signal can change over the frequency, but also the phase of the output signal relative to the input signal.

On a graph of the frequency response, the x-axis always represents the frequency f_{signal} . The amplitude ratio is displayed either linearly or logarithmically (preferably in the unit dB [decibel]) in the y-axis. Depending on the analysis objective, the linear or logarithmic scaling shows certain characteristics better. It should be emphasized that the scaling (linear/logarithmic) is independent of the unit (Hz, ppm, dB)!

Scaling variants		x axis / frequency	
		Linear [Hz]	Logarithmic (then preferably in [dB])
y axis measurement uncertainty Attenuation	Linear	Helpful for accuracy considerations in the ppm range	Unusual, with increasing frequency attenuation is no longer clearly shown 
	Logarithmic (then preferably as attenuation in [dB])	Not very helpful the lower frequency range is poorly resolved	Usual for dB representation 

The unit dB (decibel, 1/10 Bel) is used to describe the ratios of two values to each other. It has no unit itself! A dB is defined for two powers P_1 and P_2 by the following equation

$$dB = 10 \cdot \log_{10} \left(\frac{P_2}{P_1} \right)$$

With this representation method, for example, it is possible in a system chain with amplifying and attenuating elements to determine a total value simply by the addition and subtraction of the individual values instead of multiplication and division.

For the two electrical power values on the same resistance, the general equation $P = U \cdot I$, together with Ohm's law, produces a square ratio for the two currents I_1 and I_2 as well as for the two voltages U_1 and U_2 :

$$P = I^2 \cdot R \quad \text{and} \quad P = \frac{U^2}{R}$$

transferred to the ratio of the two powers P_1 and P_2 :

$$\frac{P_2}{P_1} = \frac{I_2^2}{I_1^2} \quad \text{and} \quad \frac{P_2}{P_1} = \frac{U_2^2}{U_1^2}$$

The square can be written before the logarithm and the following equation thus results in general for two amplitudes A_1 and A_2 as field variables:

$$dB = 20 \cdot \log_{10} \left(\frac{A_2}{A_1} \right)$$

In this context it is helpful to note the following conversions of dB and amplitude ratios:

[dB]	$[A_2/A_1]$
40	100
20	10

[dB]	$[A_2/A_1]$
3	1.414
0	1
-3	0.707
-20	0.1
-40	0.01

The following illustration shows the double logarithmic amplitude response of an "ideal", i.e. "calculated" RC circuit configured as a low-pass filter, where $R = 1\text{ M}\Omega$ and $C = 1\text{ nF}$. Both amplitude and frequency are represented logarithmically:

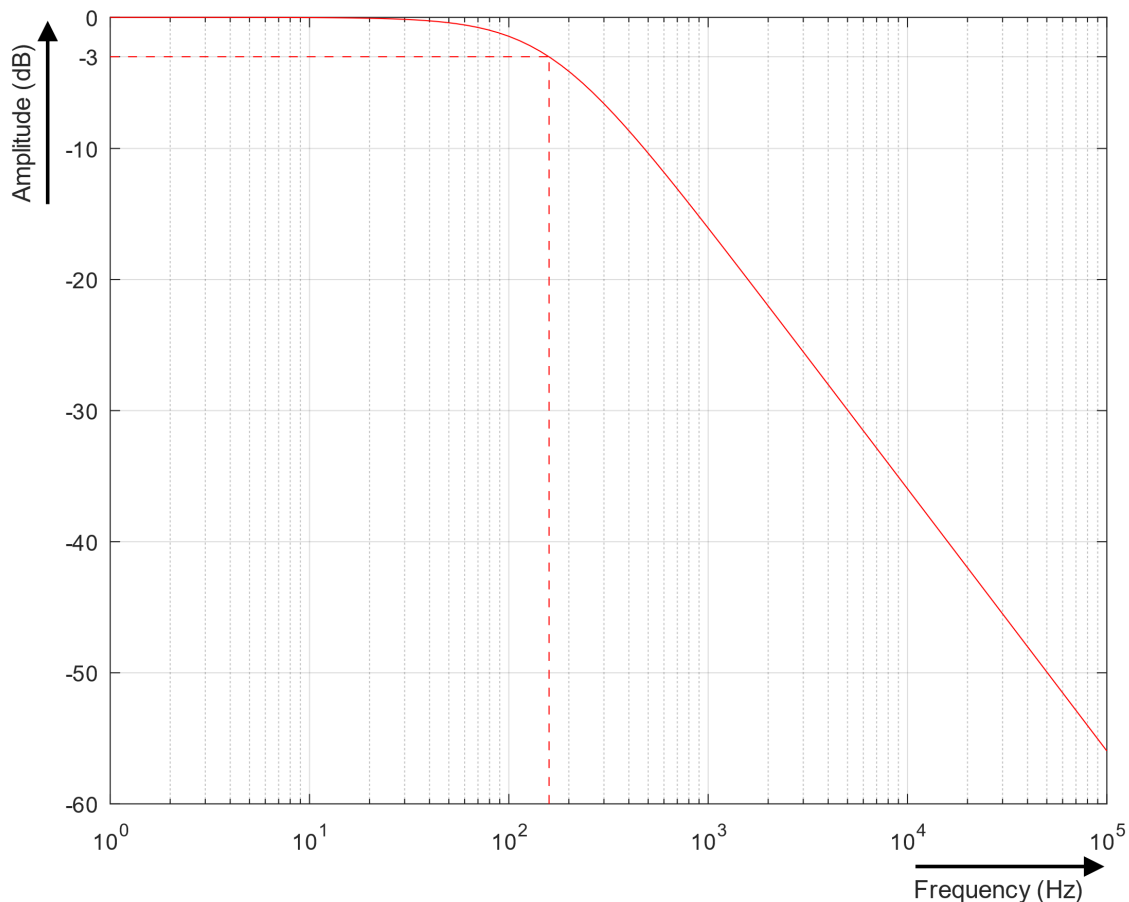


Fig. 44: Amplitude response of a low pass RC circuit

The input signal passes through almost without attenuation up to the frequency marked by the dotted line ($f_{\text{signal}} \approx 159\text{ Hz}$, amplitude at -3 dB , $10^2 = 100!$). Above = to the right of this frequency (obviously even a little before that), the circuit begins to attenuate the input signal noticeably. The marked frequency obviously separates two areas with different behaviors. It is therefore also referred to as the cut-off frequency f_c .

Depending on the background to the problem, there are various parameters to describe the amplitude/frequency responses. The -3 dB point is one possible parameter and is often used with analog RC filters or digital Butterworth filters.

The graph gives the impression that the amplitude passes through entirely unattenuated up to $f = 20\text{ Hz}$, but that is not the case. Like a view from afar, the dB representation conceals the fact that, from a microscopic point of view with a resolution in $\% = 1/100$ or $\text{ppm} = 1/1000000 = 10^{-6}$, attenuation does indeed take place. And this is particularly interesting when it comes to analog measurement modules that are specified with a basic accuracy in the ppm range.

The next illustration shows the same relative attenuation, but in ppm. It is a double-linear representation of the amplitude response of the RC circuit:

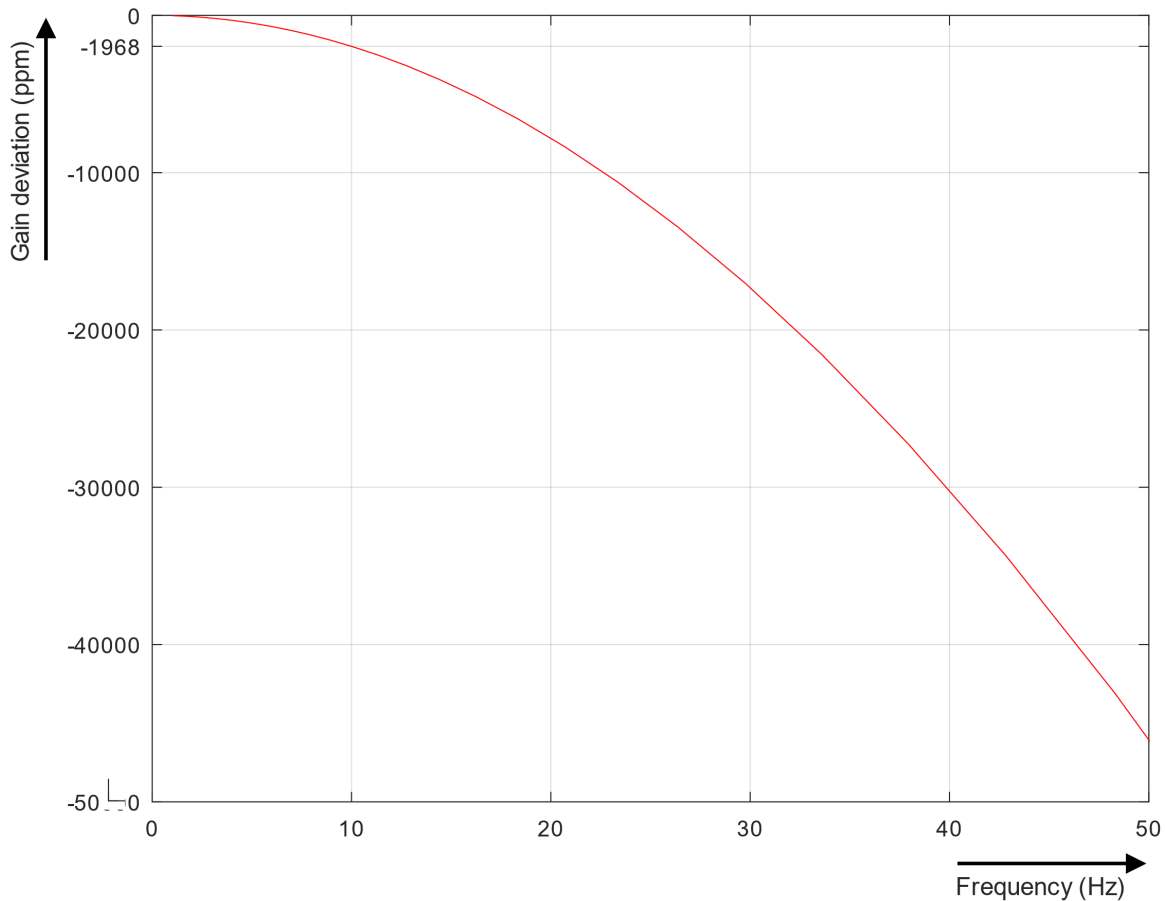


Fig. 45: Relative "gain" deviation of the RC circuit in ppm up to 50 Hz

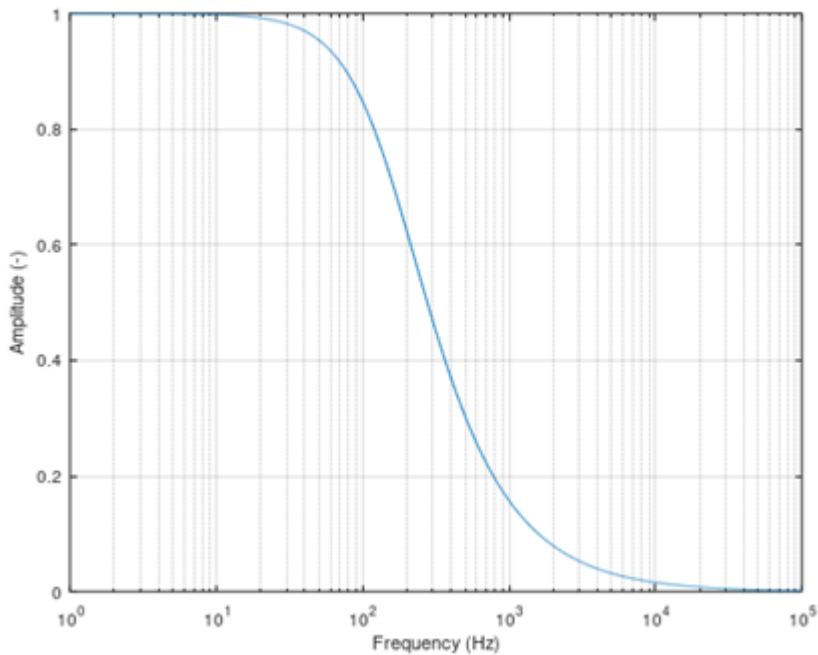
The graph shows that at 10 Hz the output amplitude is already smaller relative to the input amplitude by 1968 ppm - in fact a measurement error. Since it is known in concrete terms, this can even be called a measurement error.

From the above table, we therefore select the small attenuation range of interest for metrological devices with some example values:

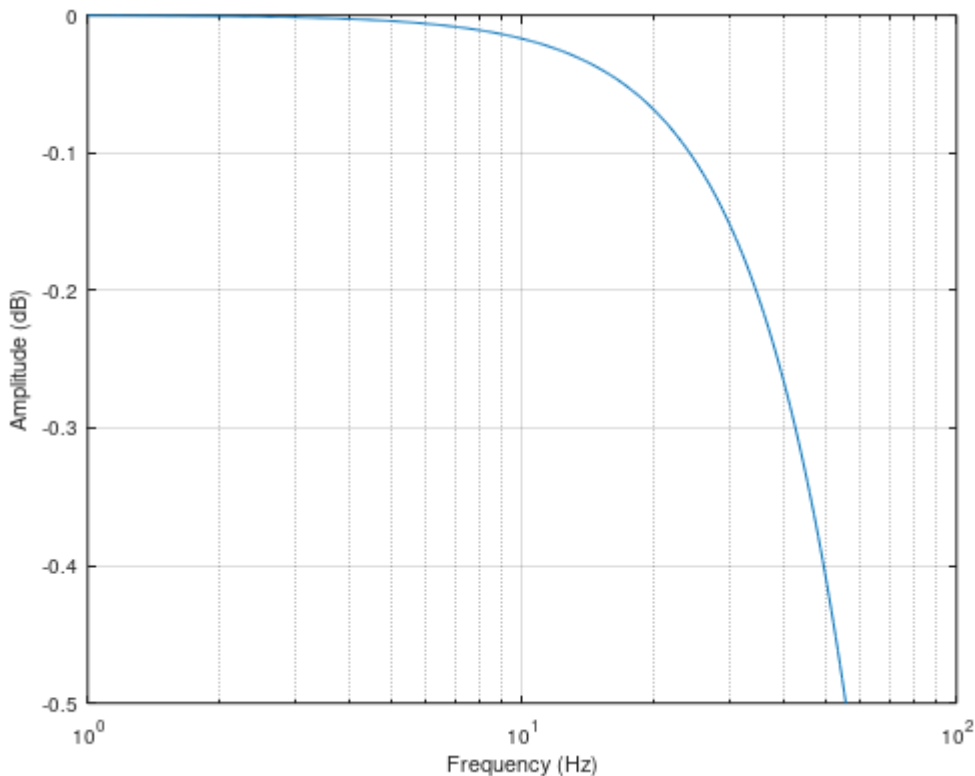
dB vs. ppm		
[dB]	[%]	[ppm]
-0.001	0.01	115
-0.005	0.06	575
-0.01	0.12	1151
-0.02	0.23	2300
-0.04	0.46	4595
-0.08	0.92	9168
-0.2	2.28	22763
-0.4	4.5	45007
-0.8	8.8	87989
-1.6	16.82	168236
-3	29.21	292054

An attenuation of -3 dB thus means almost 30%_{F_{SV}} or almost 300000 ppm_{F_{SV}} amplitude error! And measurement accuracy of 0.1% corresponds to about 0.01 dB. This sounds dramatic, and rightly so, and is lost in the usual logarithmic dB representation.

The "problem" of the dB representation, however, is mainly due to the fact that a dB representation usually extends over several Hz orders of magnitude - precisely in order to represent the high attenuations and to show linear behavior over wide frequency ranges.



When zooming into the dB representation and for consideration only lower frequency parts, the information is much better:



But before we look at the effect of the frequency response specifically on analog inputs, we need to look at other phenomena.

Filters are everywhere

The above-described "manipulation" of the frequency response takes place by means of so-called filters along the signal processing chain

- unavoidably in all electrical, i.e. analog elements
- manipulably in the digital, i.e. software elements

Filter can be subdivided according to their application and their implementation. On the one hand, filters are used to influence or change the signal in the time domain, for example to smooth signals or to remove the DC component. Frequency-selecting filters aim to separate certain frequency bands from one another. The above example with the RC circuit is a low-pass filter that allows low frequencies to pass through with almost no attenuation while strongly attenuating higher frequencies. In addition to low-pass filters there are other filter types, such as high-pass filter, band-pass filter and band-stop filter. Other user-defined filters can be designed for other applications that don't fit into these categories, or for complicated applications.

Filters can be constructed either as analog filters (active or passive) or as digital filters in software.

Filters are characterized by their response to certain signal types. Each linear filter has a pulse response or step response and a frequency and phase response. The step response describes the temporal amplitude curve when an (ideal) step is connected to the input; the frequency response describes the amplitude gain (or phase shift) between the output and input signal. If one of the three graphs is known, the other two graphs can be calculated from it.

With many filters, the -3 dB frequency indicates the signal frequency at which the signal is attenuated by -3 dB. As already indicated above, it is also referred to with certain filter types as a cut-off frequency, at which the output power has been halved and the amplitude has fallen to $1/\sqrt{2} = \text{approx. } 70\%$ in comparison with the input amplitude, corresponding to a attenuation of approx. 30%.

Digital filters can be divided into two categories: FIR filters (finite impulse response filters) and IIR filters (infinite impulse response filters). As the names suggest, the two filter types differ by their pulse response in the time range. The following illustrations show the differences in the pulse response of the two filter types:

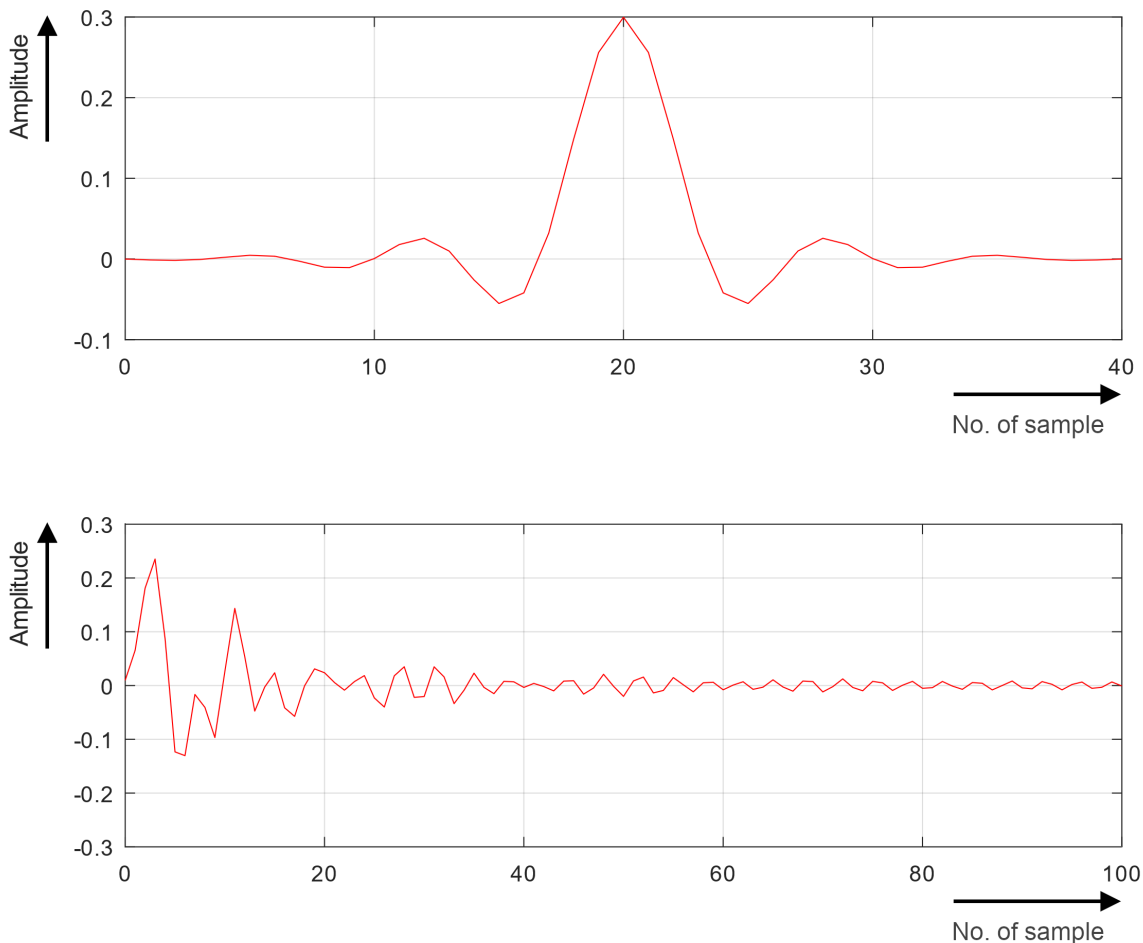


Fig. 46: Example Impulse response of two filters; top FIR filter, bottom IIR filter

FIR filters are described by the mathematical equation

$$y_k = \sum_{i=0}^N b_i \cdot x_{(k-i)}$$

Only input data $x_{(n-k)}$ are used which are accordingly sampled amplitude and time discrete values. With an FIR filter, the impulse response becomes zero after a finite time, which ultimately means that it is always stable, since there is no feedback, and can exhibit a linear phase response. However, FIR filters require a higher filter order to achieve a performance similar to IIR filters, which results in a longer calculation time. "Higher order" means that more filters have to be calculated one after the other.

