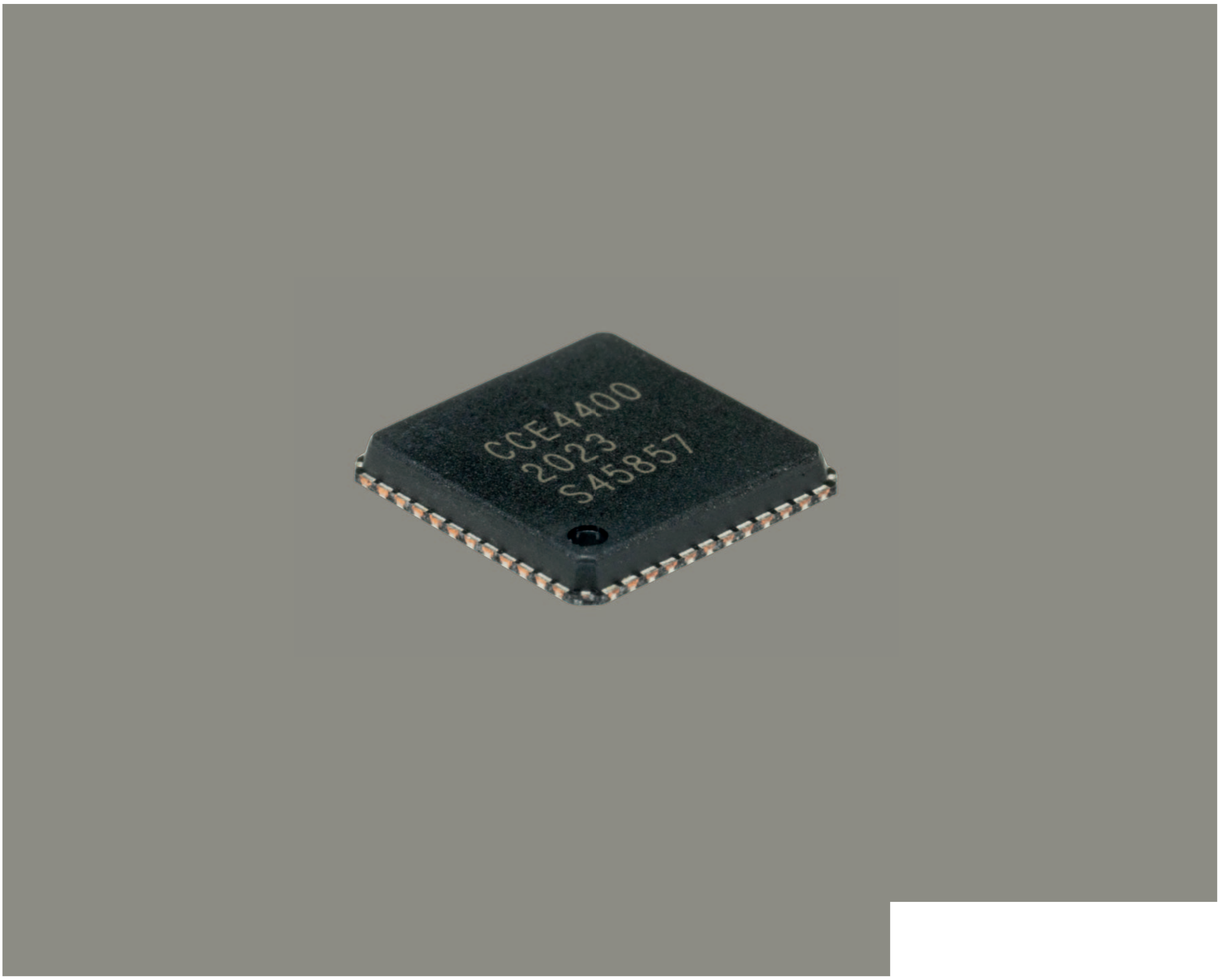
Manual EN

Residual current sensing with Bender ASIC CCE4400 and firmware D0569



FUNCTIONAL SAFETY

UL2231-2,
CSA C22.2 No. 281.2
UL991
ANSI/UL 1998

Chipset_D0569_D00508_00_M_XXEN/03.2024

Table of contents

1. Introduction

This manual describes the design-in of the Bender residual current sensing solution using Bender ASIC CCE4400 and a microcontroller with firmware D0569.
The intended usage is for IC-CPD applications according to IEC 62752 and UL 2231.

Any requirements of these standards other than residual current sensing are not in the scope of this solution and shall be covered by the application in which the residual current sensing is integrated in. Some, but not all, examples are clearance and creepage distances, insulation and protective features, spacings or emc performance.

The Bender solution is based on the residual current sensor CCE4400, which is able to measure residual currents from DC up to 2 kHz with a resolution better than 0.2 mA. To ensure correct switch-off behaviour according to the requirements of IEC 62752, a microcontroller is used which communicates with CCE4400, builds the measurement values, compares them with the limit values from IEC 62752 and signals switch-off conditions at its port pins. Optionally the limits according to UL 2231-2 can be used to set up a residual current measurement "CCID20" or "CCDI5".
For details refer to Chapter 3. "Data sheet".

2. Block diagram measuring residual currents

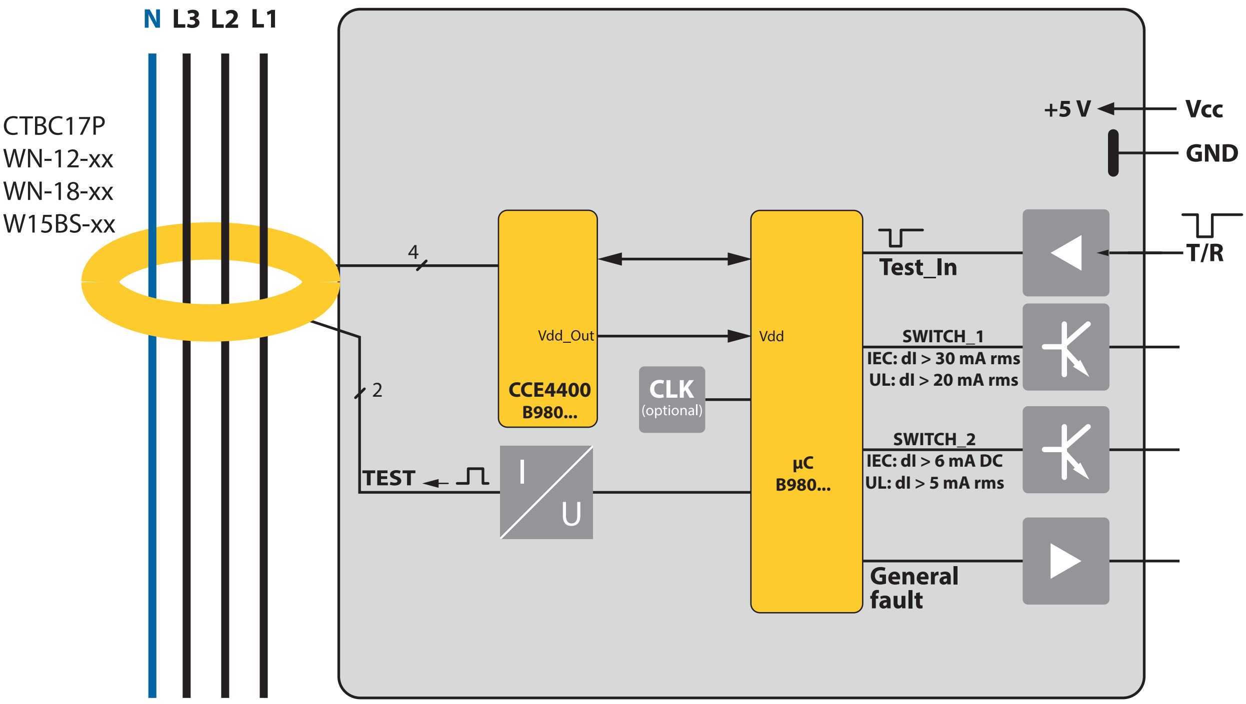


Fig. 2.1: Block diagram of measuring residual currents in IC-CPDs

The yellow components can be ordered from Bender (see Chapter 9. "Ordering information"). Please find enclosed schematic for electric circuit recommendations.

Block diagram integrating residual current sensor

Recommended integration of the residual current sensing into the end application:

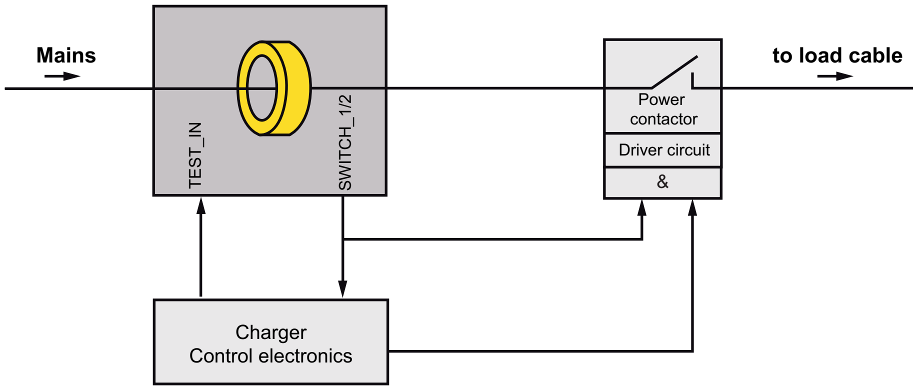


Fig. 2.2: Block diagram integrating residual current sensor

3. Data sheet

3.1 Technical data

Technical data		
Standard	IEC 62752	UL 2231-2
Supply voltage	5 V ±5 %	
Supply current	max. 45 mA	
Response values for microcontroller pin "Switch_1"	AC/DC 30 mA rms	AC/DC 20 mA rms
Response values for microcontroller pin "Switch_2"	DC 6 mA + AC 30 mA	AC/DC 5 mA rms
Return value $I_{\Delta n\ ret}$ for mode "auto-reclose" (in non-auto-reclose mode, the regular response values are used)	**$I_{\Delta n}$ 30 mA rms** $I_{\Delta n\ ret}$ = 10 mA rms **$I_{\Delta n}$ DC 6 mA** $I_{\Delta n\ ret}$ = DC 2.5 mA	**$I_{\Delta n}$ 5 mA rms** $I_{\Delta n\ ret}$ = 2 mA rms **$I_{\Delta n}$ 20 mA rms** $I_{\Delta n\ ret}$ = 10 mA rms
Measuring range	0…100 mA	
Frequency range	DC…2 kHz	
Resolution	< 0.2 mA	
Trip tolerance microcontroller B98039701	**DC 6 mA DC** DC 4…6 mA **30 mA rms** 15…100 Hz 21…30 mA 100…400 Hz 24…75 mA 400 Hz…2 kHz 45…150 mA	**5 mA rms** 50…500 Hz 4…6 mA 500 Hz…2 kHz 4…12 mA **20mA rms** 50…500 Hz 15…20 mA 500 Hz…2 kHz 15…50 mA