IIR filters are described by the following equation

$$y_k = \sum_{i=0}^N b_i \cdot x_{(k-i)} + \sum_{j=1}^N a_j \cdot y_{(k-j)}$$

In order to calculate the output value $y_{(n)}$, the previously calculated output data $y_{(n-k)}$ are used in addition to the input data $x_{(n-k)}$. The filter is therefore recursive. For that reason, IIR filters are also called recursive filters. The pulse response of an IIR filter is infinite and thus never settle to zero stationary. This can ultimately lead to instability.

A fundamental effect was mentioned here by the way: the more effect/costly a digital filter is, the higher its complexity and thus the longer its calculation time in the software. This leads in practice to a signal delay.

Nyquist, Shannon and false signals: "Aliasing"

The fundamental sampling theorem states that, if a measuring device samples an analog signal at a constant (steady) sampling rate that is more than twice the highest frequency component present in the signal, the original analog signal can be fully restored from the discrete data points.

(Note: the highest frequency present in the signal is referred to as the bandwidth of this signal.)

After all, this is the actual aim of an analog measurement, i.e. the original signal should be available digitally as accurately as possible ("correct") and complete in the control system for further processing in the program. However, a limit must be imposed here that only signal components (frequency ranges are meant here) that are essential for the further process need to be detected. Ideally, the user will make a conscious choice and reflect this limitation. Example: A slow temperature control must be insensitive to low-frequency signals, because this could disturb the controller.

In order to record the analog signal as accurately as possible, the signal bandwidth f_{signal} must be limited through suitable filtering (see chapter on "Filters") so that only the desired signal but no interfering signals pass through, and the sampling rate f_{sampling} must be selected such that the signal can be restored from the data points as a true representation of the original signal. We therefore have to examine the relationship between the actual sampling rate f_{sampling} and f_{signal} .

(Note: each measurement takes place in the two dimensions time and measured variable. Here we concentrate on the temporal dimension, i.e. the sampling).

Theoretical considerations relating to the sampling theorem are illustrated with an analog signal and different sampling rates.

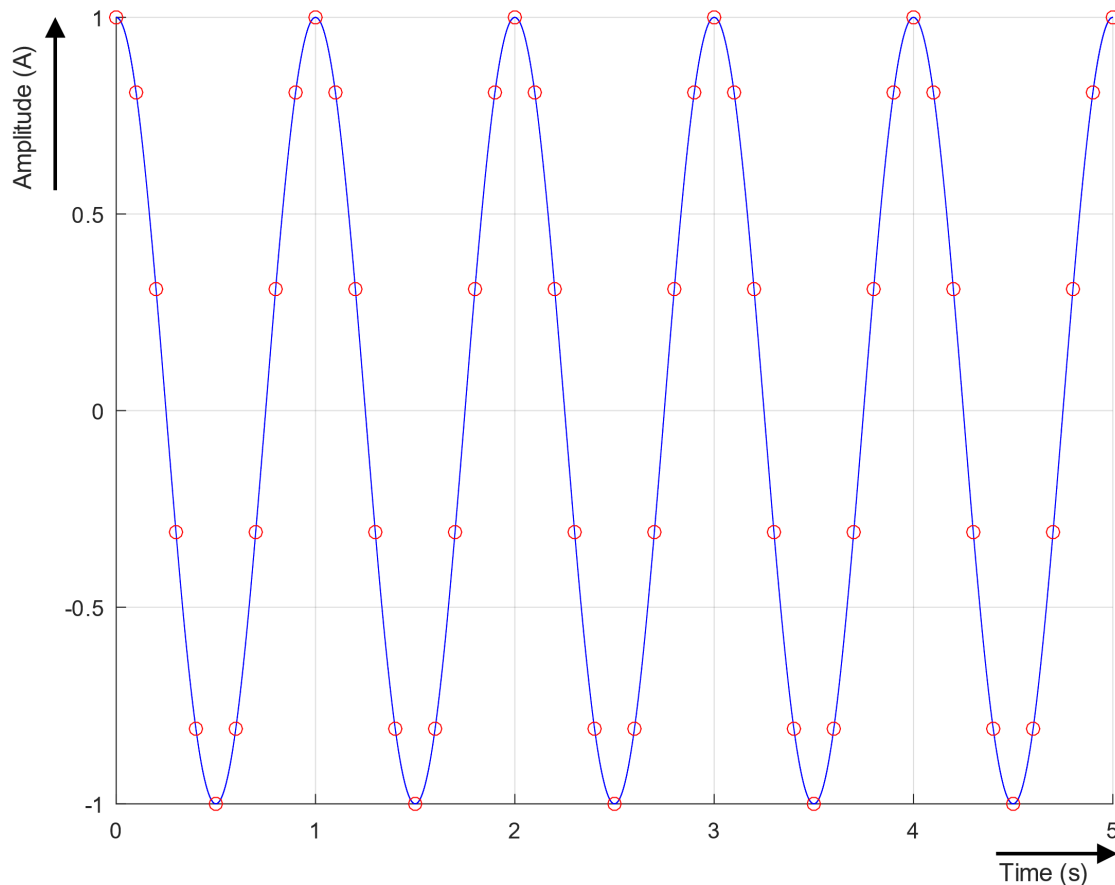


Fig. 47: Analog signal (cos) with a frequency of 1 Hz (blue line) sampled at 10 Hz (red circles)

The analog signal with $f = 1$ Hz was sampled with $f_{\text{sampling}} = 10$ Hz. The largest (and only) frequency component in this sample is 1 Hz, therefore $f_{\text{signal}} = 1$ Hz and $f_{\text{sampling}} = 10 \cdot f_{\text{signal}}$. It is easy to see that the original analog signal can be reconstructed from the discrete values. For example, a fast Fourier transform (FFT) could be calculated from the above data. This would easily be possible, and the resulting spectrum would extend to $f_{\text{sampling}}/2 = 5$ Hz, with a resolution of 0.2 Hz.

If the analog signal had not been a "pure" sine wave but had been harmonically distorted and noisy, then f_{signal} would no longer be 1 Hz but usually much larger due to the higher frequency components contained in it. In this case the chosen f_{sampling} must be significantly greater than f , depending on the evaluation aim. This also applies in general terms, as will be explained a little later.

The next figure shows what happens if the $f_{\text{Signal}} = 1$ Hz signal is sampled at $f_{\text{sampling}} = 2$ Hz, i.e. $f_{\text{sampling}} = 2 \cdot f_{\text{Signal}}$.

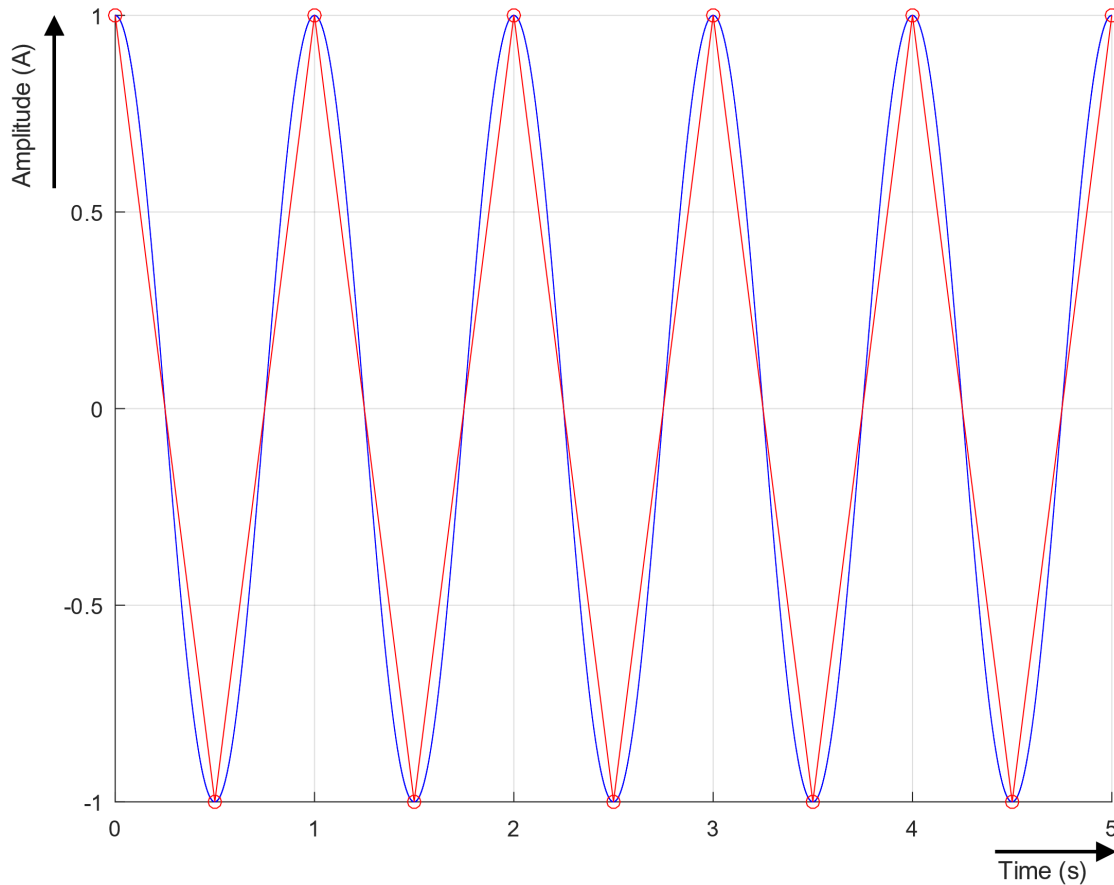
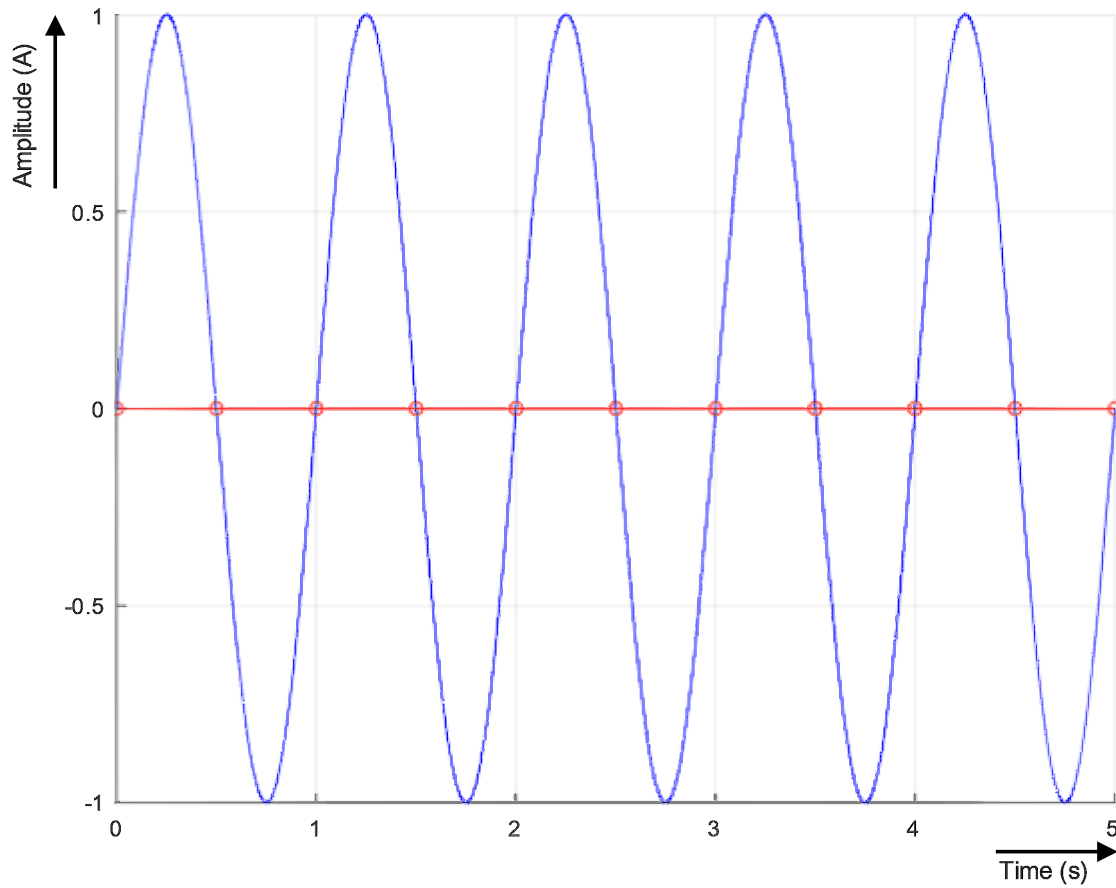


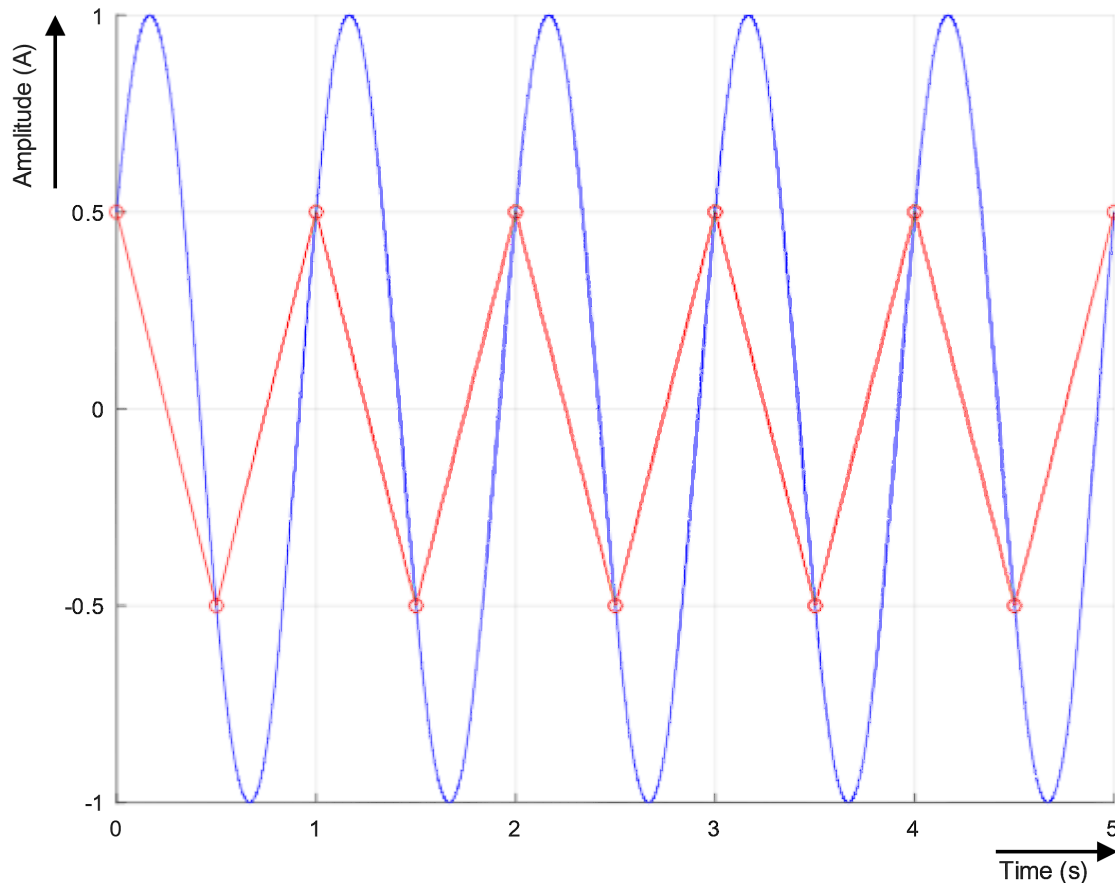
Fig. 48: Analog signal (cos) with a frequency of 1 Hz (blue line), sampled at 2 Hz (red circles) and interpolated / "traced" (red line)

Since in this sample a specification resulting from the sampling theorem is just about met, it is still possible to detect the frequency and amplitude of the signal: f_{sampling} is equal to $2 \cdot f_{\text{Signal}}$.

However, this is no longer possible in general, as the following problem becomes apparent here, if one imagines that the sampling moments would be randomly shifted by 90° relative to the signal. In this case the value of the signal at each sample point would be zero, and it would no longer be possible to detect the frequency or amplitude.

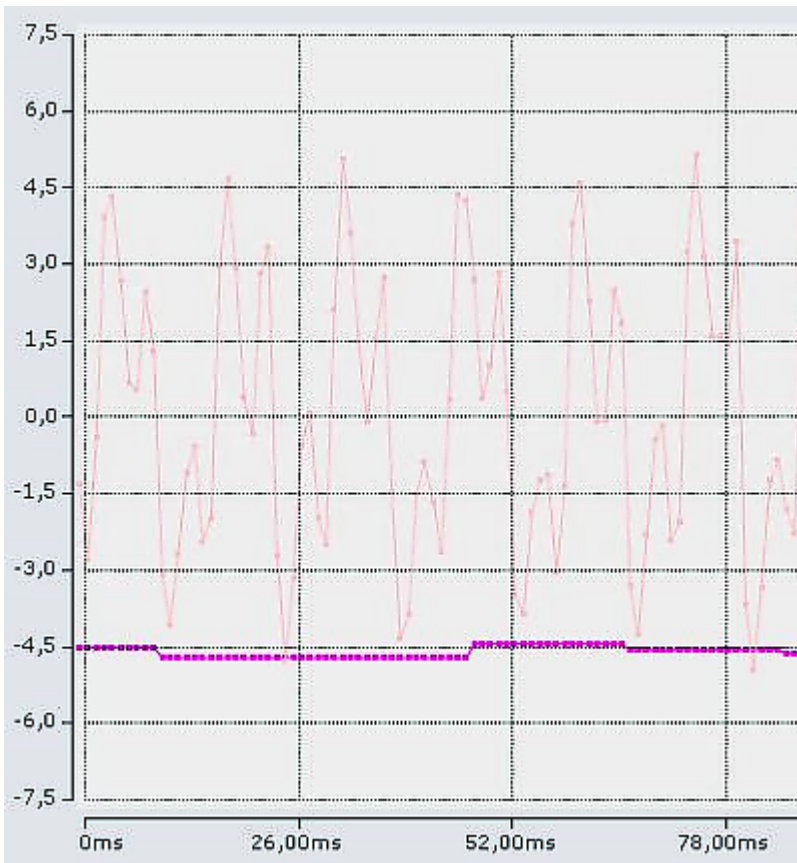


In practice, it is much more likely that the measuring points lie "somewhere" on the signal:



In this case, at least the frequency can still be determined due to the zero crossings, but the peak value (and thus very important signal information) cannot be determined because it is not clear where the measuring points are located on the original signal. In practice, however, neither f_{sampling} nor f_{signal} will be highly constant, and longer observation will result in variable phasing and the peak value will still be caught "at some point". However, this is of little use with fast-moving industrial signals.

After these theoretical considerations, let us now look at a concrete real example: the induced voltage of a rotating gear wheel on a coil as speed sensor results in the following representation in TwinCAT ScopeView:



Selecting a higher sampling frequency (sampling rate) would be advantageous here in order to be able to follow the amplitude curve better, because signals seem to overlap here. The zero crossings may be sufficient for speed observation.

The frequency

$$f_{\text{Nyquist}} = \frac{1}{2} f_{\text{sampling}}$$

is also called the Nyquist frequency. If an analog signal contains frequency components equal to or greater than the Nyquist frequency, the original signal can no longer be reconstructed. In practice, the Nyquist frequency is selected to be at least a factor of two to three times greater than the bandwidth of the signal frequency f_{signal} .

The resulting problem of the non-reconstructable original signal due to $f_{\text{signal}} \geq f_{\text{Nyquist}}$ was already hinted at in the previous example. The figure below illustrates the problem.

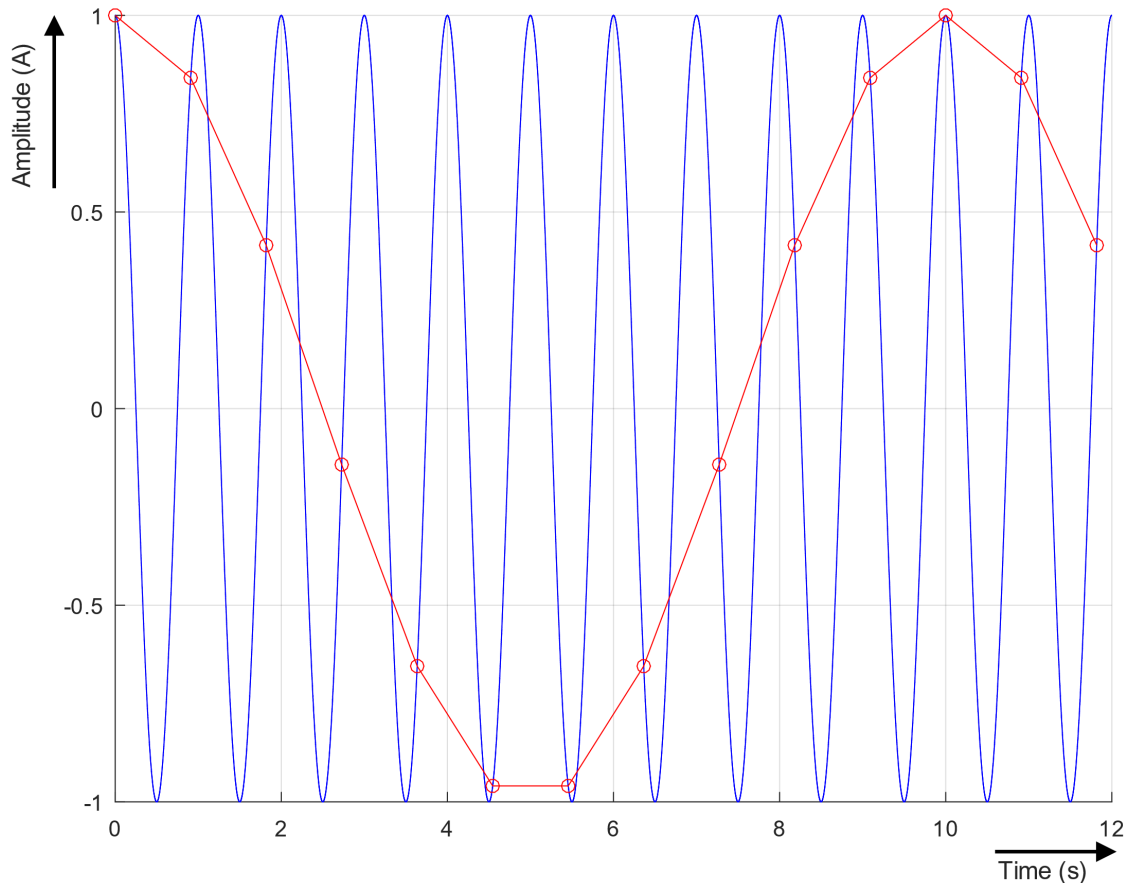


Fig. 49: Analog signal (cos) with a frequency of 1 Hz (blue line), sampled at 1.1 Hz (red circles) and interpolated / "traced" (red line)

Here $f_{\text{sampling}} = 1.1 \cdot f_{\text{Signal}}$. The frequency information of the original blue signal has been lost. From the control system point of view (which only "sees" the red measuring points), it appears that the measured red signal is a signal with a lower frequency. This effect is called aliasing because a different frequency is detected. It is a common problem when the fundamental sampling theorem (also called the Shannon-Nyquist sampling theorem) is violated. The apparently detected alias frequency in this case is $f_{\text{alias}} = 0.1$ Hz.

The Shannon-Nyquist theorem and alias effects focus solely on the question of whether the original analog signal can be reconstructed from the sampled values. This cannot be the sole criterion for selecting an analog input, but it is an essential one. In practice, there are situations where the sampling theorem is deliberately violated, e.g. in order to reliably detect fast signal changes. Since the user already knows a lot about the analog signal to be measured, such considerations are quite possible and in many cases help to optimize the measuring system.

Further effects

Further phenomena from the field of measurement of alternating variables such as noise, distortion, signal cross-talk and signal delay in detail will be further illuminated here in due time.

Reaction or recording? Or both?

Finally, from an application perspective, it is important to consider whether the application is a response task, a data recording task, or a mixture of both.

- Reaction:
 - Example: a distance sensor with a 10 V analog output detects an object approaching on a conveyor belt at 10 m/s and, if 5 V is exceeded, a valve for a paint application should be opened in the shortest possible time. Another extreme example would be current control in a software-controlled magnetic bearing.

- The following would need to be selected:
 - # an analog input with high sampling rate, open filter, possibly even DistributedClock timestamp function (although the reference to the absolute world time probably does not matter)
 - # short EtherCAT cycle time and short PLC cycle time, if necessary 100 μ s or less
- Analog accuracy is secondary here; a long-term recording of the measured values will probably not be carried out either
- Data recording
 - Example: a strain test lasting several days on a steel structure with slow movements in the seconds range.
 - The following would need to be selected:
 - # a precision analog input; important here are low noise and high temperature insensitivity, synchronization across multiple channels, possibly even absolute time synchronization to the GPS clock
 - # slow EtherCAT cycle time, the analysis program in C/PLC/Matlab will probably demand quite a lot of the controller
 - The sampling rate is probably secondary here. Signals with short rise and fall times as well as attenuation issues due to high frequencies are not expected
- In addition to the above extreme examples, most industrial applications are a mixed form of the two. That said, only the user can judge whether a reaction in the 100 μ s range is "fast" in view of his problem: for temperature monitoring in the seconds range, this is "too fast", for laser monitoring "too slow".

At the end of the day, therefore, the analog and temporal characteristics of the Beckhoff analog devices have to be judged against the problem.

Effect on analog input devices and the design of the same

Depending on the intended application objective, some basic decisions have to be made by the manufacturer of analog inputs during the design phase. The different answers to the questions

- Attenuation: at what frequency does attenuation occur, how does it proceed?
- Sampling rate: which signal frequency should be measured at all, and with what accuracy?
- Delay: with what delay may the signal arrive in the controller?

have also been formulated at Beckhoff in the form of analog input devices. The user can find the right device for his application with the help of

- the Beckhoff documents (e.g. this manual)
- Beckhoff Sales
- and if necessary practical

tests.

NOTICE

kHz vs. kSps

Note: in order to avoid linguistic misunderstandings in documentation and sales meetings, the incoming signal frequency f_{signal} is described at Beckhoff with the unit [Hz], and the technical sampling rate f_{sampling} of the analog input with (samples per second) or [kSps] (kilo samples per second).

Here is a rough classification for this:

- The **EL30xx** class with its 10 V/20 mA inputs is designed for simple measurements on slow signals with 12-bit resolution. Therefore, the hardware filter and the sampling rate are set very low.
- The **EL31xx** class (also: EP31xx, EJ31xx) with its 10 V/20 mA inputs with 16-bit resolution is designed for fast signals and reaction tasks. In order to promptly inform the controller of fast-changing signals, even the hardware filter is purposely selected higher than the sampling rate. However, this can lead to alias signals in measuring applications.

- The product group measurement technology of the **ELM3xxx** class (and: EPP35xx) are consistently designed for signal correctness in recording applications; the hardware filter lies well below half the sampling rate with its -3 dB point. The ELM3x0x class "10 ksp/s" is more suitable for faster tasks, while the ELM3x4x class "1ksp/s" is more suitable for slower tasks.

Moreover, key data that are suitable for the application area have been specially defined in the various **special function terminals**, which cannot all be listed here in detail. For example, the EL3632 / EPP3632 has variable hardware filters that can be adapted to the sampling rate.

5.4 Signal quality when outputting signals with digital analog outputs – distortion factor

The modular Beckhoff I/O system IP20/IP67 features analog outputs in various designs, e.g. the EL41xx, EL47xx, EJ4xxx or EP4xxx series ("xx" or "xxx" stands for the respective specific product number).

What all devices have in common is that they

- operate with electronic DACs (digital-to-analog converters): a digital value sent by the controller (TwinCAT) via the fieldbus, e.g. $4567_{\text{dec}} = 11D7_{\text{hex}}$, is converted by the DAC per channel to an analog output (voltage or current, depending on the device) and possibly also amplified,
- operate cyclically: the controller sends its output values, time-discrete, in a fixed real-time rhythm ("control cycle"), e.g. every millisecond. The analog output device receives this value via the fieldbus and outputs it according to the set operation mode; three modes are available, depending on the device
 - immediate output after reception: SyncManager-synchronous,
 - triggered by the local clock: DistributedClocks-controlled,
 - free-running: the device firmware continuously repeats its MAIN loop and outputs the received value according to its own requirements.

Overall, this means that a smooth signal curve cannot be produced, and instead a stepped (in terms of time and amplitude) signal curve is seen at the output (particularly if there is no internal or external signal smoothing):

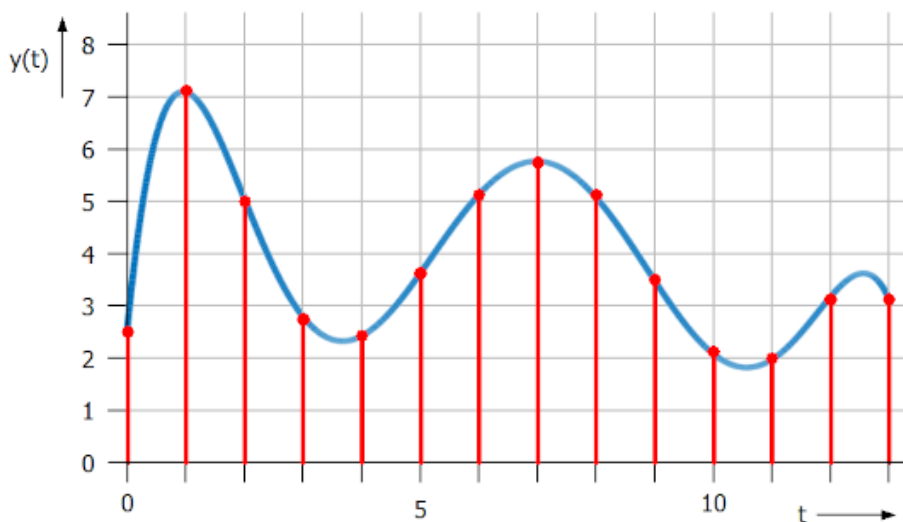


Fig. 50: Analog signal (schematic, discretized)

The actually specified analog signal (blue) can only be electrically mapped by dedicated interpolation points (red dots). As a result of this, the real output signal is stepped both in the time dimension and in the amplitude dimension – it is discretized.

See the following example with the EL4732 (analog output ± 10 V, max. 100 kSps, oversampling-capable):

- for the output of a sinusoidal signal, the following TwinCAT 3 PLC code is used [► 136], in which sine values are calculated for the configured oversampling field for each calling cycle:

Declaration:

```
FUNCTION_BLOCK FB_sine_generator
VAR CONSTANT
  // TwinCAT / Terminal configuration:
  CnMaxIdx      : UDINT :=10; // Fixed amount for Oversampling
  tCycleTime    : LTIME :=LTIME#1MS; // Configured task cycle time
  nOversampling : UDINT :=10; // Used oversampling of the terminal
END_VAR
VAR_INPUT
  // Output configuration:
  rFreq_Hz      : LREAL :=1; // Destination frequency
```

```

    rAmplitude      : LREAL :=1;    // Destination amplitude
  END_VAR
  VAR_OUTPUT
    bError          : BOOL;
    arOut           : ARRAY[1..CnMaxIdx] OF LREAL;
    aiOut_EL4732 AT%Q* : ARRAY[1..CnMaxIdx] OF INT; // 10 V max
  END_VAR
  VAR
    nIdx           : UDINT;
    rPosition      : LREAL := 0;    // Init, if for startup important
    rPeriod_Sec,
    rStep,
    rPositionPi,
    rValue         : LREAL;
  END_VAR
END_VAR

```

Execution:

```

// This code generates values of a sinus for an EL4732 analog output terminal
IF nOversampling > CnMaxIdx OR (nOversampling = 0) OR
  (tCycleTime = LTIME#0S) THEN
  bError := TRUE;
ELSE
  bError := FALSE;
  rPeriod_Sec := 1 / rFreq_Hz;

  // Calculate a step width (percentual of 1):
  // Divide the cycletime by the destination periode and ovs factor:
  rStep := (1E-9 * LTIME_TO_LREAL(tCycleTime)
    / (rPeriod_Sec * UDINT_TO_LREAL(nOversampling)));
  // (Note:
  // factor of 1E-9 for value in seconds due to LTIME data type's unit is ns)

  // fill the array bound to oversampling output for one task cycle
  FOR nIdx := 1 TO nOversampling DO

    // Calculate next X-Position of the sine:
    rPosition := FRAC(rStep + rPosition);
    // (usage of FRAC for saturation of rPosition to < 1)

    // Calculate percent from 1 to an angle of radians:
    rPositionPi := (rPosition * 2 * PI);

    // Calculate next Y-Value:
    rValue := rAmplitude * SIN(rPositionPi);
    arOut[nIdx] := rValue; // allocate to array

    // Convert output to PDO of EL4732:
    aiOut_EL4732[nIdx] := LREAL_TO_INT((rValue / 10) * 16#7FFF);
  END_FOR
END_IF

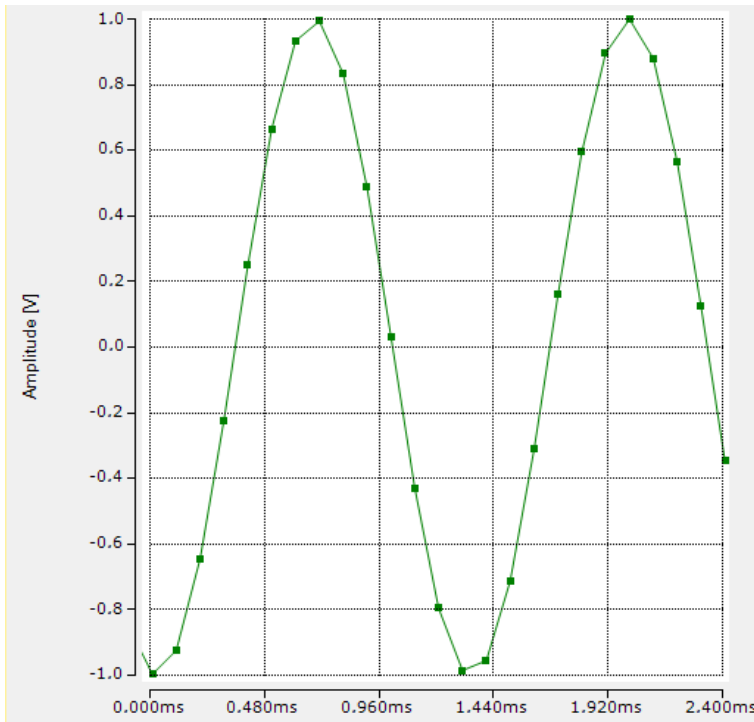
```

● i Using the sample programs

This document contains sample applications of our products for certain areas of application. The application notes provided here are based on typical features of our products and only serve as examples. The notes contained in this document explicitly do not refer to specific applications. The customer is therefore responsible for assessing and deciding whether the product is suitable for a particular application. We accept no responsibility for the completeness and correctness of the source code contained in this document. We reserve the right to modify the content of this document at any time and accept no responsibility for errors and missing information.

Explanation of the example

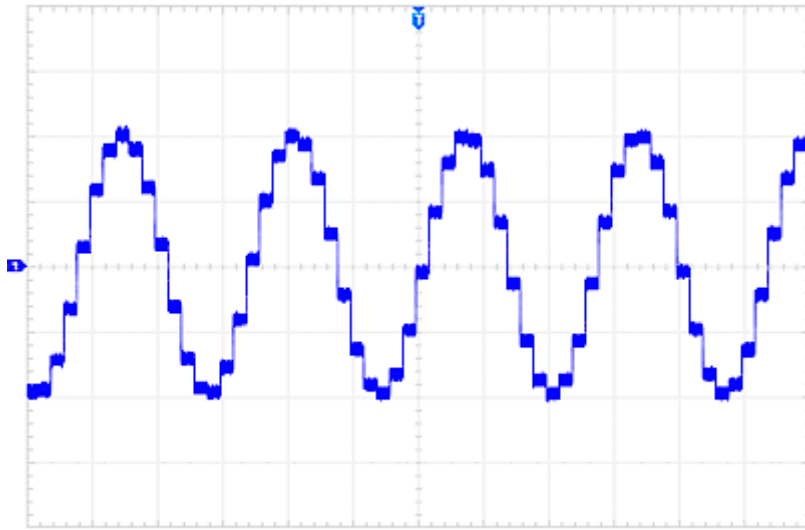
- with cycle time = 1 ms, oversampling = 10, amplitude = 1 V and $f = 758$ Hz, the ScopeView displays the following image of the PLC variable *arOut*:



The individual calculated interpolation points can clearly be seen (setting of the channel property: property group "Marks", property "Mark State" = On, "Mark Size" = 4).

- The preset channel property "Graph Type" under the property group "Line" in the scope is preset to the representation "Line". For that reason, the above ScopeView output does not correspond to the actual electrical output signal of the terminal. A change in the "Stair" representation comes closer to that:

- For that purpose the electrical signal that in reality leaves the analog device, which operates digitally and is thus discretizing in the time and amplitude dimensions, is recorded with an oscilloscope EL4732/ Ch1 across a load of 1 kΩ:



- The resolution in the time range (x-axis) depends on the configured task cycle time (CycleTime) and the set oversampling factor (Oversampling):
 $Resolution [s] = CycleTime / Oversampling$
 With the above values, $1\text{ ms}/10 = 0.1\text{ ms}$. The number of consecutive analog values per second results from the reciprocal value of the resolution: hence, in this example (1 ms cycle time, 10-fold oversampling), 10,000 consecutive analog values can be output with a resolution of 100 μs (colloquially "output at 10 kHz").