Technical data	
Current transformer	CTBC17P-xx: ø 17 mm WN12-xx: ø 12 mm WN18-xx: ø 18 mm W15BS-xx: ø 15 mm
Rated current	CTBC17P-xx: 3 N AC 32 A WN12-xx: 1 N AC 16 A WN18-xx: 3 N AC 32 A W15BS-xx: 3 N AC 32 A
Output at microcontroller pin "Switch_1"	**high** not tripped **low** tripped
Output at microcontroller pin "Switch 2"	**high** not tripped **low** tripped
Output at microcontroller pin „ERR_OUT"	**high** no errors **low** error occurred

3.2 Frequency response IEC

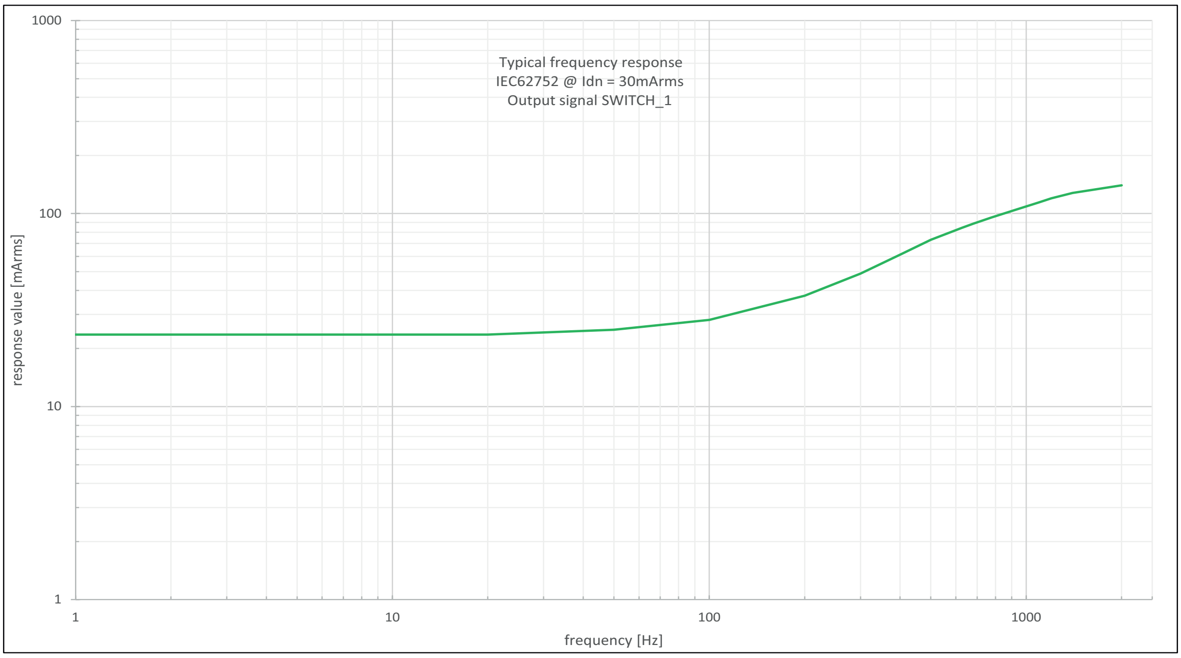


Fig. 3.1: Frequency response IEC (SWITCH_1 at 30 mA rms)

3.3 Frequency response UL

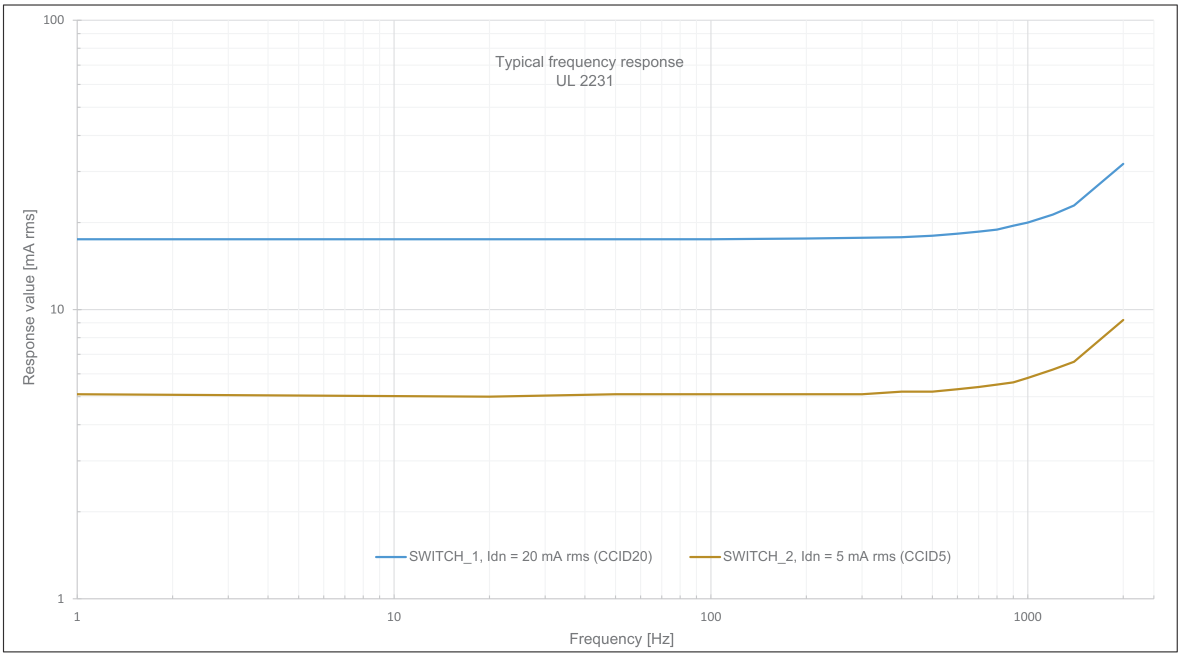


Fig. 3.2: Frequency response UL2231

4. ASIC CCE4400

4.1 Ratings

4.1.1 Absolute maximum ratings

Parameter	Symbol	Conditions	Min.	Max.	Unit
Voltage at digital input pins	VIN_MAX		VGND-0.5	VDD+0.5	V
Voltage at output pins	VOUT_MAX		VGND-0.5	VDD+0.5	V
Temperature range (storage)	ϑ_{st}		–55	+150	°C
ESD protection	VESD	Human body model	2		kV
Latch-up performance		JEDEC JESD78 Class1			
Reliability	MTBF	@ ϑ_{amb} = 27 °C		50	FIT

4.1.2 Operating conditions

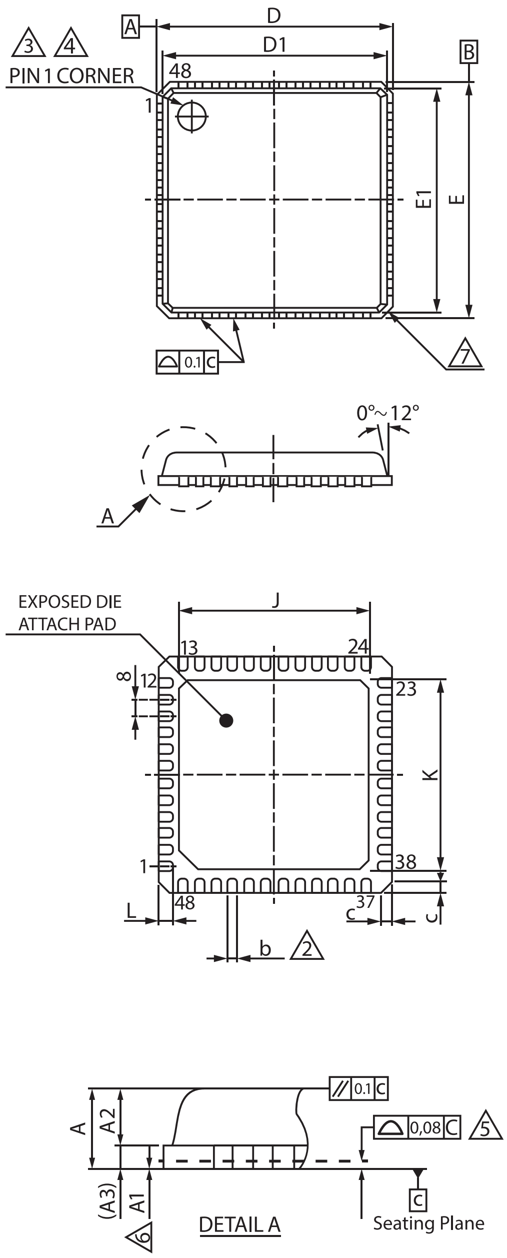
Parameter	Symbol	Conditions	Min.	Typ.	Max.	Unit
Supply voltage	VS	5 V application	4.75	5	5.25	V
Operating temperature range	ϑ_{run}		-40		85	°C
Internal voltage regulator						
Reference voltage	VDD_OUT	V(VS) = 5 V	3.1	3.3	3.5	V
Output current 5 V	I_VDD_5V	V(VS) = 5 V	0		40	mA
Capacitive load	C_VDD_OUT		2		10	µF

4.1.3 Power supply requirements

For correct functionality of the residual current sensor solution, it must be ensured by the end application circuit that the supply voltage +5 V is always within the tolerance of ±5 %. Exceeding any of the absolute maximum limits may cause malfunction or permanent malfunction or damage of the component.

4.1.4 Mechanical data CCE4400

Case: QFN 48, 7x7 mm



Symbols	Min.	Nom.	Max.
A	0.80	0.90	1.00
A 1	0.00	0.02	0.05
A 2	0.65	——	1.00
A 3	0.203 REF.		
b	0.18	0.25	0.30
C	0.24	0.42	0.60
D	7.00 BSC.		
D 1	6.75 BSC.		
E	7.00 BSC.		
E 1	6.75 BSC.		
e	0.50 BSC.		
J	2.25	4.70	5.25
K	2.25	4.70	5.25
L	0.30	0.40	0.50

Unit: mm

Notes:

1. Jedec: MO-220-J
2. Die thickness allowable is 0.305 mm maximum (0.012 inches maximum).

2 Dimension applies to plated terminal and is measured between 0.2 and 0.25 mm from terminal tip.

3 The Pin #1 identifier must be placed on the top surface of the package by using indentification mark or other feature of package body.

4 Exact shape and size of this feature is optional.

5 Applied to exposed pad and terminals. Exclude embedding part of exposed pad from measuring.

6 Applied only to terminals.

7 Exact shape of each corner is optional.

Fig. 4.1: Mechanical data

Note: The exposed pad must be connected to GND.