So much for the theory. Now, in some tasks the question may arise as to the analog signal fidelity in relation to the theoretical signal. There are various evaluation criteria for this, for instance the **distortion factor**.

For sinusoidal signals, the distortion factor states the harmonic content of the real signal in relation to the total signal, in other words the magnitude of the contents in the signal that do not correspond to the ideal sine wave, i.e. that distort it. The distortion factor lies between 0 and 1; in general, a low distortion factor close to 0 shows a real signal that is very close to an ideal sine wave and contains few (undesirable) harmonics.

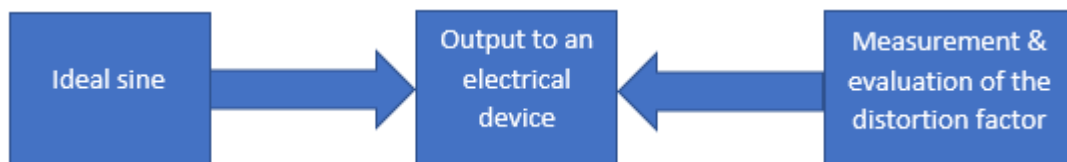


Fig. 51: Distortion factor: ideal sine, output, measurement and evaluation

Measurement and evaluation as follows:

- output of the sinusoidal signal across a known load,
- measurement with the oscilloscope and FFT evaluation,
- determination of the RMS value of the integer harmonics, and from that
- the calculation of the distortion factor.

In the following example, this distortion factor calculation is to be performed on the sinusoidal output of an EL4732 (±10 V, 10 kSps per channel), where $f = 1\text{ kHz}$ and $R_{Load} = 1\text{ k}\Omega$.

A simple oscilloscope with FFT function is used: the 1 kHz sinusoidal signal can be seen in the time range (blue) with 10-fold oversampling:

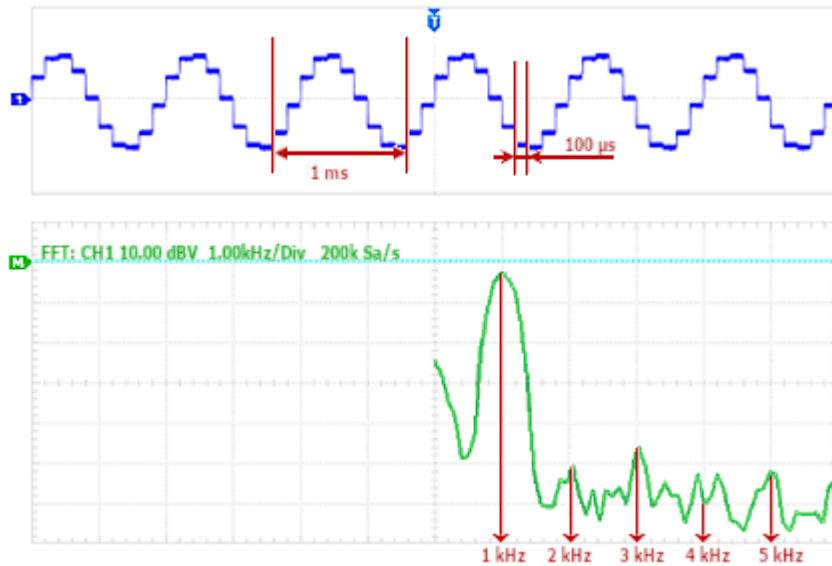


Fig. 52: Sinusoidal output signal of the EL4732 and FFT evaluation

The FFT evaluation is green. The RMS values [dBV] read from this (note: observe the base line "M") and converted to $V_{rms} = 10 \cdot (-dBV/20)$ are as follows:

Frequency [kHz]	RMS value [dBV]	RMS value [Vrms]
1	-4	0.630
2	-51	0.0028
3	-46	0.005
4	-60	0.001
5	-53	0.002

According to the equation:

$$k = \sqrt{\frac{U_2^2 + U_3^2 + U_4^2 \dots}{U_1^2 + U_2^2 + U_3^2 + U_4^2 \dots}}$$

a distortion factor of 0.92% results.

5.5 Note on Beckhoff calibration certificates

Basically every Beckhoff analogue device (input or output) will be justified i.e. will be calibrated during production. This procedure won't be documented unique. This documentation as a calibration certificate is only provided for devices that are expressly delivered with a certificate.

The calibration certificate (or German: "Kalibrierschein") entitles the residual error after compensation/adjustment to the used standard (reference device). The calibration certificate (as a PDF document) is to be assigned to the device via a unique number. It is therefore not a statement about a device class such as e.g. an approval, but always only applies to a single, named device. It is available for [download](#).

The calibration certificate documents the measurement accuracy at the time the certificate was issued and contains, among other things, information on the ambient conditions and the reference instrument used. It does not contain statement about the behavior or the change of the measuring accuracy in the future. A calibration certificate acts as a backtracking view to the previous time of usage. By reiterated certification procedures over years (without justification) it allows making conclusions about its ageing behavior, so called calibrate history.

Performance levels of the calibration certificates

Different "qualities" of a calibration certificate are common:

- Beckhoff calibration certificates
Such IP20 terminals can be usually identified by the product suffix -0020. The certificate is issued in Beckhoff production as PDF.
The terminals can be obtained from Beckhoff and recalibrated by the Beckhoff service department.
- ISO17025 calibration certificates
Such IP20 terminals can be usually identified by the product suffix -0030. The certificate is issued by a service provider on behalf of Beckhoff as part of Beckhoff production and delivered by Beckhoff as a PDF.
The terminals can be obtained from Beckhoff and recalibrated by the Beckhoff service department.
- DAkkS calibration certificates (German: "Deutsche Akkreditierungsstelle GmbH")
Such IP20 terminals can be usually identified by the product suffix -0030. The certificate is issued by a accredited service provider on behalf of Beckhoff as a part of Beckhoff production and delivered by Beckhoff as a PDF.
The terminals can be obtained from Beckhoff and recalibrated by the Beckhoff service department.

Unique device number

Depending on the device, the following numbers are used for identification:

- EL/ELM terminals up to year of manufacture 2020: the ID number which is lasered on the side.



Fig. 53: ID number

- From year of manufacture 2021 onwards, the BTN number (Beckhoff Traceability Number) will gradually replace the ID number, this is also lasered on the side.

Beckhoff produces a wide range of analog input/output devices as IP20 terminal or IP67 box. A selection of these is also available with factory/ISO/DaKkS calibration certificates. For specific details and availability, see the technical data of the devices or contact Beckhoff Sales.

i Linguistic note

In American English, "calibration" or "alignment" is understood to mean compensation/adjustment, thus a modifying effect on the device. "Verification", on the other hand, refers to observational determination and documentation of the residual error, referred in German language use as "*Kalibrierung*".

5.6 Readjusting the specification

The analog input terminal is a function block of the modular DIN rail-mountable IP20 system. It follows that there is an almost infinite number of combination options for terminals on the DIN rail, size of the terminal segment, and also a wide range of applications at different ambient temperatures, control cabinet configurations or packing densities. Other influencing factors affecting an analog input terminal as measuring device include cable routing, EMC and earthing measures, the ventilation situation and contamination. In order to ensure reliable replication of the assured specification, despite this variety of factors, a reference configuration is defined below, which should be used as reference environment for verifying the properties of one or several terminals.

NOTE: This does NOT mean that the terminal specification can only be met with this exact configuration. The reference configuration should only be used as an aid for creating a uniform environment for Beckhoff and customer hardware, in order to ensure comparability of the measurement results and simplify the analog communication. This configuration enables undesirable interference in the real system to be separated from the terminal, to facilitate troubleshooting of the system.

The configuration is within the definition space of IEC 61131-2 and essentially follows the rules of EMC-compliant control cabinet construction.

Definition of the environment

- The terminals to be examined should be self-cooling through unobstructed natural convection. All further details are based on this premise
- The terminals are installed in an enclosed control cabinet. This control cabinet is located in a temperature-controlled environment, e.g. a temperature chamber. The control cabinet should have the following dimensions: 600 mm x 600 mm x 350 mm (width x depth x height). The lid must open to the front.

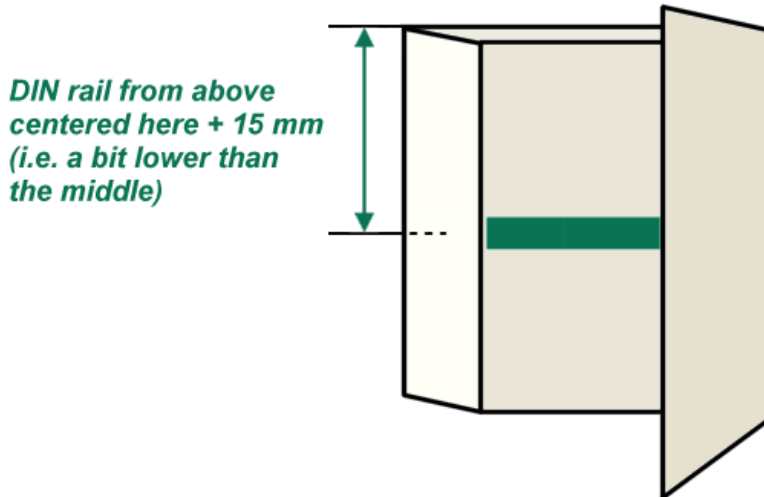


Fig. 54: Representation the mounting position of the DIN rail

- A 35 mm x 15 mm DIN rail according to EN 50022 is used for the mounting. This rail is mounted horizontally at the rear panel of the control cabinet. It must extend over the entire width of the control cabinet. The DIN rail must be installed such that the terminals are positioned vertically and exactly centrally in the control cabinet. The terminals should also be centered horizontally.
- The DIN rail must conductively connected to the control cabinet. The DIN rail is earthed with a cable (low-interference PE). Ensure the door is properly connected.
- The supply lines to the devices under test and the power feed terminals should exit at the front. The space above and below the terminals must be clear. The supply lines should be bundled such that convection in the control cabinet is obstructed as little as possible.

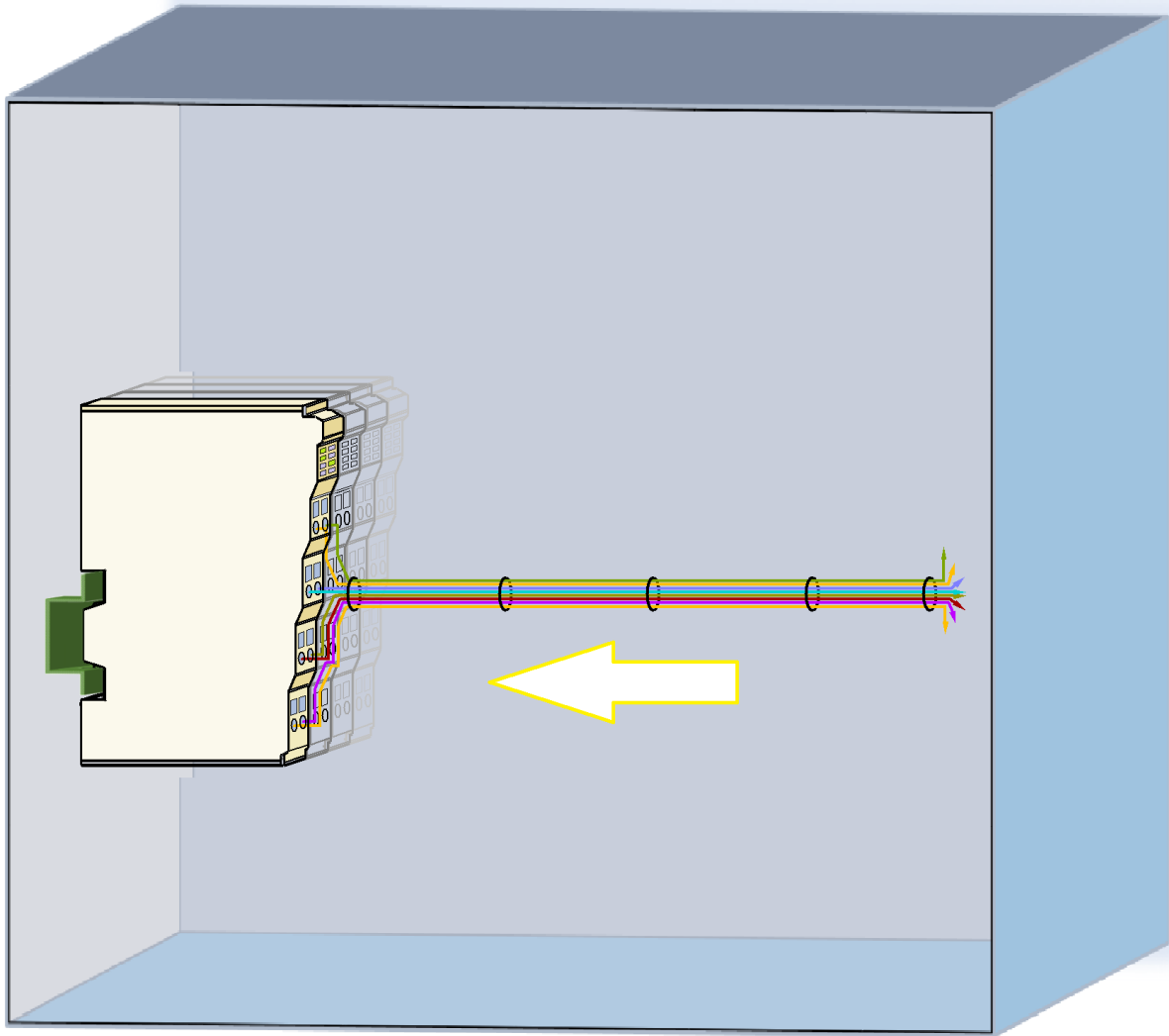


Fig. 55: Arrangement of the supply lines to and from the device under test in the control cabinet

- The control cabinet temperature is measured according to IEC 61131-2 at the indicated position at the air inlet point upstream of the terminal when the unit is ventilated. The ambient temperature must be measured with a (verifiable) accuracy of better than ± 0.2 °C. The temperature sensor must be mounted horizontally. The temperature outside the control cabinet must be controlled such that the temperature at the measuring point is a constant 23°C.

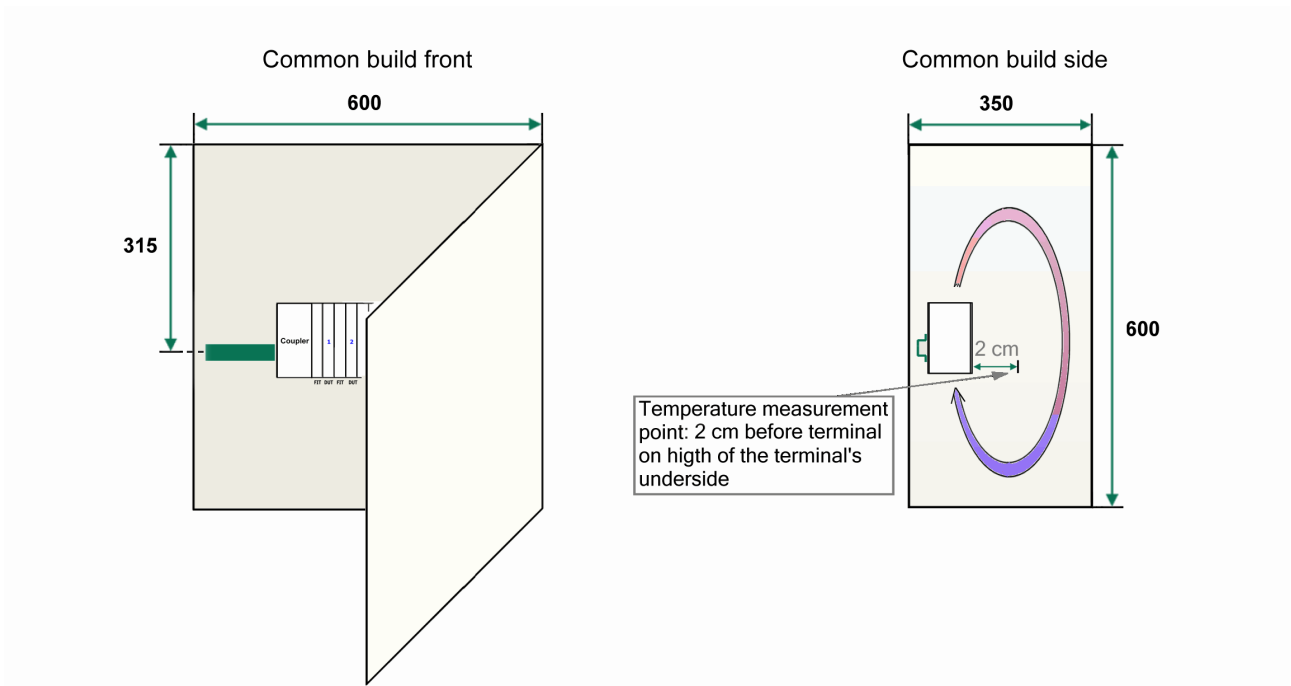


Fig. 56: Dimensions and installation in the control cabinet

- The control cabinet must be empty, except the terminals that are part of the measurement configuration, the supply lines and the temperature sensor.
- Any other terminals that may be required must be installed outside the control cabinet. The control cabinet feed-through should match the supply lines.
- Shielded cables should be used for the signal lines. The shield should be connected to the DIN rail. State of the art shielding should be used; cf. widely available documents, e.g. from ZVEI. Components from the Beckhoff shielding connection system (ZB8500, ZB8510, ZB8520) should be used for this purpose. The shielding should be connected on one side to the devices under test and the control cabinet.

Definition of the configuration

- The following terminals are required for the measurement configuration as a minimum; the configuration can include 2-10 devices under test. Configuration as follows, based on two devices under test as an example:
 - 1x Bus Coupler EK1100
 - 2x terminals to be measured ("devices under test")
 - 4x EBUS/KBUS power feed terminal EL9410
 - 1x bus end cap/end terminal EL9011
- The terminals are then lined up as shown below (for 2 devices under test):

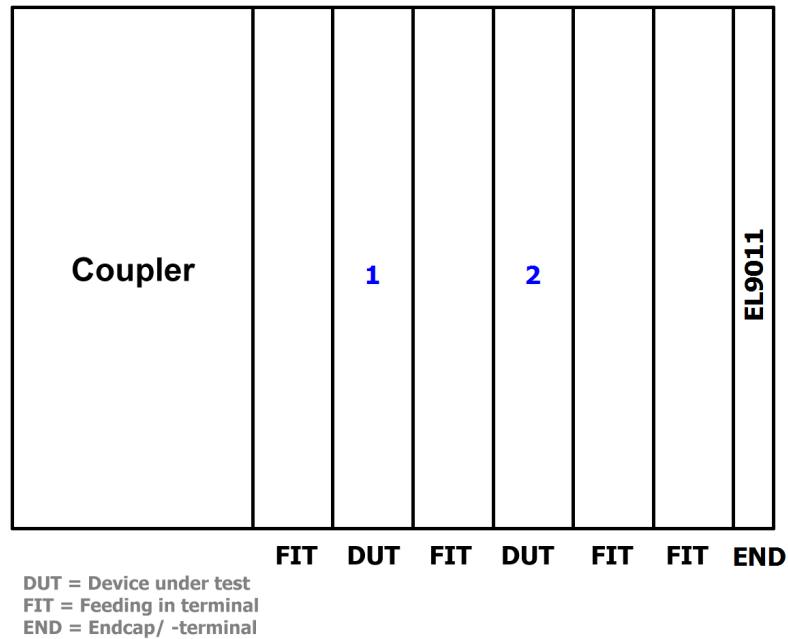


Fig. 57: Schematic diagram of the test configuration

- For thermal reasons, 2x EL9410 are connected at the end of the terminal segment. These ensure that the preceding "devices under test" 2 is operated in a way that is thermally similar to a center position in the terminal segment.
- Both supply voltages (U_s and U_p) must be connected to the Bus Coupler and all power feed terminals. The operating voltage must be $+24\text{ V} \pm 0.5\text{ V}$, unless an individual terminal requires a different U_p voltage.
- The ground connections of U_s and U_p may be short-circuited. The PE connections of the Bus Coupler and the power feed terminals do not have to be connected.
- If the devices under test have shielding (functional earth) at a terminal point, this must not be connected, since the terminals have a shield spring on the DIN rail at the rear.