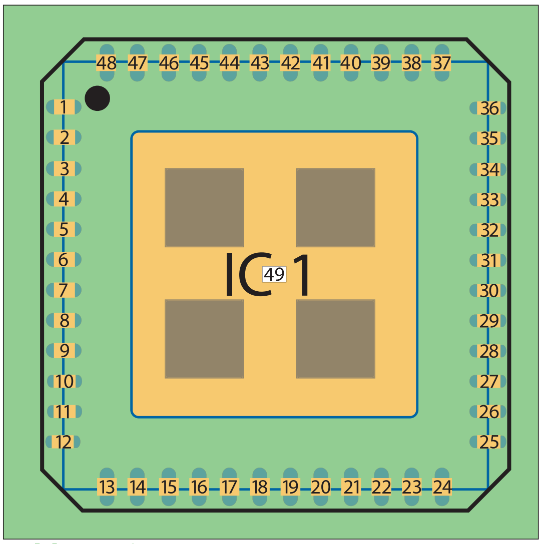
4.1.5 Design recommendations

Observe precautions for handling electrostatic sensitive devices!

4.1.6 Recommendation for placement of electronic components

- Use multilayer structure with min. 4 layers.
- One layer should have a solid ground plane.
- Place the blocking capacitors as close as possible to the pins.
- The clock line (8 MHz) between CCE4400 and microcontroller should be as short as possible.
- Route the SPI bus as short as possible.
- No tracks under inductive components.
- Connect the exposed pad to a ground plane.

4.1.7 CCE4400 - Footprint



Solder resist (green)
Copper (orange)
Solder paste (brown)

Fig. 4.2: CCE4400 - Footprint

The solder paste should not exceed 60 % of the area of the exposed pad.

4.1.8 Soldering profile

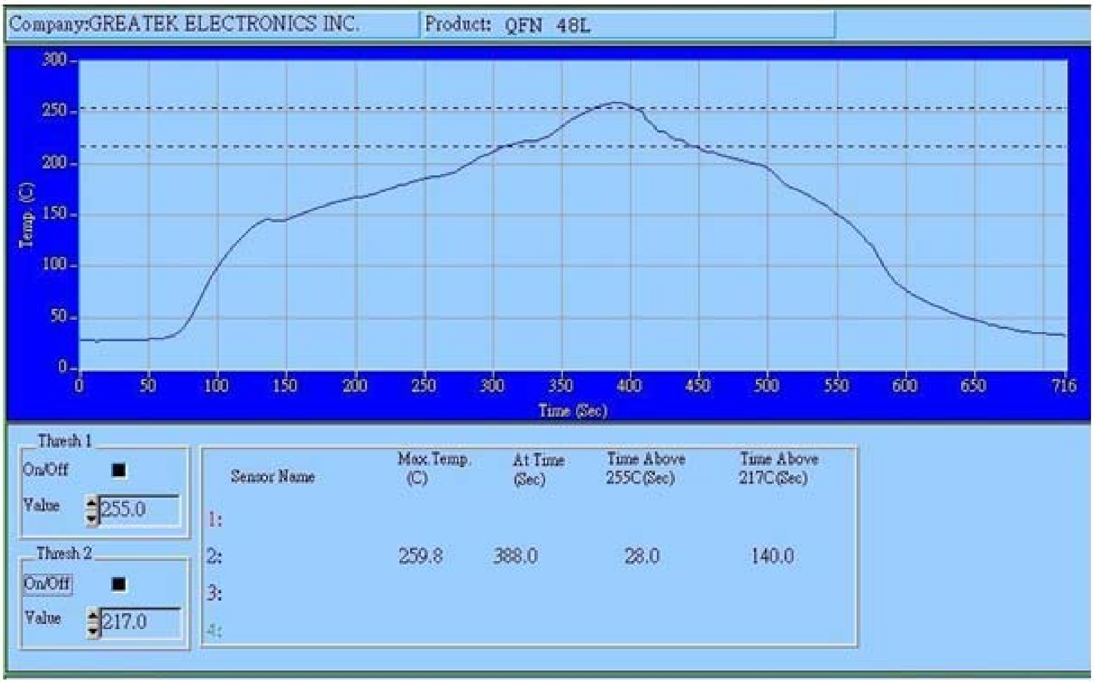


Fig. 4.3: Soldering profile

4.1.9 Design proposals

Guidelines to assist the design and manufacturing engineers in optimising the PCB and the process:

- Five or more thermal vias in the PCB thermal pad for heat transfer
- NSMD solder masking of thermal pad
- NSMD solder masking of pads for package pins
- 50 to 75 micron solder joint standoff height
- Laser-cut, electro-polished 0.125 mm stainless steel stencil (standard)
- No clean, type 4 solder paste
- Hot gas reworks process

MSL level: MSL 2 – 1 year (approximately 30 °C/60 % RH).

5. Microcontroller

The microcontroller used to process and evaluate the residual current readings from ASIC CCE4400 is an ST microelectronics STM8S005K6T6C, LQFP32 7x7 mm, –40…+85 °C.
It is shipped with programmed firmware for connection to CCE4400 to set up a residual current measuring circuit which fulfils the requirements for such measurement described in IEC 62752 and UL 2231-2.
Required features beyond residual current measurement described in these standards (e.g. check correct PE connection) are to be implemented by the end application. An exception is the weld check of power relay contacts according to UL 2231 requirement which is implemented in the software and can be used in UL configuration only (of course the end application controller can do this if a more comprehensive check is desired).

5.1 Pinout

Pin	LQFP32	Pin function	Remark	Signal name	Configuration [5)]
1	NRST	Reset	Active low		
2	PA1	OSCIN	Optional 16 MHz oscillator		
3	PA2	OSCOUT	Optional 16 MHz oscillator		
4	VSS	Digital ground		GND	GND
5	VCAP	Internal regulator capacitor	2.2 µF	VCAP	VCAP
6	VDD	Digital supply		3.3 V	VDD
7	VDDIO	I/O supply		3.3 V	VDDIO
8	PF4	Feedback input for power contactor weld check	**high** = power contactor closed or welded **low** = power contactor open	RELAY_FEEDBACK	Input pull up
9	VDDA	Anlogue supply	Same as digital supply	3.3 V	VDDA
10	VSSA	Anlogue ground	Same as digital ground	GND	GND
11	PB5	General fault	**high** = ok **low** = fault	ERR_OUT	Output push-pull
12	PB4	Switching output 1	**high** = no alarm **low** = alarm **IEC**: dI > 30 mA rms **UL**: dI > 20 mA rms	SWITCH_1	Output push-pull
13	PB3	Switching output 2	**high** = no alarm **low** = alarm: **IEC**: dI > 6 mA DC **UL**: dI > 5 mA rms	SWITCH_2	Output push-pull
14	PB2	Request test or reset	Test = short-time low level (40 ms…1.2 s) Reset = long-time low level (> 1.2 sec)	TEST_IN	Input pull up

Pin	LQFP32	Pin function	Remark	Signal name	Configuration [5]
15	PB1	Acknowledge the request for test	**low** = normal measurement **high** = test in progress	ACK_OUT	Output push-pull
16	PB0	Select standard	**low** = UL 2231 **high-z** = IEC 62752	STANDARD [1) 2)]	Input pull up
17	PE5	Chip select CCE4400			
18	PC1	PWM analogue-out	*f* = 8 kHz **IEC**: 0…100 % duty = 0…30 mA DC **UL**: 0…100 % duty = 50 mA rms	PWM_ANALOG [4)]	Output push-pull
19	PC2	PWM test winding	Activated during functional test	PWM_TEST	Output push-pull
20	PC3	RS485 nRE/DE	**low** = RS-485 receive enable **high** = RS-485 drive enable	RS485_RE_DE	Output push-pull
21	PC4	LED	LED on **high** = no general fault LED blinking general fault LED off **low** = no supply voltage	LED	Output push-pull
22	PC5	SPI_CLK			
23	PC6	SPI MOSI			
24	PC7	SPI MISO			
25	PD0	CLK_CCO	Keep pcb track as short as possible.		
26	PD1	Reserved	Do not connect.		
27	PD2	Select reclose behaviour	**low** = no auto-reclose after alarm **high-z** = auto-reclose after alarm	RECLOSE [1) 2)]	Input pull up
28	PD3	Reserved	Do not connect.		
29	PD4	Start gain calibration of connected current transformer	**low** = start automatic gain calibration **high-z** = no calibration	CALIBRATE [1) 3)]	Input pull up
30	PD5	UART transmitter		UART_TX	Output push-pull
31	PD6	UART receiver		UART_RX	Input pull up
32	PD7	Select µC clock source HSI or HSE	**low** = use external 16 MHz oscillator (HSE) **high-z** = use internal oscillator (HSI)	SELECT_CLOCK [1)]	Input pull up

Notes:

1) Input sampled only during power up

2) Input is checked during runtime if its state is the same as during power up.

3) It is essential that no current is present through the current transformer (CT) during calibration phase. Additionally, it must be ensured by the hardware that exactly the current marked in the schematic can flow through the test winding during calibration.

4) PWM signal proportional to residual current for monitoring purposes only. It shall not be used to switch off a power relay since the required switch-off timing is not guaranteed.

5) During reset, the microcontroller I/O port pins are input floating.

5.2 Offset measurement

If a test is conducted (by activating the "TEST_IN" input), the offset is measured at the end of this test sequence, but only if the test resulted in a switch-off condition for both outputs "SWITCH_1" and "SWITCH_2".
The offset is calculated to be the arithmetic average value of the residual current during the measuring time.
The offset value is stored permanently in the internal non-volatile memory and its value is used until the next test is conducted.
Only in UL configuration, the digital input "RELAY_FEEDBACK" is checked at the end of the offset measurement to detect an erroneously closed power relay contact. See chapter 5.6
It is essential that the end application ensures that no residual current is present during offset measurement. Otherwise the DC component of this current is set to 0. If the value of this DC component is too high (> approx. 15 mA), a general fault is detected which causes the outputs to remain off. This state is held until power down.

5.3 Request a trip test or a reset

By activating the input "TEST_IN" with a low level applied, it can be selected whether a test sequence or a reset sequence shall be conducted. The signal at this pin is detected to be active if its state is stable at low level for 40 ms.
During power up the software waits until the input "TEST_IN" has a high level.

5.3.1 Trip test

If "TEST_IN" is activated for 40 ms…1.2 s, a test request is detected. The test is used to verify that the device detects a residual current greater than the trip level and switches connected circuits off.