5.7 Note on oscillation effects with analog 20 mA inputs

The standard analog signal "20m" (0...20 mA, 4...20 mA) is used for simple information transport between a signal transducer (usually a sensor) and the measuring device (here: Beckhoff analog input in the form of an IP20 terminal, IP67 box or similar).

For this purpose, it is important that the encoder/sensor can drive the set current I_0 (here: 20 mA) through the measuring device. Accordingly, the voltage U_{sensor} available at the sensor must be high enough to drive the set current through the "load" in the measuring device $R_{\text{measuring device}}$; this results in the load impedance from:

$$R_{\text{max, measuring device}} = U_{\text{sensor}} / I_0$$

As a rule, the sensor manufacturer specifies the max. permissible load impedance $R_{\text{measuring device}}$ in its data sheet. Similarly, for most 20 mA measuring devices, the load impedance should be specified in the associated data sheet; for some Beckhoff EL3xx Terminals, for example, it is 85 Ω.

In detail, however, the sensor (signal source) and the measuring device (signal sink) also form a complex network of various impedances, since both sides (must) contain capacitive/inductive elements for EMC protection reasons. In spite of the fact that both sides are designed in accordance with the specifications, however, an unfavorable combination of these impedances within the circuit consisting of the sensor and the measuring device can lead to permanent oscillations, which are superimposed on the signal to be measured from the sensor and thus falsify it: it must be taken into account that the capacitive/inductive elements, together with the regulation of the sensor voltage, cause the circuit to oscillate (the sensor may try to apply its set current "very dynamically").

Real observed examples of this with different combinations:

- Oscillation of about 200 kHz with amplitude ±3.6 V around an offset of about 0.2 V at the 85 Ω load of the input terminal used here; the analog input apparently measures about 2.3 mA.

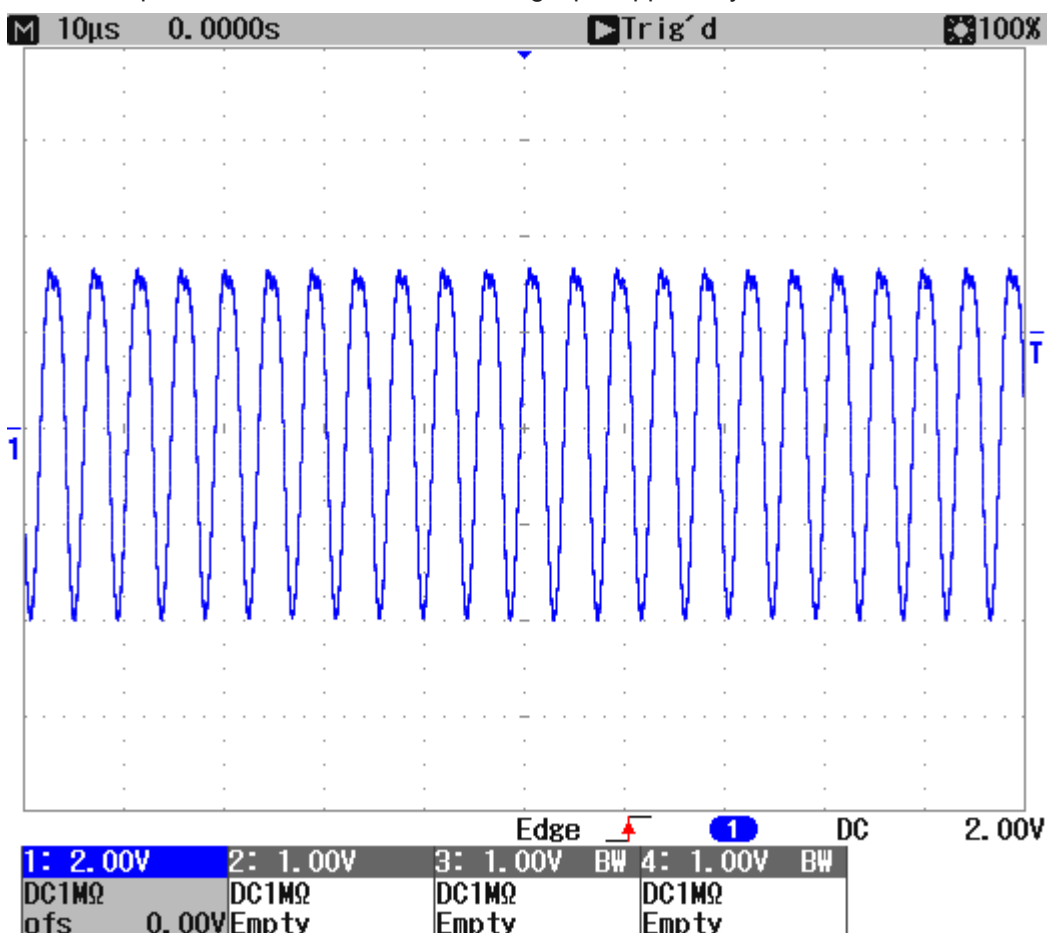


Fig. 58: Oscillation signal at load of an analog input terminal in the 20 mA measuring range (X: 10 μs/div, Y: 2 V/div)

- Oscillation of approx. 100 kHz with amplitude ± 0.2 V around approx. 1 V, measured at the load of an input terminal

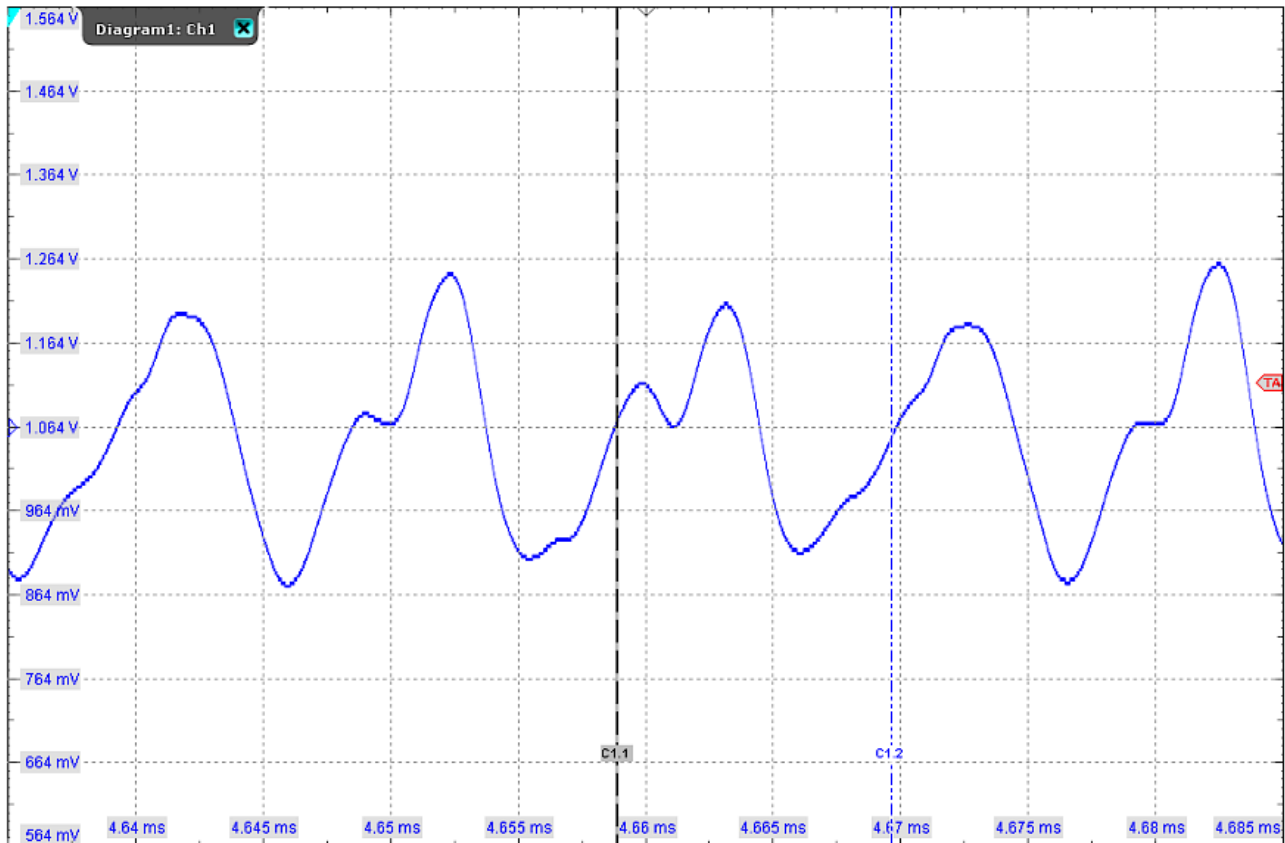


Fig. 59: Oscillation signal at load of an analog input terminal in the 20 mA measuring range (X: 5 μ s/div, Y: 100 mV/div)

Depending on how fast the measuring device scans, it then detects a more or less incorrect measured value, which may not change even if the sensor signal changes. Since this involves oscillations in the kHz range, the oscillating, distorted sensor signal can only be recorded from the control point of view by a measuring device (e.g. oscilloscope) with a high sampling rate ($\gg 1$ kSps).

In case of obviously wrong measurement, check first:

- Correct sensor connection, sensor supply, wiring,
- Transition resistances, wire breakage, connector, shielding, interferences
- Compatibility of the load (see above)

If permanent oscillation is still suspected after this,

- the effect on the 20 mA line can be determined by oscilloscope (see above),
- a series resistance of several 10 Ω (e.g. 100 Ω) can be inserted into the 20 mA line as a test; the system is thus changed and the tendency to oscillate is usually reduced.

To remedy this,

- you can use a functionally identical input of another series: e.g. EL307x instead of EL301x/ EL302x/ EL304x/ EL305x; EL317x instead of EL311x/ EL312x/ EL314x/ EL315x or,
- the experimentally determined series resistance can be used permanently (observe max. permissible load!).

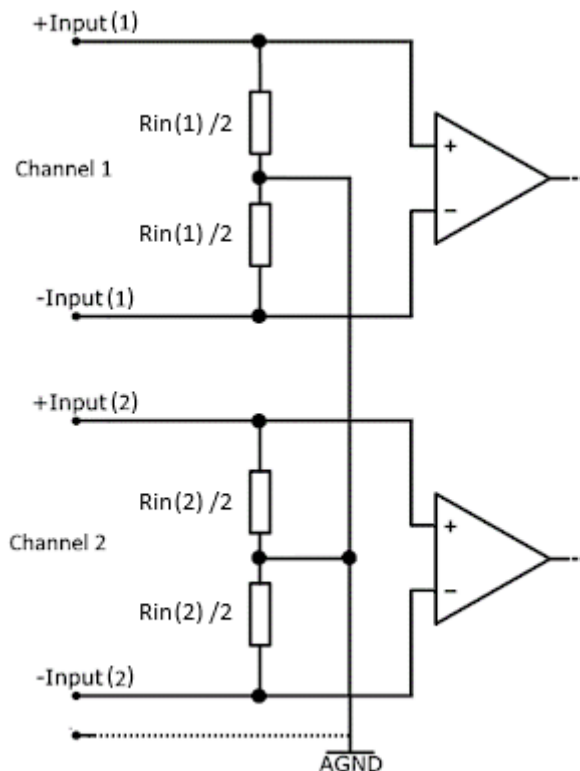
5.8 Electrically (un)isolated channels

5.8.1 Explanations

Channels isolated or not? That is the question!

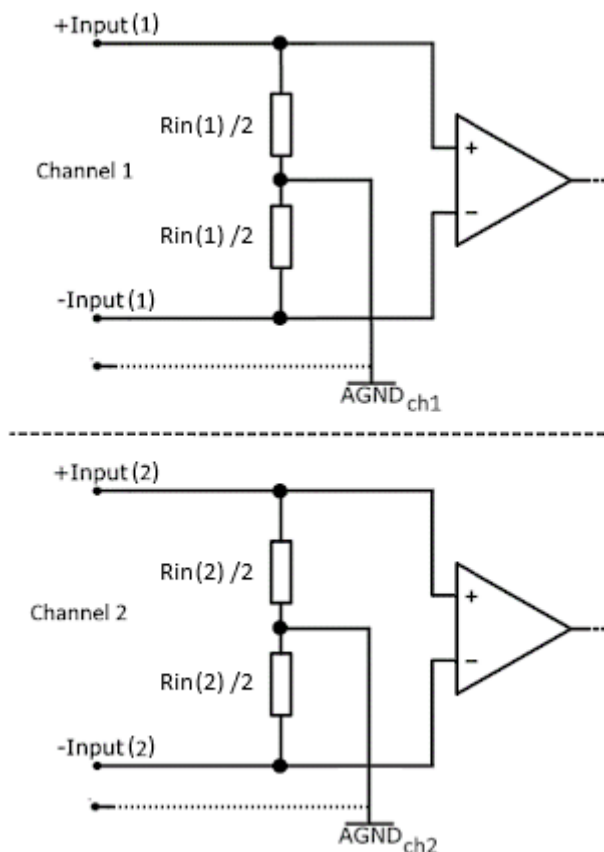
For multi-channel terminals such as the EL3xxx/ ELM3xxx or equivalent electronic measuring devices from Beckhoff (as EPP35xx), one particular property is quite essential and, depending on the application, requires intensive attention: the electrical isolation between the channels. There are only two classes:

- **The channels are not electrically isolated from one another:**
 - They have at least a common ground potential in the device, which is sometimes also accessible from the outside via line connection or power contact.



- Such devices are usually simpler (and thus cheaper) in their internal construction than the following class. However, the fact that the channels are electrically coupled leads to effects that must be considered. This applies to both static (DC) input signals that "drag along" a secondary channel (in the device) via ohmic coupling (common mode effect), and dynamic (AC) signals that also "drag along" or inductively/capacitively overcouple (crosstalk).
 - Industrial automated machines and test benches move in a spatially delimited, normally controlled space and usually have a common power supply, as a rule a 24 V DC network with a common ground (0 V). With proper wiring, potential differences greater than 30 V do not occur in most applications. For this reason, most analog channels for industrial use (also in the case of Beckhoff) do not have complex electrical isolation but are designed to operate as specified with common mode differences up to approx. 30 V (common mode voltage).
 - Most analog channels from Beckhoff are constructed without electrical isolation between one another in the device.
- **The channels are electrically isolated from one another:**

- They are completely isolated from one another; their grounds and supplies are not connected to one another in the device and device plug. But insulation also has a limit, which is quantified in the so-called insulation voltage or electrical isolation.



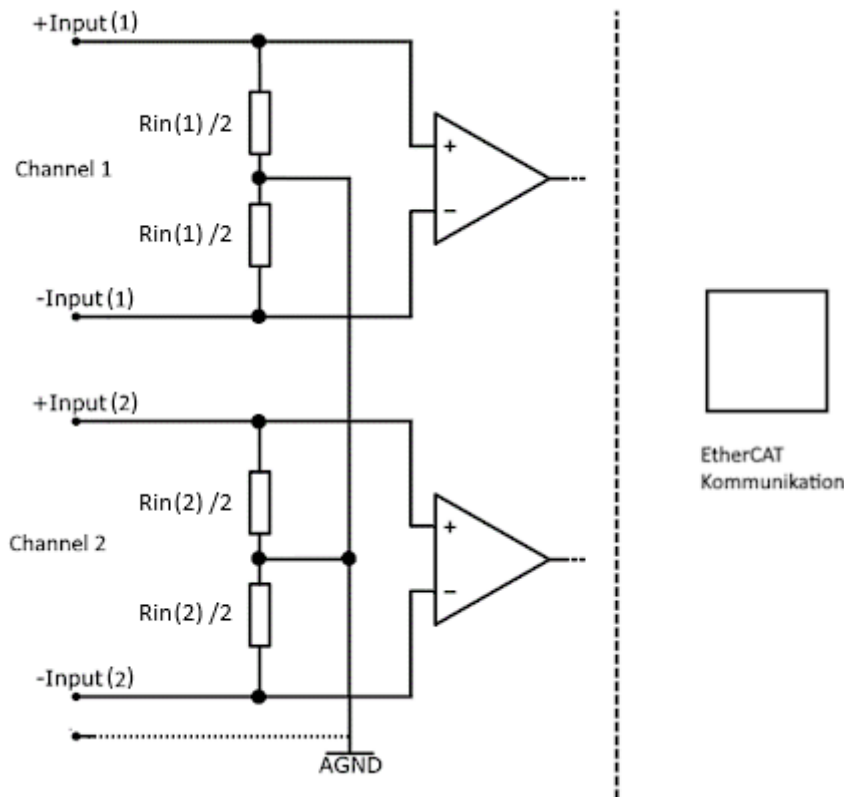
- Such devices are more complex in their internal structure than the representatives of the aforementioned class. The big advantage, however, is that at least the "ohmic" common mode effect (the "dragging along") of the DC signal (see [note \[► 151\]](#)) is negligible as long as the electrical isolation is not exceeded. But even with this concept, crosstalk from AC signals can be noticeable, although basically many orders of magnitude less pronounced than with non-isolated channels. If the channels are reconnected outside the device on the application side (common ground, common supply), the concept is bypassed, and the effects mentioned above occur again.
 - The channels of such devices behave independently of one another and are therefore easier to use, fewer considerations have to be made with regard to potential differences - however at the cost of a significantly higher price. They are therefore often used in test benches and complex measurement scenarios (stacked battery cells, high voltages).
 - Beckhoff offers some EL3xxx/ELM3xxx analog input devices with electrically isolated channels for special applications, such as the EL3174-0002, EL3314-0002, ELM3702-0101, ELM3102-0100, etc. Note the insulation voltage specified in each case and the quality (functional insulation, double insulation, basic insulation) in which it is designed.
- **Mixed structure**
 - Both classes can be mixed in one device by combining the channels into groups, each with a common ground.

Note: Regardless of whether and how the channels are isolated from each other, it can always be assumed that the field side and the communication side are electrically isolated from each other in the case of automation technology equipment.

- For EtherCAT components,
 - field side means digital or analog inputs/outputs, RS232/485, Ethernet, ...
i.e. everything that is connected "from the field" = from outside.
- For EtherCAT Terminals,
 - communication side means "inner" part, EtherCAT backplane communication "E-bus",

- For Fieldbus Box modules,
 - communication side means "inner" part, EtherCAT connections IN/ OUT.

The magnitude and quality of this isolation are specified in the technical data.



The isolation of the field/bus side also allows the channels of devices that have no reference to the system supply on the field side (e.g. because they have no power contacts) to be operated as isolated islands. With 1-channel analog measurement modules, this creates electrically isolated channels.

Note:

You are reminded of the chapter [Notes on analog aspects - dynamic signals \[► 114\]](#) for the AC/DC structure of signals in this documentation.

5.8.2 On the mutual influence of non-isolated differential channels

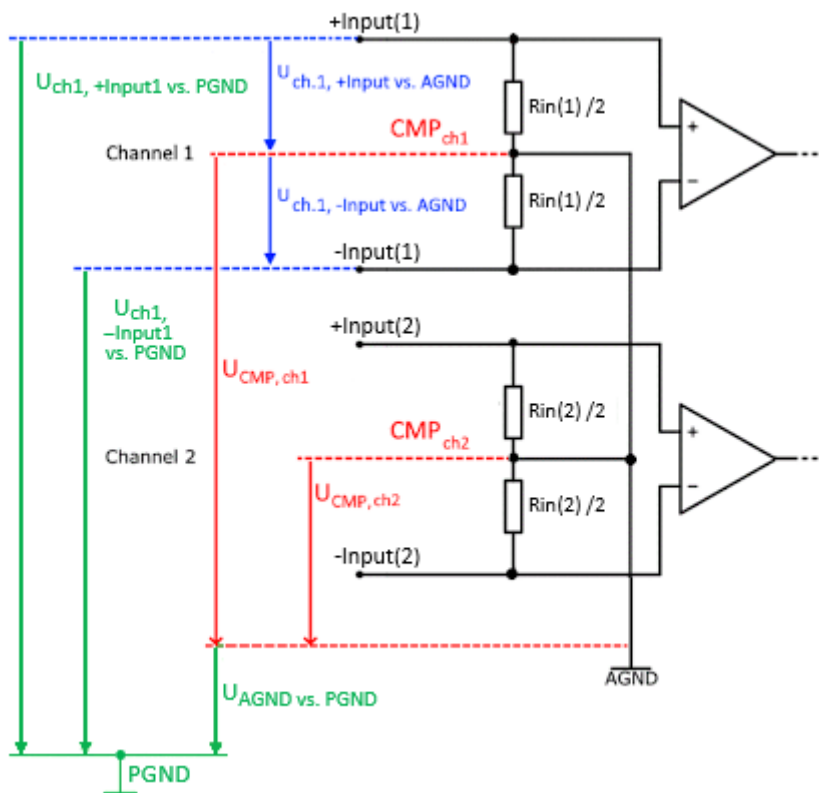
This section assumes the following chapters as prior knowledge

- "Explanation of electrically (un)isolated channels" [► 149]
- "Ground reference: single-ended/differential typification" [► 89]
- "Explanation of the term GND/Ground" [► 99]

In the following, we will further deal with the channels that are not isolated in the device and that are fed with signals with a common ground (PGND). The common ground of the connected channels (accessible from the outside, if necessary) and the differential measurement namely generate an electrical phenomenon that must be controlled on the application side by a short calculation to ensure that the device can do what it is expected to do - especially if high-precision measurement technology of the ELM3xxx series (or equivalent Beckhoff measuring devices as EPP35xx) is involved, i.e. with the claim of lowest measurement uncertainty.

Note: (High impedance) voltage measurement specifically is focused on here, for explanations on current measurement refer to the chapter [Ground reference: single-ended/differential typification](#) [► 89].

In addition, a detailed insight into the differential inner workings, taking the example of a circuit with two unisolated channels:



Let R_{in} be the input resistance of the channel (see device documentation, input impedance/internal resistance specification). In *real* terms, it consists of two resistances with $R_{in}/2$ each. The two resistances form a voltage divider for the respective channel and actually define the respective CMP (CommonMode-Point) with its voltage $U_{CMP, ch}$ vs. AGND, depending on which voltage

$$\frac{U_{+Input vs. PGND} + U_{-Input vs. PGND}}{2}$$

is applied externally via +Input/ -Input. The CMP is the channel local AGND. However, since all AGND are related, all voltages and therefore all voltages applied to +input/-input are involved in the AGND definition! Because it must become: $U_{CMP, ch1} = U_{CMP, ch2} = \dots = AGND$.

Knowledge of the final potential level of AGND is important for assessing whether specified application limits are exceeded, because each channel will have its own, possibly unbalanced voltage differences $U_{ch(n), +/-input}$ vs. U_{AGND} ! Due to the AGND shift, even an outgoing voltage on an unconnected channel can be measurable, which is also loadable to a limited extent (source resistance is then half the input resistance).

However, this topic, which seems complex at first glance, can be approached quite easily and thus a high degree of operational reliability can be achieved with the low-cost, unisolated differential channels. The following procedure is recommended:

1. Calculate U_{AGND} referred to U_{PGND}
PGND (system ground, supply) is selected as reference level for the above reasons,
2. Calculate all inputs on potential difference to AGND in use
(for steps two and three see calculation table below),
→ <https://infosys.beckhoff.com/content/1033/ioAnalogManual/Resources/12222836875/.xlsx>
3. Check for exceeding the specification.

Regarding 1: calculation of AGND

U_{AGND} can be calculated as a weighted average of the external voltages, where the weighting factors are the electrical conductances (reciprocals of the input resistances) of the individual inputs to AGND. For DC voltages:

$$U_{AGND} = \frac{\sum_{n=1}^N \left[\frac{1}{R_{in(n)}} \cdot (U_{+Input(n)} + U_{-Input(n)}) \right]}{2 \cdot \sum_{n=1}^N \left(\frac{1}{R_{in(n)}} \right)}$$

Note: n is the channel index and goes from 1 to the last connected channel N . All voltages U are referenced to PGND. If the internal resistances of all inputs are (theoretically) equal, the simplified result for U_{AGND} is the average value of all input voltage differences:

$$U_{AGND} = \frac{\sum_{n=1}^N (U_{+Input(n)} + U_{-Input(n)})}{2 \cdot N}$$

With some measurement modules the internal analog ground AGND is externally accessible. The voltage can be measured easily there. Care must be taken that the measuring device used (in the typical case a multimeter) does not distort the voltage U_{AGND} by its own internal resistance!

A selection:

ELM3502-00x0, ELM3504-00x0, EPP3504-0023	Via the -Uv connection on the push-in socket
ELM314x-00x0	Via Up-. For this, the setting "Connect Up- to GNDA" in the CoE (F800:01) must be set to TRUE.
ELM334x-00x0	Via the AGND connection (5 and 6) to the push-in sockets

Regarding 2: calculation inputs

After we have learned about U_{AGND} , the max. permissible voltages or the voltages at the connection contacts are to be calculated.

Steps two and three can easily be performed using this sample table
→ <https://infosys.beckhoff.com/content/1033/ioAnalogManual/Resources/12222836875/.xlsx>

Usage: fill grey cells
 1. set with "x" which channel is in usage
 2. set Rin each channel
 3. set input voltages at + and - point
 4. check columns K against device spec

Channel	in Usage	Rin [Ohm]	Point	+Input vs. PGND	Denominator	Input vs. AGND
1	x	660.000	+	30,0 V	0,0000909 [V]	16,9 V
			-	0,0 V		-13,1 V
2	x	4.100.000	+	2,0 V	0,0000010 [V]	-11,1 V
			-	0,0 V		-13,1 V
3		4.100.000	+	0,0 V	0,0000000 [V]	0,0 V
			-	0,0 V		0,0 V
4		4.100.000	+	0,0 V	0,0000000 [V]	0,0 V
			-	0,0 V		0,0 V
	Sums:	0,000007 1/Ohm			0,0000919 [V]	
			AGND vs. PGND:	13,059 V		

Regarding 3: testing

The results are to be compared with the specification limits according to the documentation with respect to

- usage limit: "max. permitted voltage during specified normal operation",
- destruction limit: "dielectric strength – destruction limit"

Notes:

- As can be seen from the steps above, changes at the inputs usually result in a change to AGND, regardless of whether the signal +input and -input change uniformly (same magnitude, same sign) (common mode influence, CommonMode) or separately. An influence of the other channels will always be visible in the measured values at high magnification.
Exception: if +input changes by the opposite amount to -input, then the CMP of the channel and its influence on the other channels remains unchanged
- these explanations concern differential channels. Single-ended channels, on the other hand, are connected at one end to a signal ground (which need not necessarily be PGND) and are thus inevitably coupled to one another; depending on the wiring, AC crosstalk can be observed. An AGND shift in the device also occurs here, but since AGND is usually not accessible in these devices, this represents the normal operation of the device and is covered by the specification.
Cf. the Beckhoff definition of "SingleEnded" in chapter "Ground reference: single-ended/differential typification" [[▶ 89](#)]

Here are a few examples ¹⁾:

- **Example 1:**

ELM3004-0000, all channels in $U \pm 10\text{ V}$ mode, all negative inputs (-Input) connected to PGND (external reference potential) (single-ended operation), channel 1 measures +10 V, all other channels -10 V, $R_{in} = 4.1\text{ M}\Omega$

- Usage limit: typ. $\pm 12.5\text{ V}$ against $-U_v$ (AGND)
- According to equation: $V_{AGND} = -2.5\text{ V}$

- $V_{+Input(1), AGND} = +10\text{ V} - (-2.5\text{ V}) = +12.5\text{ V OK}$
- $V_{-Input(1), AGND} = 0\text{ V} - (-2.5\text{ V}) = +2.5\text{ V OK}$
- $V_{+Input(2), AGND} = -10\text{ V} - (-2.5\text{ V}) = -7.5\text{ V OK}$
- $V_{-Input(2), AGND} = 0\text{ V} - (-2.5\text{ V}) = +2.5\text{ V OK}$
- $V_{+Input(3), AGND} = -10\text{ V} - (-2.5\text{ V}) = -7.5\text{ V OK}$
- $V_{-Input(3), AGND} = 0\text{ V} - (-2.5\text{ V}) = +2.5\text{ V OK}$
- $V_{+Input(4), AGND} = -10\text{ V} - (-2.5\text{ V}) = -7.5\text{ V OK}$
- $V_{-Input(4), AGND} = 0\text{ V} - (-2.5\text{ V}) = +2.5\text{ V OK}$

• **Example 2:**

ELM3002-0000, both channels in $U \pm 2.5\text{ V}$ mode. Channel 1 measures a high-side shunt (i.e. +Input(1) to +24 V) with -300 mV, channel 2 measures a low-side shunt (i.e. -Input(2) to PGND) with +800 mV.

- Usage limit: typ. $\pm 12.5\text{ V}$ against $-U_v$ (AGND)
- According to equation: $V_{AGND} = +12.125\text{ V}$
- $V_{+Input(1), AGND} = +24\text{ V} - 12.125\text{ V} = +11.875\text{ V OK}$
- $V_{-Input(1), AGND} = +23.7\text{ V} - 12.125\text{ V} = +11.575\text{ V OK}$
- $V_{+Input(2), AGND} = 0.8\text{ V} - 12.125 = -11.325\text{ V OK}$
- $V_{-Input(2), AGND} = 0\text{ V} - 12.125\text{ V} = -12.125\text{ V OK}$

• **Example 3:**

As above, but the high-side shunt is connected to +30 V:

- According to equation: $V_{AGND} = +15.125\text{ V}$
- $V_{+Input(1), AGND} = +30\text{ V} - 15.125\text{ V} = +14.875\text{ V NOK}$
- $V_{-Input(1), AGND} = +29.7\text{ V} - 15.125\text{ V} = +14.575\text{ V NOK}$
- $V_{+Input(2), AGND} = 0.8\text{ V} - 15.125 = -14.325\text{ V NOK}$
- $V_{-Input(2), AGND} = 0\text{ V} - 15.125\text{ V} = -15.125\text{ V NOK}$

• **Example 4:**

ELM3002-0000, channel 1 in $U \pm 30\text{ V}$ mode (other R_{in} !), channel 2 in $U \pm 10\text{ V}$ mode. Both negative inputs (-Input) connected to PGND (external reference potential). Channel 1 measures +20 V, channel 2 measures +2 V:

Usage limits:

Channel 1: typ. $\pm 35\text{ V}$ against $-U_v$ (AGND), channel 2: typ. $\pm 12.5\text{ V}$ against $-U_v$ (AGND)

- According to equation: $V_{AGND} = +7.816\text{ V}$
- $V_{+Input(1), AGND} = +20\text{ V} - 7.816\text{ V} = +12.2\text{ V OK}$
- $V_{-Input(1), AGND} = 0\text{ V} - 7.816\text{ V} = -7.8\text{ V OK}$
- $V_{+Input(2), AGND} = 2\text{ V} - 7.816\text{ V} = -5.8\text{ V OK}$
- $V_{-Input(2), AGND} = 0\text{ V} - 7.816\text{ V} = -7.8\text{ V OK}$

• **Example 5:**

as above, but channel 1 measures +30 V:

- $V_{AGND} = +13.059\text{ V}$
- $V_{+Input(1), AGND} = +30\text{ V} - 13.059\text{ V} = +16.9\text{ V OK}$
- $V_{-Input(1), AGND} = 0\text{ V} - 13.059\text{ V} = -13.1\text{ V OK}$
- $V_{+Input(2), AGND} = 2\text{ V} - 13.059\text{ V} = -11.1\text{ V OK}$
- $V_{-Input(2), AGND} = 0\text{ V} - 13.059\text{ V} = -13.1\text{ V NOK}$

¹⁾ The values given for usage limit and R_{in} are to be regarded as examples; valid specification values can be found in the respective device documentation.

5.8.3 Wiring of differential current inputs

This chapter is based on the previous explanations and considers the common-mode theme with respect to (differential) current measurement by shunt (integrated measuring resistance).

Shunt current measurement inputs are generally electrically connected to the current circuit. If the measuring device (e.g. analog input terminal) has multiple channels that are not electrically isolated from one another, the potential references must be considered with this measurement application as well.

The following decision tree can be followed:

- For electrically isolated current measuring channels, the specified insulation strength must be observed. In principle, such channels measure differentially on two poles between input and output; a U_{cm} consideration is not necessary.
- If the channels are not electrically isolated (i.e. they have a common reference ground inside the device) and are
 - single-ended (this means that one channel pole in the device is forcibly connected to a special potential, e.g. negative power contact and this applies to all channels in the device),
→ then no U_{cm} consideration is necessary here either; only the maximum voltage applied across the shunt needs to be compared to the channel specification
 - differential (this means that both poles are freely selectable and accessible)
→ a U_{cm} consideration is necessary because, depending on the external potentials, a CMP that may be impermissible (see previous chapter) may arise internally. $U_{CM, max}$ may not be exceeded on any of the channels inside the device.

If $U_{CM, max}$ of an analog input channel is exceeded, this may result in significantly incorrect measurements due to internal equalizing currents.

In order to consider the theoretical considerations with numbers, here is a

Consideration using a differential 20 mA measurement with the EL30xx/EL31xx as an example

NOTICE

Numerical values in the example

The numerical values used in the following should be regarded as examples; please refer to the corresponding device documentation for specific statements on the products considered.

- The EL301x, EL302x, EL311x and EL312x are designed for differential 20 mA measurement, i.e. a specific potential reference is not necessary (but recommended!).
- The individual terminal is regarded here as the system limit.
- The current is measured via a 33 Ω shunt per channel, consequently there is a maximum voltage drop of 660 mV across the shunt at 20 mA
- Additional internal resistor arrangement (voltage divider, protective resistors) with GND point (A) central to the shunt.
The layout of the resistors is so symmetrical that the potential of (A) comes to rest centrally with respect to the voltage drop across the shunt.
- The central point of the voltage dropping across the 33 Ω shunt is termed the common-mode measurement point (CMP).
According to the technical data for the product, the maximum permissible U_{CM} voltage (common mode) is referenced to the potential between the CMP of a channel and the internal GND or to the potential between the CMP of two channels inside a terminal.
It must not exceed the specified limit (typically ± 10 or ± 35 V).
- The common GND_{int} potential (A) is
 - fed to a terminal point in the case of 1- and 2-channel terminals from the above series and not connected to GND_{PC} (power contact); it is thus freely selectable and connectable from outside. The U_{CM} specification can thus be complied with through the wiring of this GND point to suit the application, making it possible to use this device even with atypical sensor wiring.
 - connected to GND_{PC} in the case of 4-channel terminals and is thus not freely selectable.
- This GND potential GND_{int} is common for all channels implemented in the terminals.

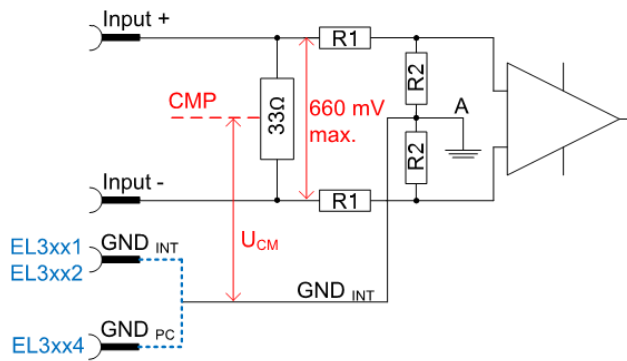


Fig. 60: Internal connection wiring of a 20 mA channel in the above series, R1/2 e.g. 10 kΩ

The connected GND points inside the terminal can be seen in the block diagram of a 2-channel terminal (Fig. [▶ 157] *Internal connection wiring of two 20 mA channels from the above series*):

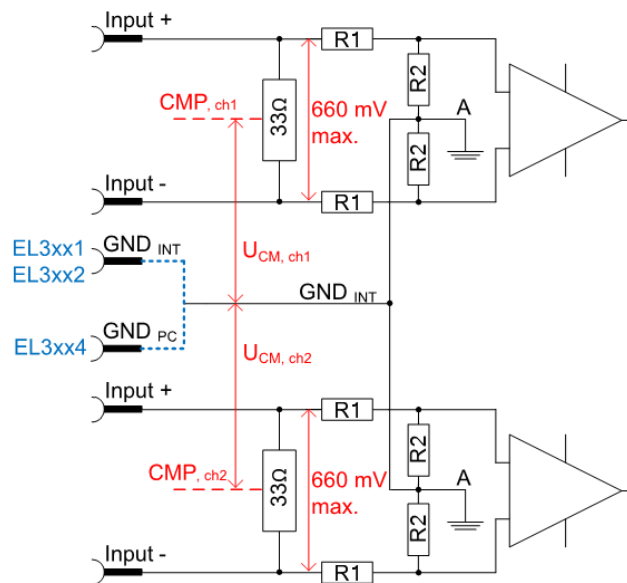


Fig. 61: Internal connection wiring of two 20 mA channels from the above series

Below, various wiring options are considered with regard to their admissibility in respect of the CMP. It is assumed that the current sensors output 100% output end value, i.e. 20 mA.

Example 1a

The 2-channel EL3012 is wired with two sensors that are supplied from 5 and 24 V. Both current measurements are executed as low-side measurements. This type of connection is permissible, because CMP_{ch1} and CMP_{ch2} each lie around 330 mV above 0 V at I_{max} ; U_{CM} is thus always < 0.5 V. $U_{CM} < 10$ V is thus complied with (applies to EL30xx).