To ensure that both outputs "SWITCH_1" and "SWITCH_2" trip, a residual current is generated by activating the test winding which is wound on the current transformer. Please refer to Chapter 12. "Schematic" for connection of the test winding and the component values for correct operation.
The test winding is activated for 0.7 s with a lower current and 0.7 s with a higher current.
During this time, the measured rms and average values of the residual current exceed the corresponding trip values and cause the switching outputs to switch off.
After 2 x 0.7 s, the test winding is deactivated.
If UL configuration is used, a test for closed or welded power relay contacts is started which takes a maximum time of 100 ms.
If both outputs are in off-state and no welded contact was detected, an offset measurement is started.

With this procedure, it is possible to detect that both outputs are able to switch between on and off and that they are not connected to each other.
To be sure that the device is able to trip, it is advised that a test is conducted at regular intervals. The interval has to be determined based on the requirements of the end application, e.g. once per day, right before usage, etc.

Timing diagram for trip test

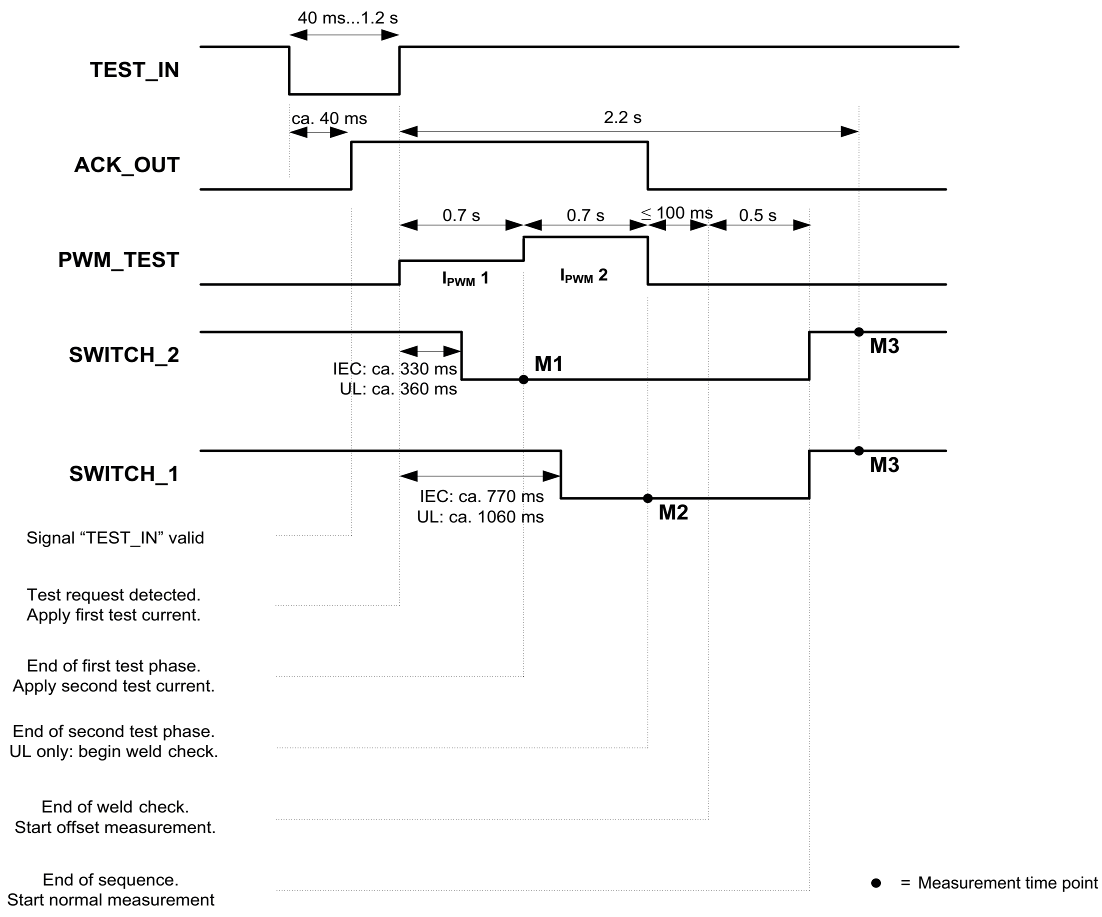


Fig. 5.1: Timing diagram trip test

After activating the test sequence, the end product has to monitor the correct state of the switching outputs being used at the following points in time:

M1: check that SWITCH_2 is disabled
M2: check that SWITCH_1 is disabled
M3: check that SWITCH_1 or SWITCH_2 is enabled

The offset is only measured if both switches are off and no welded contact is detected.
The outputs remain off at M3 until power down if UL configuration is used and a welded contact was detected.

5.3.2 Reset

If "TEST_IN" is activated for longer than 1.2 s, a reset request is detected.
The reset request is accepted only if the **manual reclose functionality** is selected with the configuration input "**RECLOSE**". Otherwise, a long activation of "TEST_IN" has no effect.

The reset is used to run an internal self-test and re-initialise the microcontroller's firmware. If no internal fault is detected and if the residual current is below the response value, the outputs are switched from the off-state back to on. A check of the input "RELAY_FEEDBACK" is not performed. During reset, the buffers and variables needed to build the measurement values (rms and average of the residual current) are also re-initialised and the measuring time must pass until the measurement values are valid.

Timing diagram to request a reset

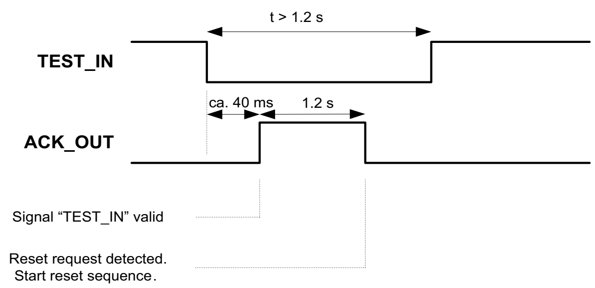


Fig. 5.2: Timing diagram to request a reset

5.3.3 Acknowledgement of test request

To verify that the residual current sensing circuit works properly, the end application must start a test sequence and check that the switching outputs used by the application ("SWITCH_1" and/or "SWITCH_2") are able to switch between on and off. This means that the state of an output has to be monitored at the beginning of the test and at the end.
The end application can determine these points in time by using an internal timer or by implementing a handshake using the test acknowledge output "ACK_OUT".

A low-to-high transition of signal "ACK_OUT" marks the accepted test request. The following high-to-low transition marks the end of the activation time of the test winding and the point in time to check that the switching outputs are now in off-state.
See Fig. 5.1, “Timing diagram trip test”.

5.4 Configure the application behaviour

Once during power up and only then, the logic state of several microcontroller inputs is sampled to decide how the application should work. This configuration cannot be changed during runtime to avoid unintended application behaviour. Nonetheless some inputs are checked during runtime to ensure that their state is the same as at power up and has not unintentionally changed. In that case, the software enters a safe state until power down.
The inputs have internal pull-up resistors activated so that they can be left unconnected to have a high level read or tied to ground to read a low level. For the value of the internal pull ups refer to the STM8S005K6 datasheet.
If extended emc performance is necessary, external pull-up resistors should be used.

5.4.1 Select standard for response values

The microcontroller software is able to compare the measured residual current with response values according to the requirements defined in UL 2231 and in IEC 62752. This means that the switching outputs are operated and can drive relays so that the necessary timings defined by these standards are fulfilled (switch-off times depend on the level of the residual current). For applications using UL 2231, the the switch-off times for the relays must not exceed 10 ms and for IEC 62752, the switch-off time for the relays must not exceed 20 ms.

- If this input is left **unconnected**, response values according to **IEC 62752** are used.
  The response value of output SWITCH_1: 30 mA rms
  SWITCH_2 : 6 mA DC
- If this input is **tied to ground**, response values according to **UL 2231** are used.
  The response value of output SWITCH_1: 20 mA rms
  SWITCH_2: 5 mA rms

This input is sampled during power up and checked during runtime.
If calibration (see chapter "5.4.4 ") is selected, the level at power up is saved in eeprom. If no calibration is to be done, the level of this input is compared to the saved value.
A difference between the values causes the outputs to switch off. This state is held until power down. This ensures that no unintended change of standard occurs.

5.4.2 Select reclose behaviour

Reclose is the method by which the microcontroller changes its state from outputs switched off back to normal operation with outputs switched on.
If automatic reclose of the switching outputs is selected, the microcontroller waits until the residual current is below a low limit, then starts a 500 ms delay and then switches the outputs back on if there is no residual current present greater than a response value.
If manual reclose is selected, the microcontroller does not switch the outputs automatically on. They remain in the off state until a reset is applied by activation of the "TEST_IN" port pin for longer than 1.2 s. If no reset is applied, a switched-off state is held until power down.

- If this input is left unconnected, automatic reclose is selected.
- If this input is tied to ground, manual reclose is selected.

This input is sampled during power up and checked during runtime to ensure that its level has not changed. If so, a general fault is detected which causes the outputs to be switched off. This state is held until power down.

5.4.3 Select clock to operate the microcontroller

The microcontroller can be configured to use an external 16 MHz oscillator or the internal RC oscillator as clock source.

- If this input is left unconnected, the internal RC oscillator of the microcontroller is used as clock source.
- If this input is tied to ground, an external 16 MHz oscillator is used as clock source and monitored continuously for failure due to a broken or disconnected oscillator.

Use an external 16 MHz oscillator if UART communication is used.

5.4.4 Calibrate CCE4400 with attached current transformer

It is necessary to adjust the output signal of CCE4400 to the correct gain factor. The microcontroller initialises CCE4400 with this factor and therefore a procedure is necessary to determine the correct factor. This calibration procedure is controlled by the microcontroller and carried out once during the final device test.

- If this input is left unconnected, the microcontroller enters normal measuring mode and uses the gain factor stored in its internal memory to initialise CCE4400.
- If this input is tied to ground, a procedure to determine the correct gain factor is started. The resulting gain factor is stored in the microcontroller´s internal memory and then used to initialise the CCE4400.

In order to be able to determine the correct gain factor, it is necessary to activate the test winding LM1a with the current specified in Chapter 12. "Schematic".

No residual current shall be present during calibration as it directly affects the resulting gain factor.

Following calibration, the microcontroller returns to normal measurement and uses the determined values for offset and gain.

Only if calibration is activated, the level of the input pin "STANDARD" is saved in eeprom. If no calibration is activated, consistency checks are done between the levels of input "STANDARD" during power up, runtime and compared to the value that is saved in eeprom.
In consequence, the procedure to change the standard requires calibration. With a functional test after calibration it can be reliably ensured that no unintended change of standard occurs in the end application.

CAUTION

Important
The ***initial value of the gain factor is an invalid value****.*
Therefore, a calibration must be performed at least once for the circuit to switch to normal measuring mode.
Unless a gain calibration is done, the circuit will always detect a general fault due to an invalid gain factor.

This is a safety feature to prevent uncalibrated devices from enabling or switching on electric circuits in the end application.