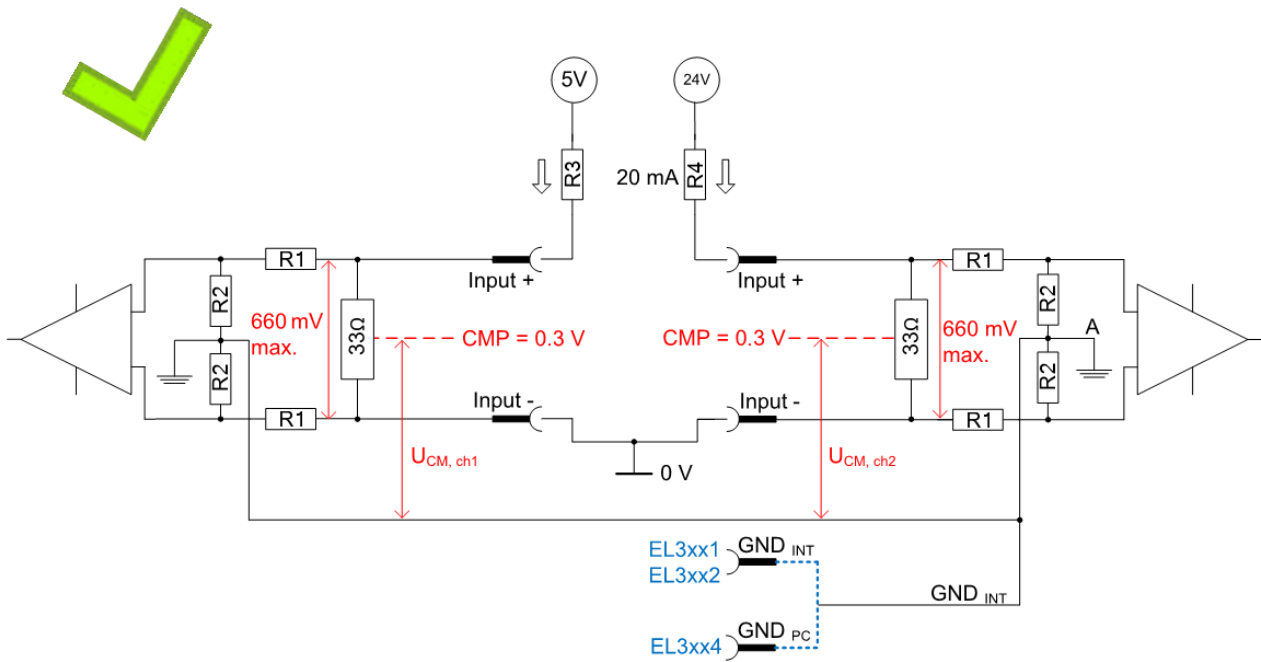


Fig. 62: Example 1a: Low-side measurement ($R_3 = 250 \Omega$, $R_4 = 1200 \Omega$)

If GND_{int} is not externally wired in the case of the EL30x1/EL30x2 or EL31x1/EL31x2, the potential on GND_{int} can settle according to necessity – it "floats". Please note that reduced measuring accuracy is to be expected for this mode.

Example 1b

This also applies accordingly if the floating point GND_{int} is pulled to a different potential.

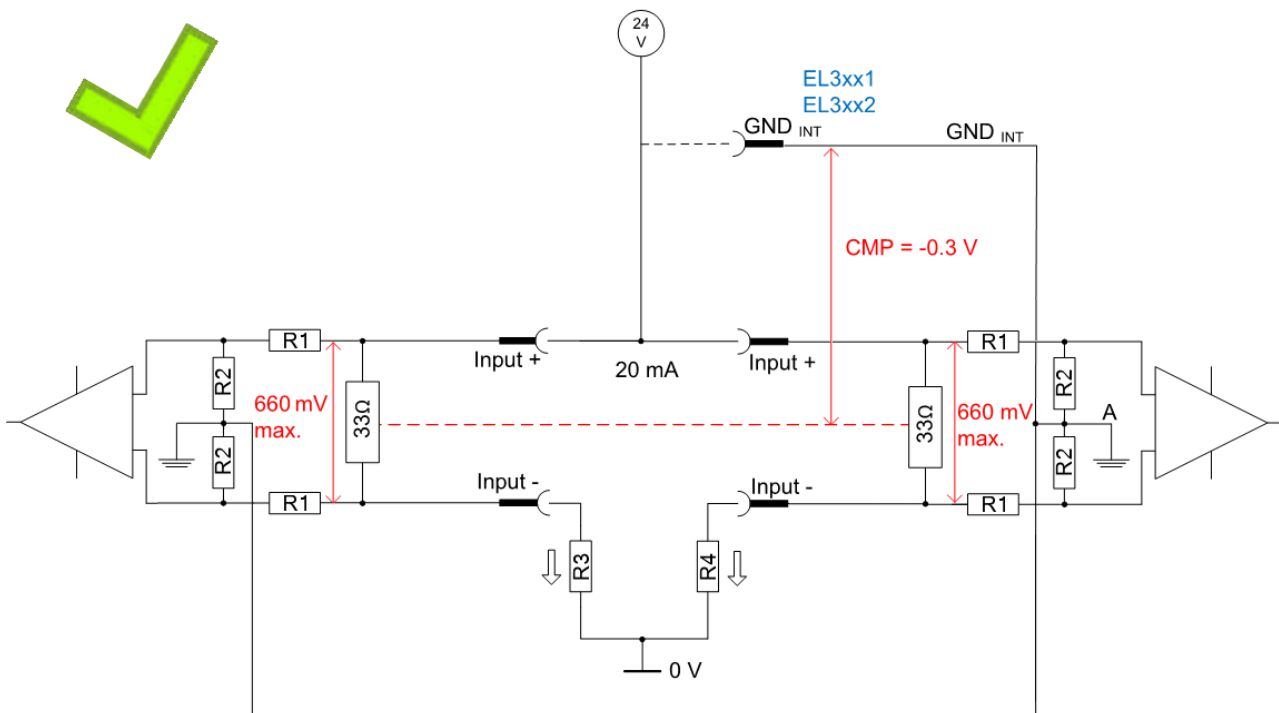


Fig. 63: Example 1b, high-side measurement ($R_3 = R_4 = 1200 \Omega$)

Example 2a

The same EL3012 is now wired again with the two 20 mA sensors, but this time once in low-side measurement at 5 V and once in high-side measurement at 12 V. This produces a considerable potential difference $U_{CM} > 10\text{ V}$ between the two channels. If $U_{CM,max}$ were to be 10 V, this would not be permissible (observe the respective device specification!)

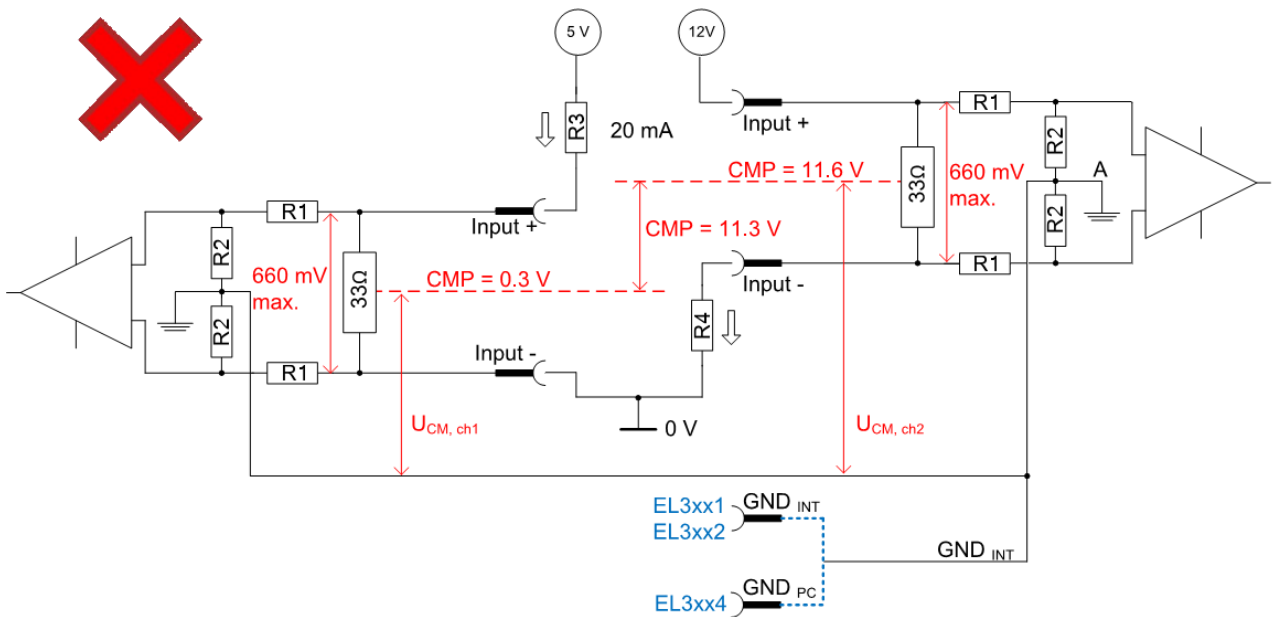


Fig. 64: Example 2a, impermissible high-side/low-side measurement ($R_3 = 250\ \Omega$, $R_4 = 600\ \Omega$)

As a remedy, GND_{int} could be connected in this case with an auxiliary potential of 6 V referenced to "0 V". A/GND_{int} thus settles approx. in the middle between 0.3 V and 11.6 V.

Example 2b

In the EL3xx4, GND_{int} is connected internally with the negative power contact. The choice of potential is therefore limited.

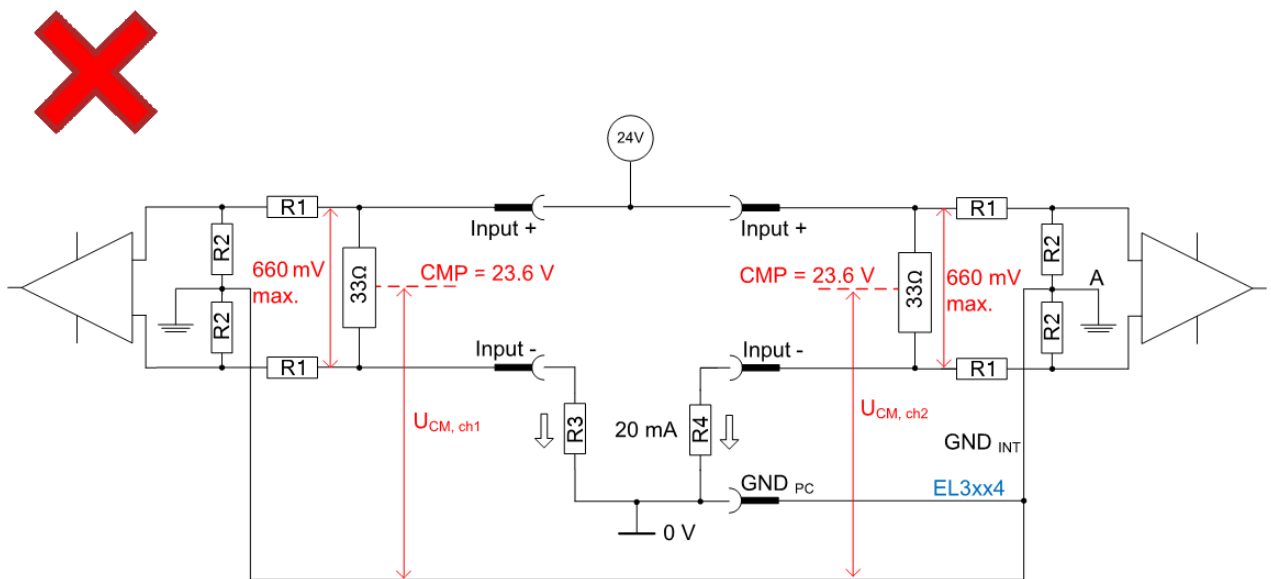


Fig. 65: Example 2b, impermissible EL3xx4 wiring ($R_3 = R_4 = 1200\ \Omega$)

The CMP settles at 23.6 V and thus $\gg 10\text{ V}$.

Summary

This results in precise specifications for the external wiring of differential current inputs with 20 mA sensors:

- It is recommended if possible to connect GND_{int} to a low-impedance, interference-free potential, as this significantly improves the measuring accuracy.
Observe the notes on the potential reference U_{CM} !
- The potential reference $CMP < U_{CM,max}$ must be complied with, both between $CMP \leftrightarrow GND_{int}$ and between $CMP_{ch(x)} \leftrightarrow CMP_{ch(y)}$.
If this cannot be guaranteed, single-channel variants or multi-channel variants with electrical isolation must be used.
- If the sensor cable is shielded, it must not be connected to the GND_{int} terminal point, but to a low-impedance shielding point provided for the purpose.

5.9 Number theory for INT32, REAL32

Some devices offer the possibility to transmit the data value as floating-point number ("Float"/ REAL).

Advantages:

- the data value can be read directly during commissioning
- no scaling to 0x7FFF or similar necessary in the PLC
- values (especially less than 1) can be represented with decimals, e.g. for weighing applications

Disadvantages:

- Practical: with 16-bit analog values larger data width, process image and thus EtherCAT load increases by a factor of 2 (INT16 → REAL32)
With 24-bit analog values no effect (INT32 → REAL32)
- Theoretical: representation errors occur

On the subject of "representation errors", a few remarks:

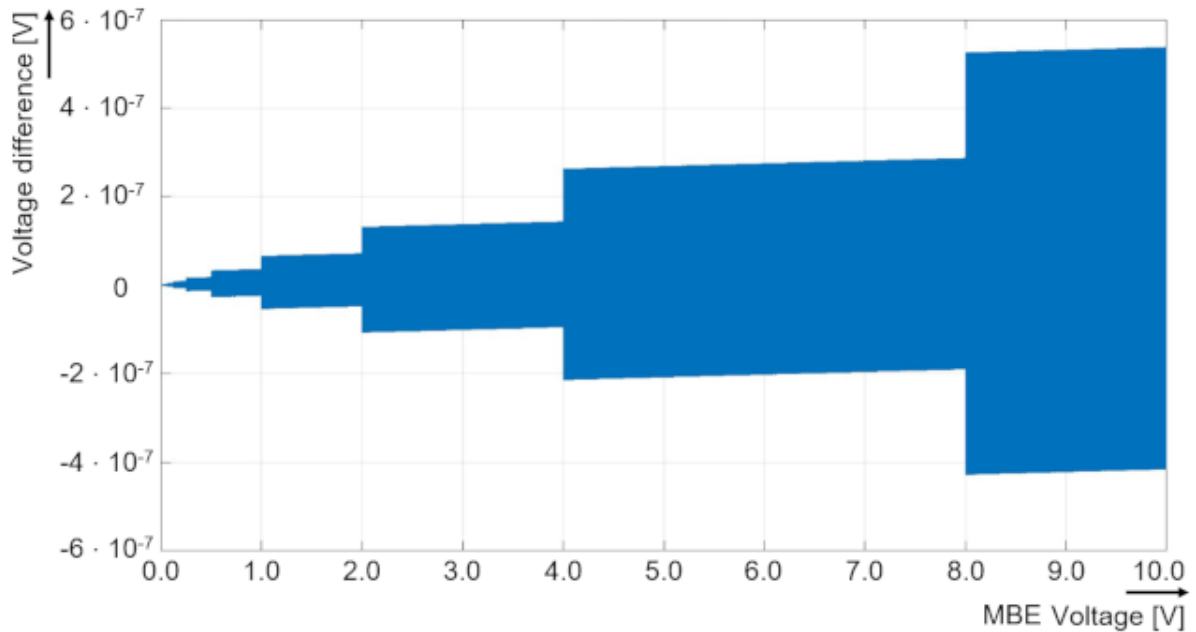
- The structure of the 32-bit data type REAL according to IEC 61131 3 / IEC 559 / IEEE754 is 1 bit sign, 8-bit exponent to base 2 with sign (-126...+127), 23-bit mantissa (0...8,388,607). The theoretical range of values is thus decimal approx. $\pm 3.402823... \cdot 10^{+38}$.
- There are two special effects when converting Integer → Float that have to be considered, no matter if the conversion is done in the analog device or in the PLC on the control side:
 - The distance between two consecutive numbers that can be represented as REAL32 varies: as soon as the steps at a decimal place become larger than 1, these decimal places are no longer suitable for a linear (complete) representation of a number space.
 - there is a loss of information due to the forced transition from decimal to binary number space (and back). If a decimal number no longer corresponds to the float representation from one decimal place, these decimal places are also no longer usable from here and downwards. In the following some number examples are listed (incl. thousand separator, analog technically usable part highlighted):

```

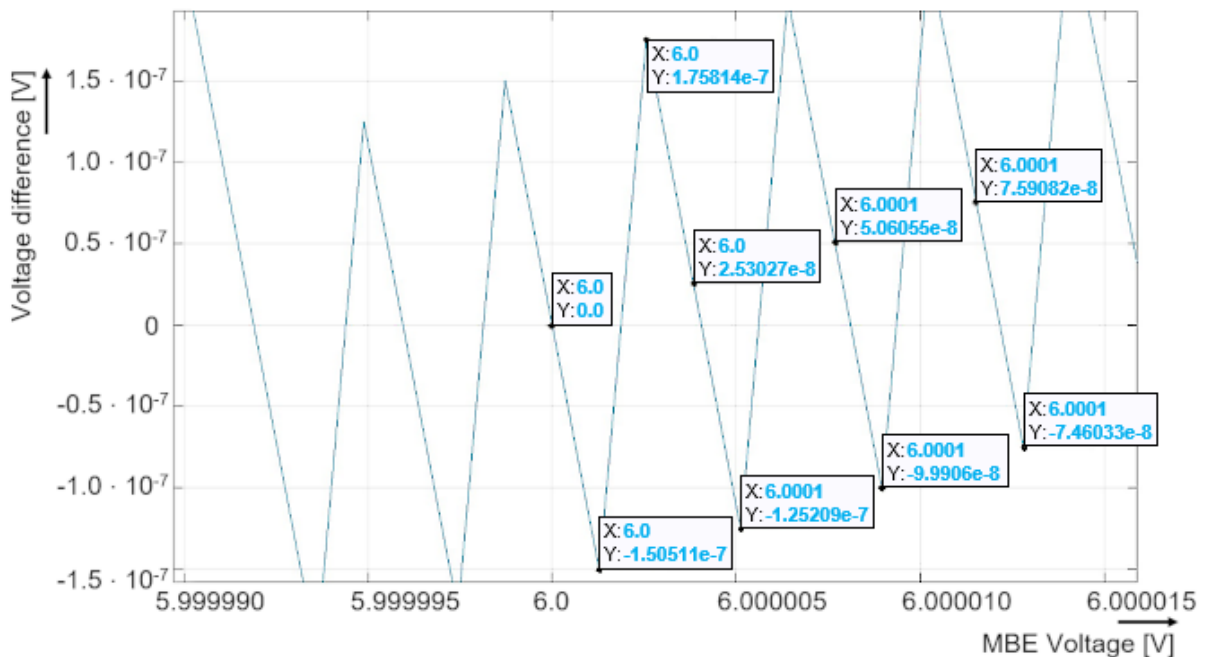
0.010,000,003,501
0.800,000,250,3
1.000,000,476,8
9.000,003,814
12.000,004,768
12,345,698.0
123,457,088.0
123,457,028,096.0
    
```

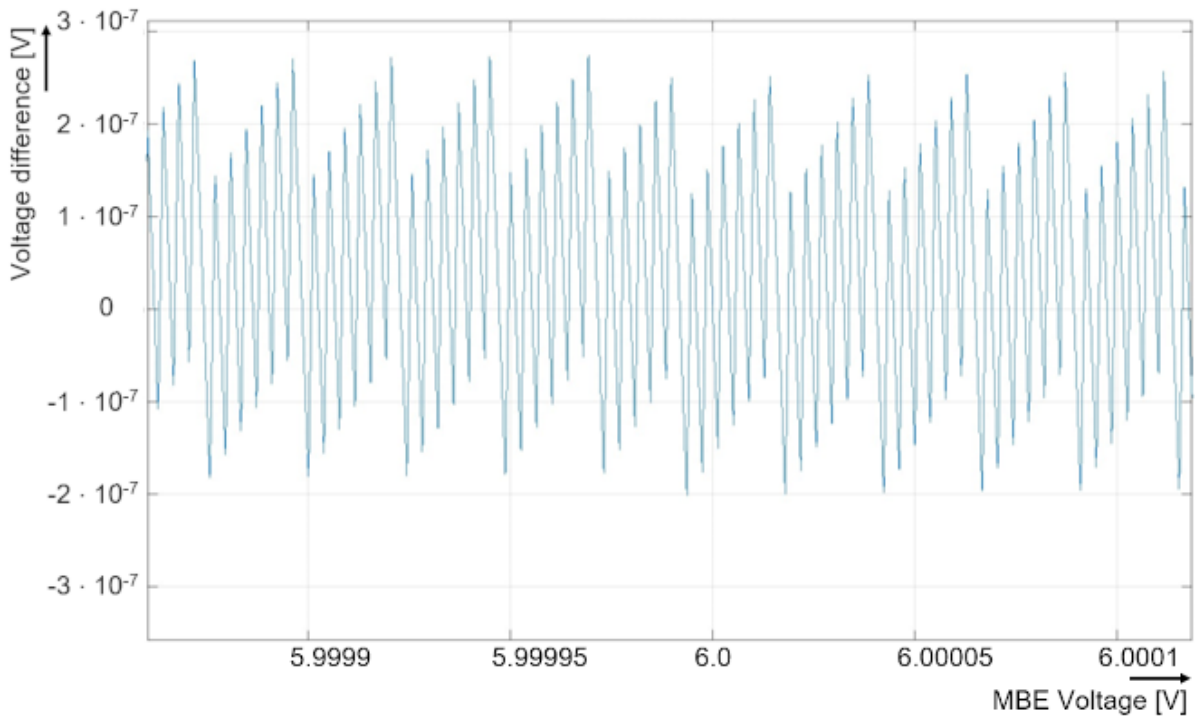
- Vendor/product specific it has to be considered with which step size data values have to be displayed at all: if a selection range of 10 V is resolved to 23 bits + sign, the step size is $10 \text{ V} / 8,388,608 = 1.192... \mu\text{V}$, in the Beckhoff extendedRange $10 \text{ V} / 7,812,500 = 1.28 \mu\text{V}$. It is therefore sufficient in the following to carry out the considerations with this fineness.