5.5 Power relay requirements

The switch-off times in standards IEC 62752 and UL 2231 define the duration from the occurrence of a residual current until mains power is interrupted. The worst case timing occurs in case of high residual currents.
The shortest permissible duration to switch off in an IEC 62752 application is 40 ms. The measuring time for the microcontroller software in that case is maximum 20 ms, which results in the requirement to use a power relay with a worst case switch-off time of 20 ms.
The shortest permissible duration to switch off in an UL 2231 application is 20 ms. The measuring time for the microcontroller software in that case is maximum 10 ms, which results in the requirement to use a power relay with a worst case switch-off time of 10 ms.

5.6 Check power relay contacts for weld condition

This check is **only** applied when using the **UL configuration**. Otherwise this test is not conducted.

According to UL 2231, clause 17.2 it is necessary that the supervisory circuit in the end product performs a test of the device's ability to trip by using a simulated ground fault. This test shall include the interrupting contacts.

The software offers the option that a sufficient check of unintentionally closed interrupting contacts can be conducted without affecting the software of an application controller.
In case a closed contact is detected, the switching outputs are held in their off-state until power down.

Important:
This check is conducted only at the end of a trip test sequence.

If the state of the interrupting contacts is of interest at other points in time, the check needs to be implemented by the end application.
The outputs "SWITCH_1" and "SWITCH_2" are only switched back to their on-state if the signal level at input "RELAY_FEEDBACK" is low for 20 ms. Refer to the timing diagram in chapter 5.3.1

Example of an electronic circuit generating a sufficient signal to detect a welded interrupting contact:

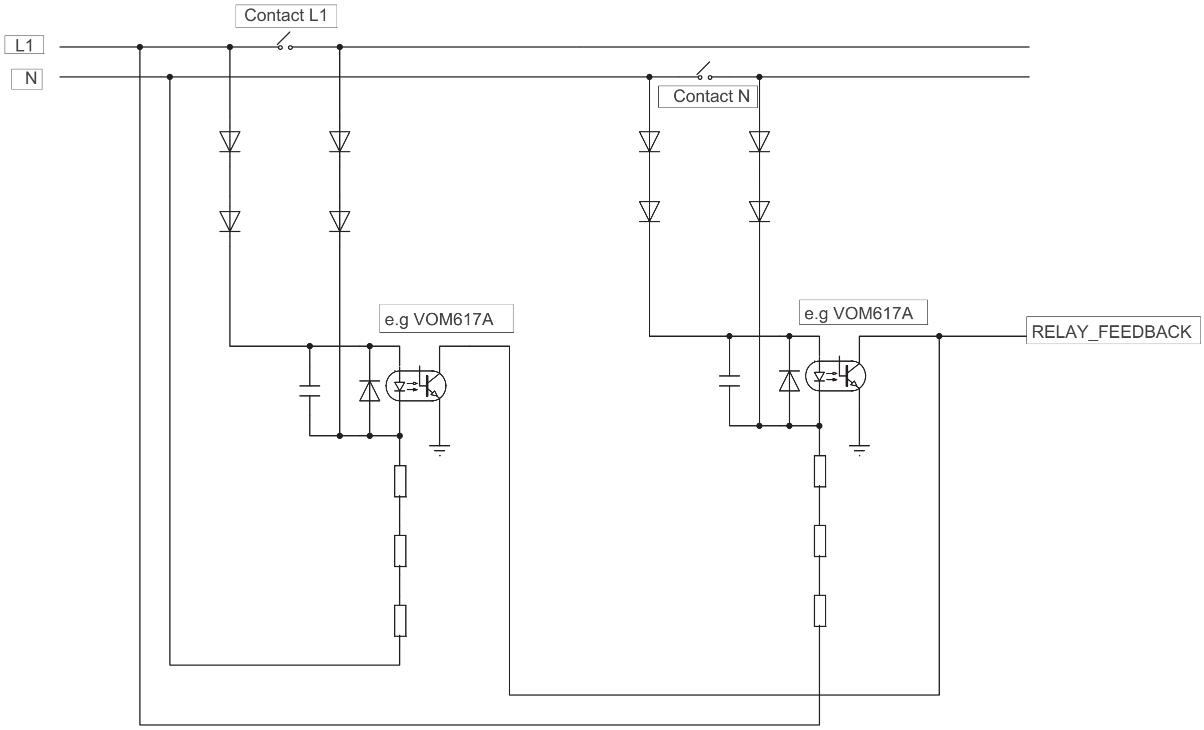


Fig. 5.3: Wiring diagram

Signal at input "RELAY_FEEDBACK" which is detected as "contact closed or welded" by the microcontroller software:

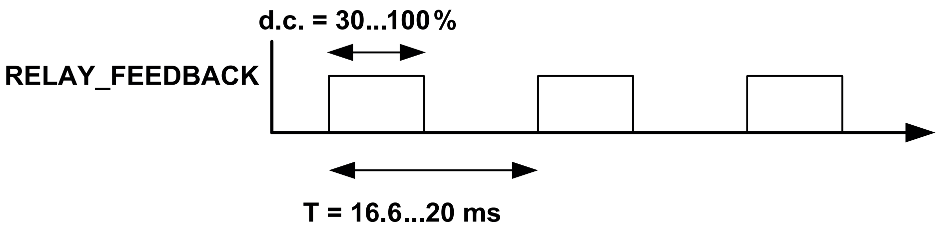


Fig. 5.4: Timing diagram: Signal at input "RELAY_FEEDBACK"

If the weld check should not be conducted by the microcontroller, the input signal "RELAY_FEEDBACK" needs to be deactivated. Recommended circuit:

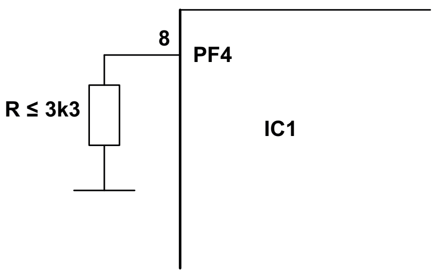


Fig. 5.5: Wiring diagram: Weld check inactive

5.7 Serial communication

To be able to have access to the sensor application and the measurement values, a serial communication with the microcontroller´s UART is implemented.
Using UART communication is not required to have a correct switching behaviour.
The microcontroller is always slave in that communication and expects a message from a master. The master addresses the slave by sending the slave address in the first byte of each message. The slave receives the message, checks for an address match, decodes it and sends an answer back to the master.
Every data exchange is triggered by a request of the master which the slave shall answer with exactly one message.
The slave never sends a message without request by the master.
The protocol described here is logically half duplex (request and answer). In that way, it is possible to directly connect a master controller to RX and TX. Alternatively, an RS-485 transceiver can be used (either a full duplex or half duplex type) with microcontroller pin nRE/DE used to control the direction of the data.

5.7.1 Communication parameters

Baud rate	19.2 kbps
Data bit	8
Parity	none
Stop bits	1

Bits in a data byte are transmitted with the least significant bit first.
The default slave address is 100.

5.7.2 Timing

An idle time of more than 2 byte times between 2 bytes is interpreted as end of the message.
The slave starts to send an answer (begin of start bit) no later than 20 ms after reception of the stop bit of the last message byte.
Between two requests to a slave, the master shall wait a minimum time of 50 ms until the next request. This is to avoid influence on the residual current measurement because of high traffic loads generated by a master.
It is required to use an external clock for the microcontroller if UART communication is used. The internal RC oscillator may not ensure proper baud rates due to higher tolerance and drift.

5.7.3 Error handling

Each transmitted message has a 16-bit checksum. The last two bytes are used to check the message integrity.
The cyclic redundancy check (crc) is calculated byte by byte incorporating the complete message and then the two bytes are appended on the end of the message.
The crc polynom used is 0x18005 ($x^{16} + x^{15} + x^2 + 1$).
If a slave detects a crc error, it does not answer that request. The master shall repeat the message up to 2 times and if the slave still does not answer, the slave shall be considered to be defective.

Algorithm

```
/**
* crc16 - compute the CRC-16 for a data buffer
* @crc:    previous CRC value
* @buffer: data pointer
* @len:    number of bytes in the buffer
*
* Returns the updated CRC value.
*/
uint16_t Crc16(uint16_t crc, const uint8_t * buffer, uint16_t len)
{
  while (len--)
  {
    crc = Crc16_byte(crc, *buffer++);
  }
  return crc;
}


uint16_t Crc16_byte(uint16_t crc, uint8_t data)
{
  return (crc >> 8) ^ crc16_table[(crc ^ data) & 0xff];
}
const uint16_t crc16_table[256] = {
         0x0000, 0xC0C1, 0xC181, 0x0140, 0xC301, 0x03C0, 0x0280, 0xC241,
         0xC601, 0x06C0, 0x0780, 0xC741, 0x0500, 0xC5C1, 0xC481, 0x0440,
         0xCC01, 0x0CC0, 0x0D80, 0xCD41, 0x0F00, 0xCFC1, 0xCE81, 0x0E40,
         0x0A00, 0xCAC1, 0xCB81, 0x0B40, 0xC901, 0x09C0, 0x0880, 0xC841,
         0xD801, 0x18C0, 0x1980, 0xD941, 0x1B00, 0xDBC1, 0xDA81, 0x1A40,
         0x1E00, 0xDEC1, 0xDF81, 0x1F40, 0xDD01, 0x1DC0, 0x1C80, 0xDC41,
         0x1400, 0xD4C1, 0xD581, 0x1540, 0xD701, 0x17C0, 0x1680, 0xD641,
         0xD201, 0x12C0, 0x1380, 0xD341, 0x1100, 0xD1C1, 0xD081, 0x1040,
         0xF001, 0x30C0, 0x3180, 0xF141, 0x3300, 0xF3C1, 0xF281, 0x3240,
         0x3600, 0xF6C1, 0xF781, 0x3740, 0xF501, 0x35C0, 0x3480, 0xF441,
         0x3C00, 0xFCC1, 0xFD81, 0x3D40, 0xFF01, 0x3FC0, 0x3E80, 0xFE41,
         0xFA01, 0x3AC0, 0x3B80, 0xFB41, 0x3900, 0xF9C1, 0xF881, 0x3840,
         0x2800, 0xE8C1, 0xE981, 0x2940, 0xEB01, 0x2BC0, 0x2A80, 0xEA41,
         0xEE01, 0x2EC0, 0x2F80, 0xEF41, 0x2D00, 0xEDC1, 0xEC81, 0x2C40,
         0xE401, 0x24C0, 0x2580, 0xE541, 0x2700, 0xE7C1, 0xE681, 0x2640,
         0x2200, 0xE2C1, 0xE381, 0x2340, 0xE101, 0x21C0, 0x2080, 0xE041,
         0xA001, 0x60C0, 0x6180, 0xA141, 0x6300, 0xA3C1, 0xA281, 0x6240,
         0x6600, 0xA6C1, 0xA781, 0x6740, 0xA501, 0x65C0, 0x6480, 0xA441,
         0x6C00, 0xACC1, 0xAD81, 0x6D40, 0xAF01, 0x6FC0, 0x6E80, 0xAE41,
         0xAA01, 0x6AC0, 0x6B80, 0xAB41, 0x6900, 0xA9C1, 0xA881, 0x6840,
         0x7800, 0xB8C1, 0xB981, 0x7940, 0xBB01, 0x7BC0, 0x7A80, 0xBA41,
         0xBE01, 0x7EC0, 0x7F80, 0xBF41, 0x7D00, 0xBDC1, 0xBC81, 0x7C40,
         0xB401, 0x74C0, 0x7580, 0xB541, 0x7700, 0xB7C1, 0xB681, 0x7640,
         0x7200, 0xB2C1, 0xB381, 0x7340, 0xB101, 0x71C0, 0x7080, 0xB041,
         0x5000, 0x90C1, 0x9181, 0x5140, 0x9301, 0x53C0, 0x5280, 0x9241,
         0x9601, 0x56C0, 0x5780, 0x9741, 0x5500, 0x95C1, 0x9481, 0x5440,
         0x9C01, 0x5CC0, 0x5D80, 0x9D41, 0x5F00, 0x9FC1, 0x9E81, 0x5E40,
         0x5A00, 0x9AC1, 0x9B81, 0x5B40, 0x9901, 0x59C0, 0x5880, 0x9841,
         0x8801, 0x48C0, 0x4980, 0x8941, 0x4B00, 0x8BC1, 0x8A81, 0x4A40,
         0x4E00, 0x8EC1, 0x8F81, 0x4F40, 0x8D01, 0x4DC0, 0x4C80, 0x8C41,
         0x4400, 0x84C1, 0x8581, 0x4540, 0x8701, 0x47C0, 0x4680, 0x8641,
         0x8201, 0x42C0, 0x4380, 0x8341, 0x4100, 0x81C1, 0x8081, 0x4040 };
```

5.7.4 General message format

1.	2.	3.	4..	5.	
Sensor Address	Message Code	Message Length	Message Data [ ]	CRC high byte	CRC low byte

1. The Sensor Address (1 byte) is the slave address in the range of 1…255.
   Address 0 is the broadcast address.
2. The Message Code (1 byte) contains the coding instruction of the following bytes.
3. The Message Length (1 byte) contains the length of the optionally following Message Data field. 0 means that no Message Data field follows.
4. The Message Data field contains the data for the message.
5. The CRC (2 bytes) is calculated from Sensor Address up to the last byte of the Message Data field.

Numbers larger than 1 byte are transmitted with the most significant byte first.
Integer numbers are represented in two's complement.

5.7.5 Get measurement and status

Master request		**Slave answer**	
Adr.	address 1…255	Adr.	Slave address
Msg-Code	0x01	Msg-Code	0x01
Msg-Length	0x00	Msg-Length	0x07
CRC	crc highbyte	Msg-Data[0…1]	dIRMS, Highbyte in Msg-Data[0]
CRC	crc lowbyte	Msg-Data[2…3]	dIDC, Highbyte in Msg-Data[2]
		Msg-Data[4]	Statusbyte 1 (Operational state)
		Msg-Data[5]	Statusbyte 2 (Fault state)
		Msg-Data[6]	Statusbyte 3 (Configuration state)
		CRC	crc highbyte
		CRC	crc lowbyte

- The measurement values of residual current rms and DC are represented in 0.1 mA resolution.
- Msg-Data[0…1] contains the rms value of the residual current. The range is 0.0…100.0 mA.
- Msg-Data[2…3] contains the magnitude of the direct component of the residual current. The range is 0.0…30.0 mA

Status byte 1

Bit	Meaning
Bit 7	General fault 1 = fault
Bit 6	Calibration 0 = normal measurement 1 = calibration active
Bit 5	Testmode 0 = normal measurement 1 = test winding active
Bit 4	Reserved
Bit 3	Reserved
Bit 2	State of SWITCH2 0=off, disabled, tripped 1=on, enabled, not tripped
Bit 1	State of SWITCH1 0=off, disabled, tripped 1=on, enabled, not tripped
Bit 0	State of ERR_OUT 0 = error, disabled 1 = no error, enabled

Status byte 2

Bit	Meaning
Bit 7	Reserved
Bit 6	Reserved
Bit 5	ASIC fault 1 = fault
Bit 4	AsiC gain fault 1 = fault
Bit 3	ASIC offset fault 1 = fault
Bit 2	Feedback fault 1 = fault
Bit 1	External oscillator fault 1 = fault
Bit 0	Configuration fault 1 = fault

Status byte 3

Bit	Meaning
Bit 7	Reserved
Bit 6	Reserved
Bit 5	Reserved
Bit 4	Reserved
Bit 3	Standard which is actually used 0 = IEC62752 1 = UL2231
Bit 2	Clock which is actually used 0 = internal RC 1 = external oscillator
Bit 1	Status of the SPI interface 0 = SPI enabled 1 = SPI disabled
Bit 0	Reclose behaviour which is actually used 0 = Reclose via TEST_IN 1 = automatic reclose

5.7.6 Start functional test

Master request		Slave answer	
Adr.	address 1…255	Adr.	Slave address
Msg-Code	0x04	Msg-Code	0x04
Msg-Length	0x00	Msg-Length	0x01
CRC	crc highbyte	Msg-Data[0]	Infobyte
CRC	crc lowbyte	CRC	crc highbyte
		CRC	crc lowbyte

A functional test is started with this command as if the input TEST_IN was activated appropriately.

Info byte

0x00 General problem, request cannot be executed.
0x01 Request accepted and will be executed.
0x02 Request cannot be executed because a test or reset is active.
0x03…0xff Reserved

5.7.7 Reset measurement

Master request		Slave answer	
Adr.	address 1…255	Adr.	Slave address
Msg-Code	0x05	Msg-Code	0x05
Msg-Length	0x00	Msg-Length	0x01
CRC	crc highbyte	Msg-Data[0]	Infobyte
CRC	crc lowbyte	CRC	crc highbyte
		CRC	crc lowbyte

A reset of the measurement is started with this command as if the input TEST_IN was activated appropriately.

Infobyte

0x00	General problem, request cannot be executed.
0x01	Request accepted and will be executed
0x02	Request cannot be executed because a test or reset is active.
0x03…0xff	Reserved

5.7.8 Reset microcontroller

Master request		Slave answer	
Adr.	address 1…255	Adr.	Slave address
Msg-Code	0x07	Msg-Code	0x07
Msg-Length	0x00	Msg-Length	0x01
CRC	crc highbyte	Msg-Data[0]	Infobyte
CRC	crc lowbyte	CRC	crc highbyte
		CRC	crc lowbyte

After sending the answer to the master, the slave executes a microcontroller software reset which restarts the firmware.

Infobyte

0x00	General problem, request cannot be executed.
0x01	Request accepted and will be executed
0x02…0xff	Reserved

5.7.9 Set new slave address

Master request		Slave answer	
Adr.	address 0…255	Adr.	Slave address (old address, 1…255)
Msg-Code	0x11	Msg-Code	0x11
Msg-Length	0x01	Msg-Length	0x02
Msg-data[0]	new adress 1…255	Msg-Data[0]	Infobyte
CRC	crc highbyte	Msg-Data[1]	New address
CRC	crc lowbyte	CRC	crc highbyte
		CRC	crc lowbyte

- The slave answers the request with its old address because it is easier for a master to assign request and answer in that case.
- If the slave receives this message with broadcast address 0, it executes the request regularly but does not send an answer.

Info byte

0x00	General problem, request cannot be executed or new address was 0.
0x01	Request accepted and will be executed.
0x02…0xff	Reserved

5.7.10 Get software ID

Master request		Slave answer	
Adr.	address 0…255	Adr.	Slave address
Msg-Code	0x20	Msg-Code	0x20
Msg-Length	0x00	Msg-Length	0x08
CRC	crc highbyte	Msg-Data[0]	ASCII "D"
CRC	crc lowbyte	Msg-Data[1]	Software ID (most significant number) 0…9
		Msg-Data[2]	Software ID 0…9
		Msg-Data[3]	Software ID 0…9
		Msg-Data[4]	Software ID (least significant number) 0…9
		Msg-Data[5]	ASCII "V"
		Msg-Data[6]	Software major version 0..255
		Msg-Data[7]	Software minor version 0..255
		CRC	crc hihgbyte
		CRC	crc lowbyte

Examples of interpretation:

D0569, V1.01:	MsgData[0] = 0x44	(Ascii „D")
	MsgData[1] = 0x00	
	MsgData[2] = 0x05	
	MsgData[3] = 0x06	
	MsgData[4] = 0x09	
	MsgData[5] = 0x56	(Ascii „V")
	MsgData[6] = 0x01	
	MsgData[7] = 0x01	
D0569, V1.31:	MsgData[0] = 0x44	(Ascii „D")
	MsgData[1] = 0x00	
	MsgData[2] = 0x05	
	MsgData[3] = 0x06	
	MsgData[4] = 0x09	
	MsgData[5] = 0x56	(Ascii „V")
	MsgData[6] = 0x01	
	MsgData[7] = 0x1F	(decimal 31)

6. Current transformers

6.1 CTBC17P-03

6.1.1 PCB variant

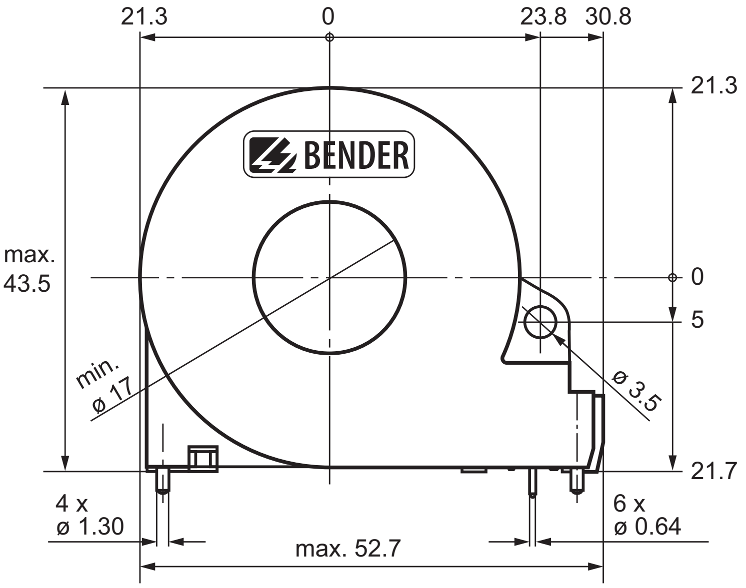


Fig. 6.1: CTBC17P-03 (PCB variant, dimensions in mm)