- For exemplary orientation the difference between a REAL32 (assumed to be information lossy) and a REAL64 (assumed to be ideally correct) in the common selection range 10 V of a Beckhoff ELM3xxx is simulated here, if both are calculated from the 24-bit ADC integer value (0...7,812,500, i.e. 1 digit = 1.28 μV):



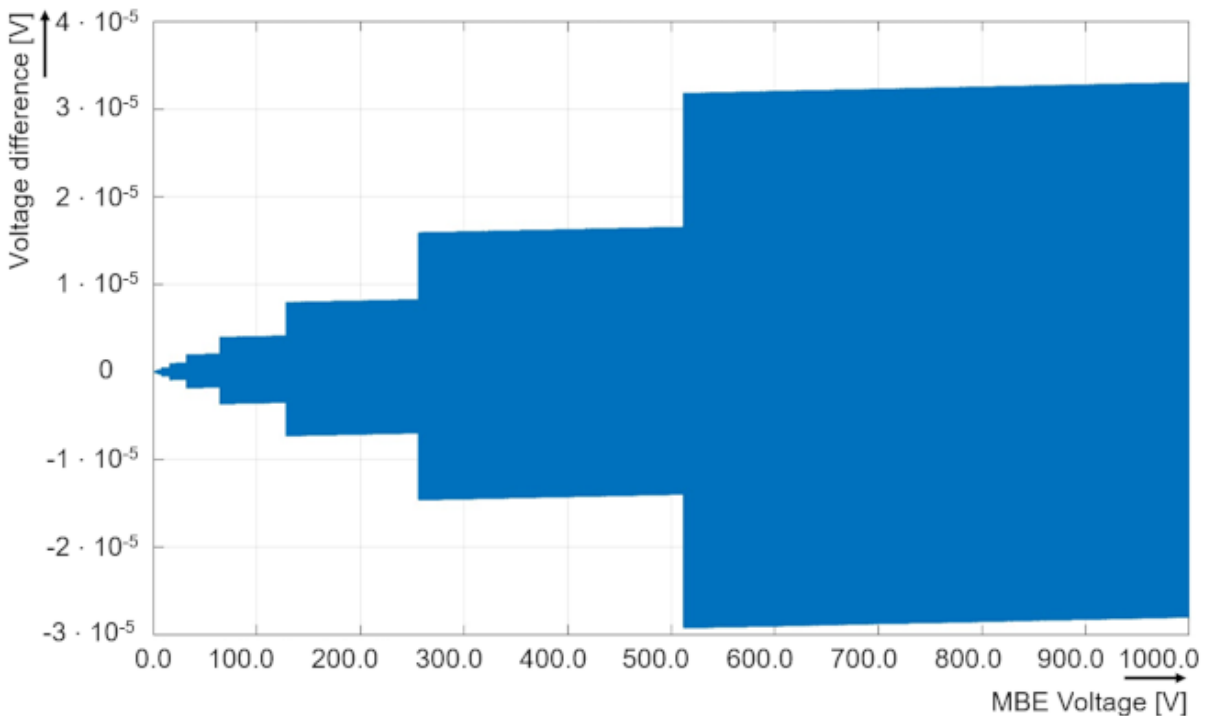
- It is noteworthy that the representation error (falsification of the data value at REAL64 \rightarrow REAL32) increases with the data value. For example, let's look at the data value 9.0 V (INT32 from ADC: 7,031,250). The simulation here shows a representation error of about $5.2 \cdot 10^{-7} \text{ V} = 0.52 \mu\text{V} = 0.052 \text{ ppm}_{\text{FSV}=10\text{V}}$. We must check this value against
 - the digital resolution: $7,812,500 = 10 \text{ V}$,
1 digit = $1.28 \mu\text{V}$ \rightarrow the representation error is 2x smaller and not relevant
 - a usual ELM3xxx basic accuracy of $100 \text{ ppm}_{\text{FSV}=10\text{V}} = 1000 \mu\text{V}$ \rightarrow the representation error is absolutely negligible
- The microscopic view into the error curve is interesting, e.g. around the point 6.0 V, plotted in the step size $1.28 \mu\text{V}$ (24-bit ADC resolution):





6.0 V can be represented error-free in REAL32; in the vicinity of the value superimposed oscillations can be seen.

- Since the representation error grows with the selection range, it is recommended to look at an FSV = 1000 V:



With $3.2 \cdot 10^{-5} \text{ V} = 35 \text{ } \mu\text{V}$ it becomes quite large, but remains at $0.035 \text{ ppm}_{\text{FSV}=1000 \text{ V}}$ and thus is not an obstacle for REAL32 transport.

- Summary: in practice, a REAL32 number can therefore represent a given numerical value to approx. 7...8 decimal places ("worst case" i.e. $10^{-7} = 0.1 \text{ ppm}$). By "decimal place" is meant here a digit of value (pre and post decimal point) without leading zero.
 For size comparison: $\text{ppm} = 10^{-6}$ (among others used in the measurement uncertainty specification, e.g. 100 ppm) or $1/7,812,500 = 128 \cdot 10^{-9} = 0.128 \text{ ppm}$ (used as bit resolution in the Beckhoff 24-bit-extendedRange).
 This means that REAL32 numbers can be used without hesitation for transporting 16-bit resolved

numbers. When transporting 24-bit analog values they approach the resolution limit but can still be used. For highest demands it is recommended to transfer integer PDO via EtherCAT and to convert it in the controller.

- The wish for a wide use of REAL64 (LREAL, Double Precision) in "simple" analog devices must be rejected at present (2024); the floating-point calculations require appropriate capabilities on the μC side, these are partially given for REAL32, but not yet to a large extent for REAL64. REAL64 calculations are preferably to be performed in the PLC.
- For further considerations on this, the study of IEEE-754 and practical testing with online computers (e.g. "IEEE-754 Floating Point Converter") or own simulations are recommended.

● Implications when using floating-point arithmetic in the PLC

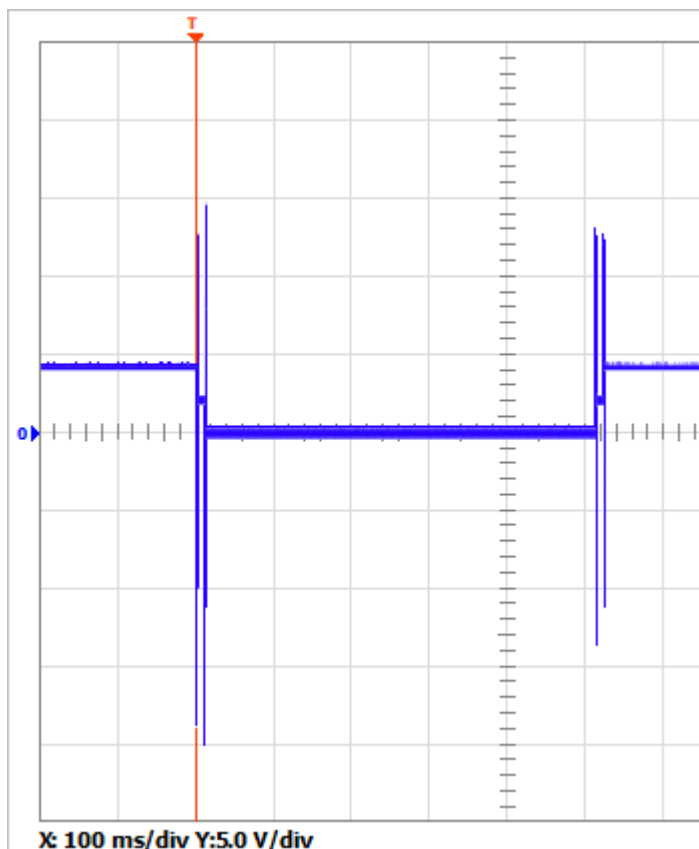
I The inevitable phenomena of rounding and representation errors described above can have significant and surprising result-warping effects in comprehensive floating-point calculations in control, especially when very large (e.g., $> 10^6$) and very small numbers (e.g., $< 10^{-6}$) coincide. To minimize (but not eliminate!) these, LREAL calculations should preferably be performed on the control side.

Keywords for further research: Unit in the last place (ULP), floating-point algorithms, floating-point exceptions, floating-point representation.

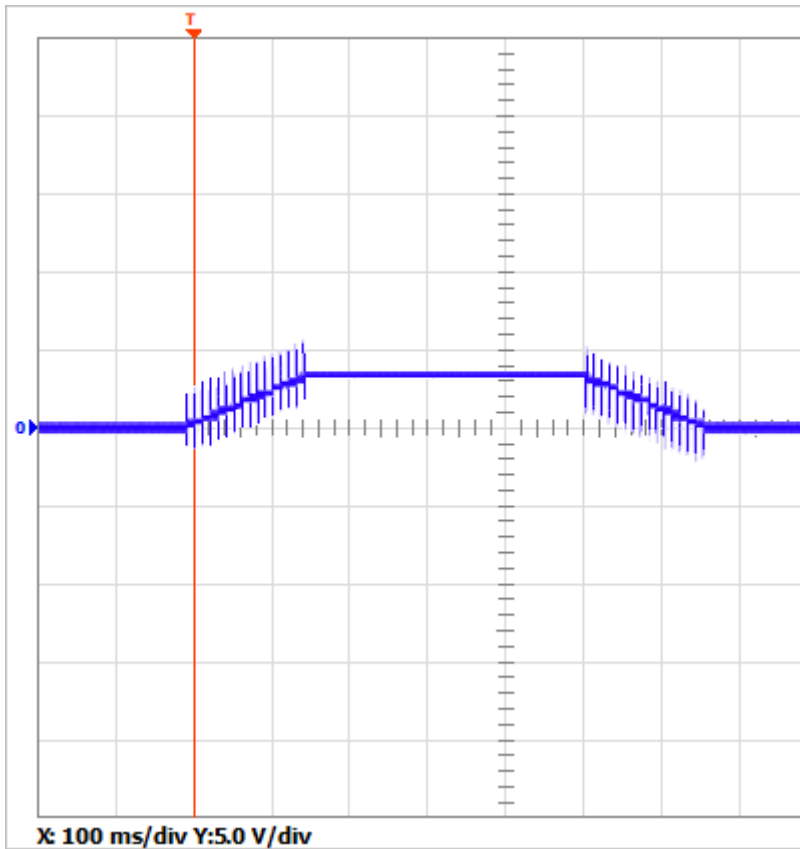
5.10 Operation of inductive/capacitive loads on analog outputs

Analog outputs such as the EL40xx/41xx/EL47xx output terminals for standard signals (10 V/ 20 mA) or EL95xx adjustable power supply terminals are designed for ohmic loads. Since ideal ohmic resistive loads are difficult to achieve in practice, they can also drive inductive/capacitive loads within limits. Two effects must be taken into consideration when doing this:

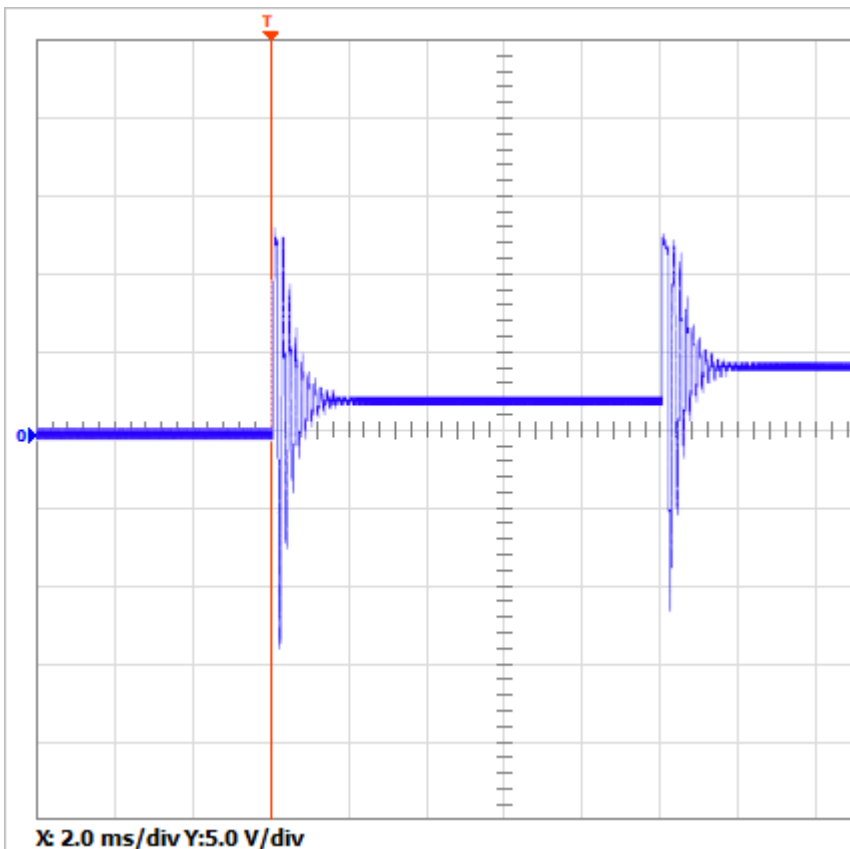
- The current flowing through the inductor causes positive/negative voltage peaks depending on the rate of voltage rise.
 - These must not exceed a level of 125 % of the max. nominal output voltage (unless otherwise specified in the respective device documentation).
Example: The EL4102 terminal specification states a max. output voltage of 10 V
→ max. ± 12.5 V voltage peaks are permitted against analog GND.
 - Since the voltage/current source (i.e. the analog output) is controlled by the controller, the voltage/current rise can and must be deliberately selected to be slow enough to prevent unacceptably high voltages at the analog output.
 - This must be checked by means of an oscilloscope during commissioning and an appropriate design must be selected to ensure that no overshoots occur at a later stage; if necessary, regular monitoring is required.
 - A simulation is not sufficient.
 - Example with EL4112 terminal: Due to big output jumps (10,000 digits/cycle), impermissibly high overvoltages occur at an ohmic-inductive load at approx. 100 mH/ 320 Ω :



→ by distributing the rise over several stages, for example 1000 digits/cycle, the overvoltages are significantly reduced:



- oscillations may occur if the overall setup (with inductive and capacitive loads) results in a system capable of oscillating;
 - an oscilloscope must be used to check that the inevitable oscillation decays again quickly (within a few milliseconds):



5.11 Repeatability

Repeatability (F_{Rep}) is an important quality term for electrical measurement technology. It expresses how far the results of consecutive averaged measurements of the same measurement object (voltage, current, etc.) deviate at maximum from a value which has been established as the measured value under constant (i.e. identical) conditions. In principle, repeatability can therefore be understood as the remaining noise over a fixed (longer) period of time.

At Beckhoff, repeatability is:

- defined as +/- value from the device measured value
- over a period of 24 h and
- after averaging over (usually) 2 seconds
- and determined at an ambient temperature of 23°C

Note: An empirical investigation of repeatability with self-selected setting parameters (e.g. average values over a specific period of time) on the installed overall setup (source, lines, external influences) can be helpful in estimating the stability of the measuring results

As an example, here is the measurement of an analog channel, with averaged measured values over 19 hours:

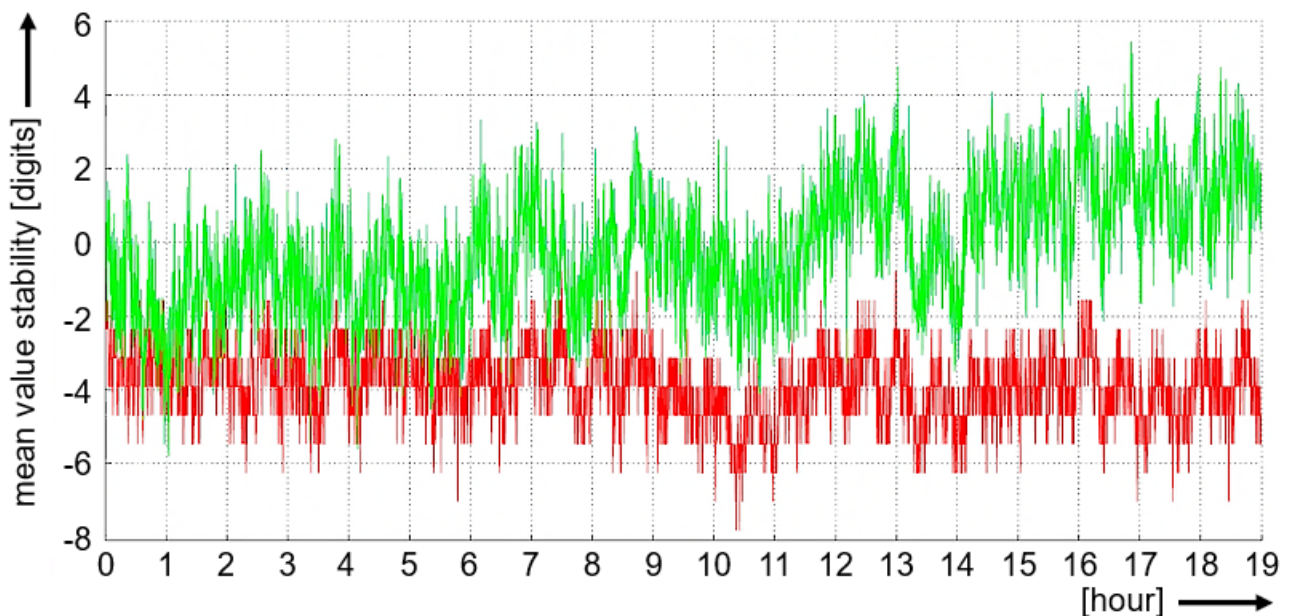


Fig. 66: Green: Analog measured value of an ELM3xxx, 24-bit resolution

Red: Measurement of the co-measuring reference multimeter (€20,000 class, 8.5-digit DMM) to record the source stability

6 Appendix

6.1 Support and Service

Beckhoff and their partners around the world offer comprehensive support and service, making available fast and competent assistance with all questions related to Beckhoff products and system solutions.

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