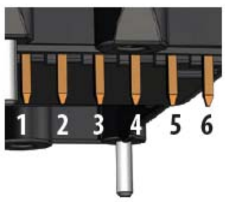
Mounting	Pin assignment sensor pin side	Pin No.	Pin name	Description
		4 , 6	1S1, 1S2	Measurement winding
		3, 5	2S1, 2S2	Measurement winding
		1, 2	3S1, 3S2	Test winding

Fig. 6.2: Pinning CTBC17P-03 (PCB variant)

6.1.2 Cable variant

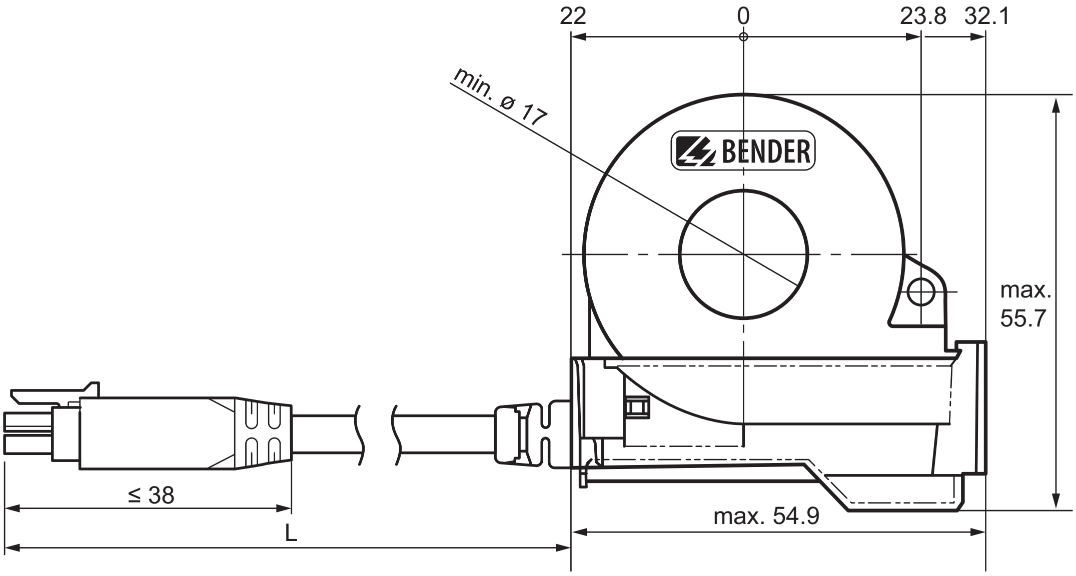


Fig. 6.3: CTBC17P-03 (cable variant, dimensions in mm)

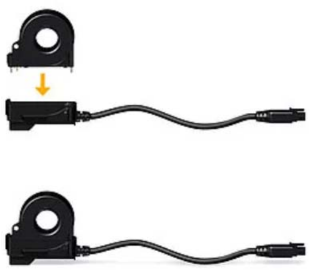
<table>
<tr><th>Mounting</th><th>Pin assignment plug application side</th><th>Pin No.</th><th>Pin name</th><th>Description</th></tr>
<tr><td rowspan="3"></td><td rowspan="3">
</td><td>1, 6</td><td>1S1, 1S2</td><td>Measurement winding</td></tr>
<tr><td>3, 4</td><td>2S1, 2S2</td><td>Measurement winding</td></tr>
<tr><td>2, 5</td><td>3S1, 3S2</td><td>Test winding</td></tr>
</table>

Fig. 6.4: Pinning CTBC17P-03 (cable variant)

6.2 WN12-01

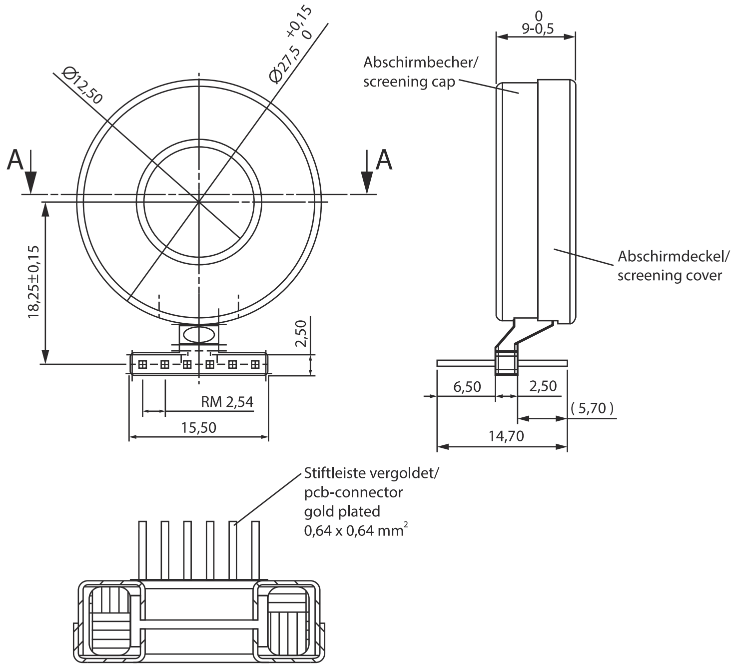


Fig. 6.5: WN12-01 (dimensions in mm)

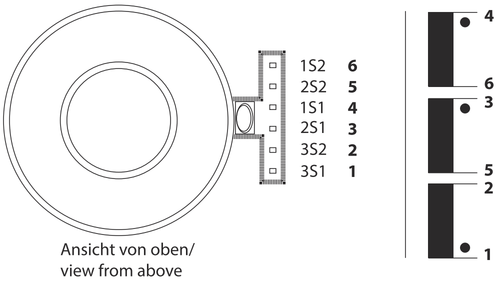


Fig. 6.6: Pinning WN12-01

Pin No.	Pin name	Description
1, 2	3S1, 3S2	Test winding
3, 5	2S1, 2S2	Measuring winding 1
4, 6	1S1, 1S2	Measuring winding 2

Possible board connector:

- SMT female header, 2.54 mm pitch, 3.70 mm profile height, mating pin size 0.64 mm
- W+P part no. 3492-06-1-60-00-PPTR or
- MPE Garry part no. 098-1-006-0-NFX-YR1

6.3 WN18-10

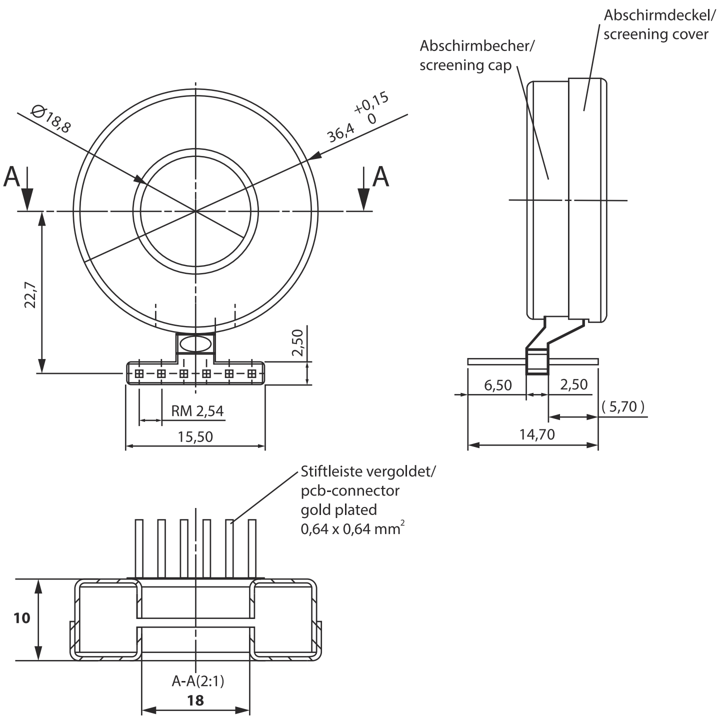


Fig. 6.7: WN18-10 (dimensions in mm)

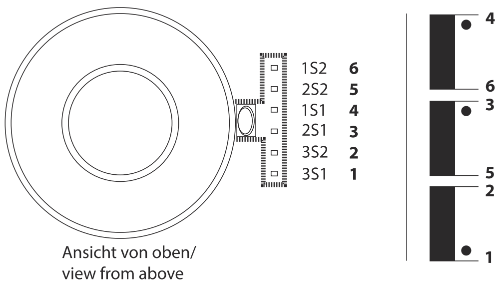


Fig. 6.8: Pinning WN18-10

Pin No	Pin name	Description
1, 2	3S1, 3S2	Test winding
3, 5	2S1, 2S2	Measuring winding 1
4, 6	1S1, 1S2	Measuring winding 2

Possible board connector:

- SMT female header, 2.54 mm pitch, 3.70 mm profile height, mating pin size 0.64 mm
- W+P part no. 3492-06-1-60-00-PPTR or
- MPE Garry part no. 098-1-006-0-NFX-YR1

6.4 W15BS-02

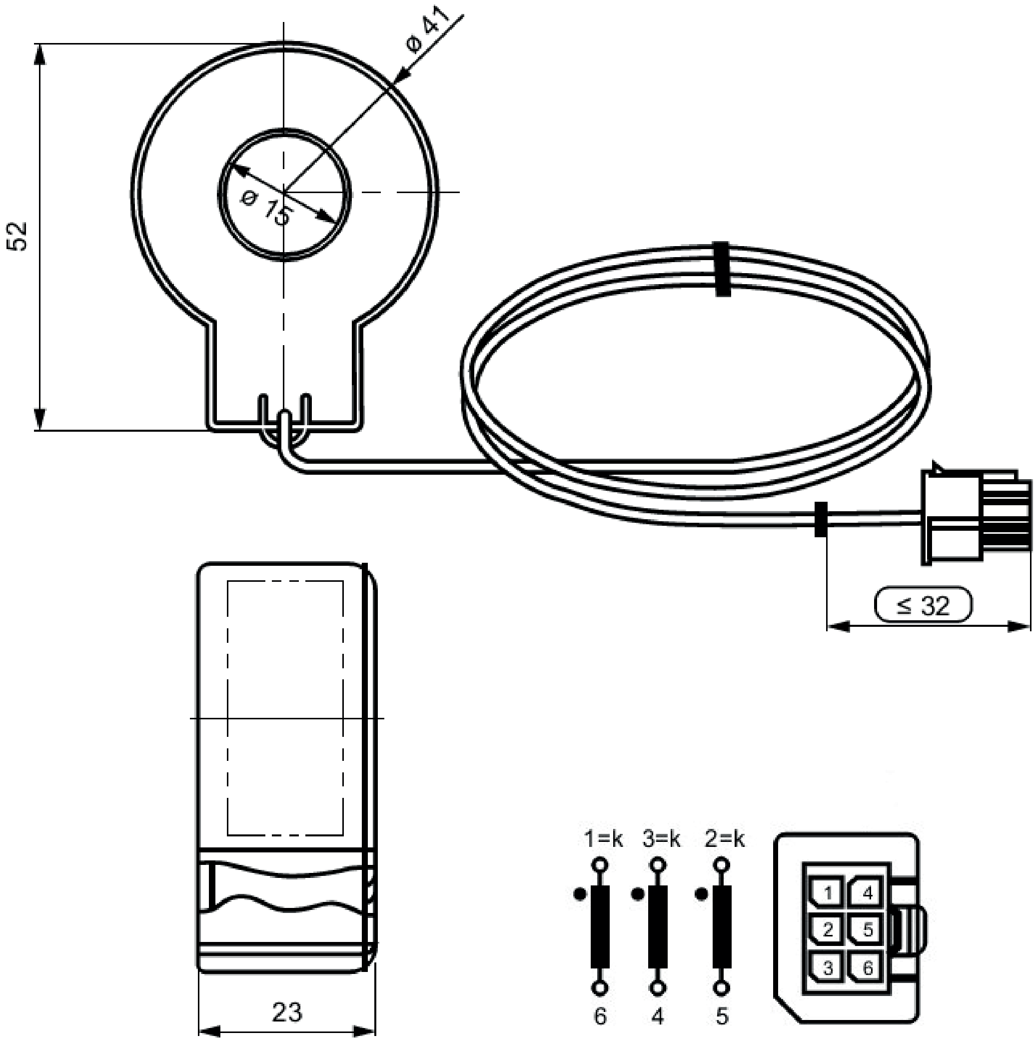


Fig. 6.9: W15BS-01 (dimensions in mm)

Dimensions are noncommittal! Please contact Bender for confirmation.

Pin No	Pin name	Description
2, 5	3S1, 3S2	Test winding
3, 4	2S1, 2S2	Measuring winding 2
1, 6	1S1, 1S2	Measuring winding 1

Possible board connector:
Molex Micro Fit 3.0 Header, Part Number: 43045-0607

7. First start-up operations and functional test

To get the residual current sensor solution to work properly (besides correct soldering and optical inspection AOI) some parameters need to be observed during the first start-up and an initial gain calibration shall be done.

7.1 Recommended first start-up procedure

Step	Result
Voltage at pins 29, 30, 31 of CCE4400	V_S = +5 V ±5 %
Current into pins 29, 30, 31 of CCE4400	I_S ≤ 45 mA
Voltage at pin 37 of CCE4400	$V_{(37)}$ = 12 V ±0.5 V
Voltage at pin 7 of CCE4400	$V_{(7)}$ = 3.3 V ±0.15 V
Voltage at pin 35 of CCE4400	$V_{(35)}$ = 2.5 V ±0.025 V
Frequency at pin 38 of CCE4400 This frequency depends on the current transformer which is used.	$f_{(38)}$ = 3.1 kHz ±0.4 kHz (for CTs A166540 and A166542)
Frequency at pin 45 of CCE4400	$f_{(45)}$ = 8 MHz ±80 kHz

7.2 Recommended procedure to calibrate the gain

Step	Action
Prepare power up	- Ensure that no residual current is present. - Apply 0 V at input CALIBRATE, e.g. with a test probe.
Power up	Apply +5 V supply voltage.
Internal calibration	Wait until signals SWITCH1 and SWITCH2 are in high state.
Start normal measurement	Remove test probe from signal CALIBRATE. Wait until signals SWITCH1 and SWITCH2 are back in low state, this signals the end of calibration.

7.3 Recommended procedure to check functionality

Step	Action
Power up	Apply +5 V supply voltage.
Check that output signals are in enabled state	Signals SWITCH_1, SWITCH_2 and ERR_OUT should be at high level.
Activate TEST_IN	Apply low level for 60 ms …1.2 s
Wait until the measuring time has elapsed	- Wait approx. 1.4 s or alternatively - Monitor signal ACK_OUT to determine the point in time when the output signals should be switched off
Check that output signals are in disabled state	Signals SWITCH_1 and SWITCH_2 should be at low level. Signal ERR_OUT should still be at high level.
Wait until the offset measuring time and time for weld check (UL only) has elapsed	Wait 0.8 s
Check that output signals return to enabled state	Depending on the level of signal "RECLOSE" at power up apply a low level for longer than 1.2 s at input TEST_IN before measuring the levels of signals SWITCH_1 and SWITCH_2.

7.4 Extended procedure to check functionality and trip points

Step	Action
Power up	
Check that output signals are in enabled state	Signals SWITCH_1, SWITCH_2 and ERR_OUT should be at high level.
Apply a residual direct current of DC 6 mA to verify functionality of signal SWITCH_2 (UL: apply 6 mA sinus)	Put a copper wire through the current transformer and connect it with a pure **DC source for IEC** and an **AC source for UL**. Using DC or AC current allows to verify the proper selection of the standard.
Wait until the measuring time has elapsed	Wait at least 500 ms.
Check output signals	Signal SWITCH_2 should be at low level. Signals SWITCH_1 and ERR_OUT should still be at high level.
Remove residual current	Switch off DC current source.
Wait until the measuring time has elapsed	Wait at least 500 ms if automatic reclose is used or activate input "TEST_IN" for longer than 1.2 s to request a reset from switch-off state.
Check output signals	Signals SWITCH_1, SWITCH_2 and ERR_OUT should be at high level.
Apply a residual AC current of 30 mA 50 Hz sinus to verify functionality of signal SWITCH_1 (for UL apply 20 mA sinus)	Put a copper wire through the current transformer and connect it with an AC current source. Using 20 mA to verify UL trip point allows to verify the correct selection of the standard.
Wait until the measuring time has elapsed	Wait at least 200 ms.
Check output signals	Signals SWITCH_1 and SWITCH_2 should be at low level. Signal ERR_OUT should still be at high level.
Remove residual current	Switch off AC current source.
Wait until the measuring time has elapsed	Wait at least 500 ms if automatic "RECLOSE" is used or activate input "TEST_IN" for longer than 1.2 s to request a reset from switch-off state.
Check output signals	Signals SWITCH_1, SWITCH_2 and ERR_OUT should be at high level.

This procedure is not required in regular measuring application, but can help to ***prove the accuracy*** *of the sensor solution at first start-up of a device.*

It is essential that the residual currents applied are verified to be correct.

When using a custom-designed circuit to drive the test winding additionally to the output PWM_TEST, be sure that only one signal source drives the test winding.

The extended procedure allows to verify the correct selection of the standard which was determined during the calibration by reading the level of input pin "STANDARD".

	SWITCH_1		SWITCH_2	
	20 mA (sinus)	**30 mA (sinus)**	**6 mA (DC)**	**6 mA (sinus)**
UL	trip	trip	trip	trip
IEC	no trip	trip	trip	no trip

8. Troubleshooting

Behaviour	Possible cause
The signal ERR_OUT remains in a low state	- No or not sufficient supply voltage. - A gain calibration was not carried out yet. - Disconnection of a wire of the current transformer. - Short circuit of current transformer wires. - The offset measurement at the end of a TEST resulted in an offset of more than 15 mA. - An internal self-test of the microcontroller failed. - Signal "SELECT_CLOCK" is active, but no external oscillator is present or functional on the microcontroller. - UL standard is selected, but input "RELAY_FEEDBACK" signals a closed interrupting contact at the end of a test sequence. - UL standard was selected during calibration, but the level of input "STANDARD" has unintentionally changed to a high state. - IEC was selected during calibration, but the level of input "STANDARD" has unintentionally changed to a low state. - The 10k pull-up resistor at SPI_CLK is missing.
Signals SWITCH1 and SWITCH2 are in low state	- A residual current of more than 30 mA is flowing. - A general fault was detected and the signal ERR_OUT is in a low state, too.
Only SWITCH2 is in low state	- A residual current of more than DC 6 mA is flowing, but not more than 30 mA. - A general fault was detected and the signals ERR_OUT and SWITCH1 are in a low state, too.
No or incorrect response to a TEST request, wrong states of switching outputs during TEST or at the end of a TEST	- Measurement not possible due to a component error in the residual current measurement circuit. - Signal "TEST_IN" permanently high or permanently low. - Signal "TEST_IN" is not activated properly. This signal is low active. - Signal "TEST_IN" is activated for less than 40 ms. - Signal "TEST_IN" is activated longer than 1.2 s and therefore a RESET request is generated instead of a TEST. - The signal PWM_TEST does not drive the test winding because of a bad solder joint. - Transistor T1 component failure. - The current through the test winding is not high enough to trip the switching outputs.
No response to a RESET request	- Signal TEST_IN is not activated properly. This signal is low active. - Signal TEST_IN is activated for less than 1.2 s thus generating a TEST request and not a RESET. - Automatic reclose is configured and a request for a RESET is therefore disabled.

9. Ordering information

<table>
<tr><th>Part</th><th colspan="2">Description</th><th>Art. No.</th></tr>
<tr><td>CCE4400</td><td colspan="2">Sensor circuit</td><td>A138530</td></tr>
<tr><td>Microcontroller</td><td colspan="2">Programmed with IC-CPD analysis software D0569</td><td>B98039701</td></tr>
<tr><td>WN12-01</td><td colspan="2">Current transformer ø12 mm, 1 N AC 16 A</td><td>A166540</td></tr>
<tr><td>WN18-10</td><td colspan="2">Current transformer ø18 mm, 3 N AC 32 A</td><td>B98080062</td></tr>
<tr><td>W15BS-02</td><td colspan="2">Current transformer with cable 18 cm</td><td>B98080067</td></tr>
<tr><td>CTBC17P-03</td><td colspan="2">Current transformer ø 17 mm, PCB mounting</td><td>B98080070</td></tr>
<tr><td>CTBC17P-03-K0325</td><td colspan="2">Current transformer ø 17 mm, cable variant (length 325 mm)</td><td>B98080071</td></tr>
<tr><td>CTBC17 cable1470</td><td rowspan="4">Cable incl.
clip enclosure</td><td>Connector length 1470 mm</td><td>B98080542</td></tr>
<tr><td>CTBC17 cable600</td><td>Connector length 600 mm</td><td>B98080543</td></tr>
<tr><td>CTBC17 cable325</td><td>Connector length 325 mm</td><td>B98080541</td></tr>
<tr><td>CTBC17 cable180</td><td>Connector length 180 mm</td><td>B98080540</td></tr>
<tr><td>Mounting screws M3</td><td colspan="2">Recommended mounting screws: 2 x Würth-WüPlast 2.5 x 8 mm</td><td>-</td></tr>
</table>

10. Standards

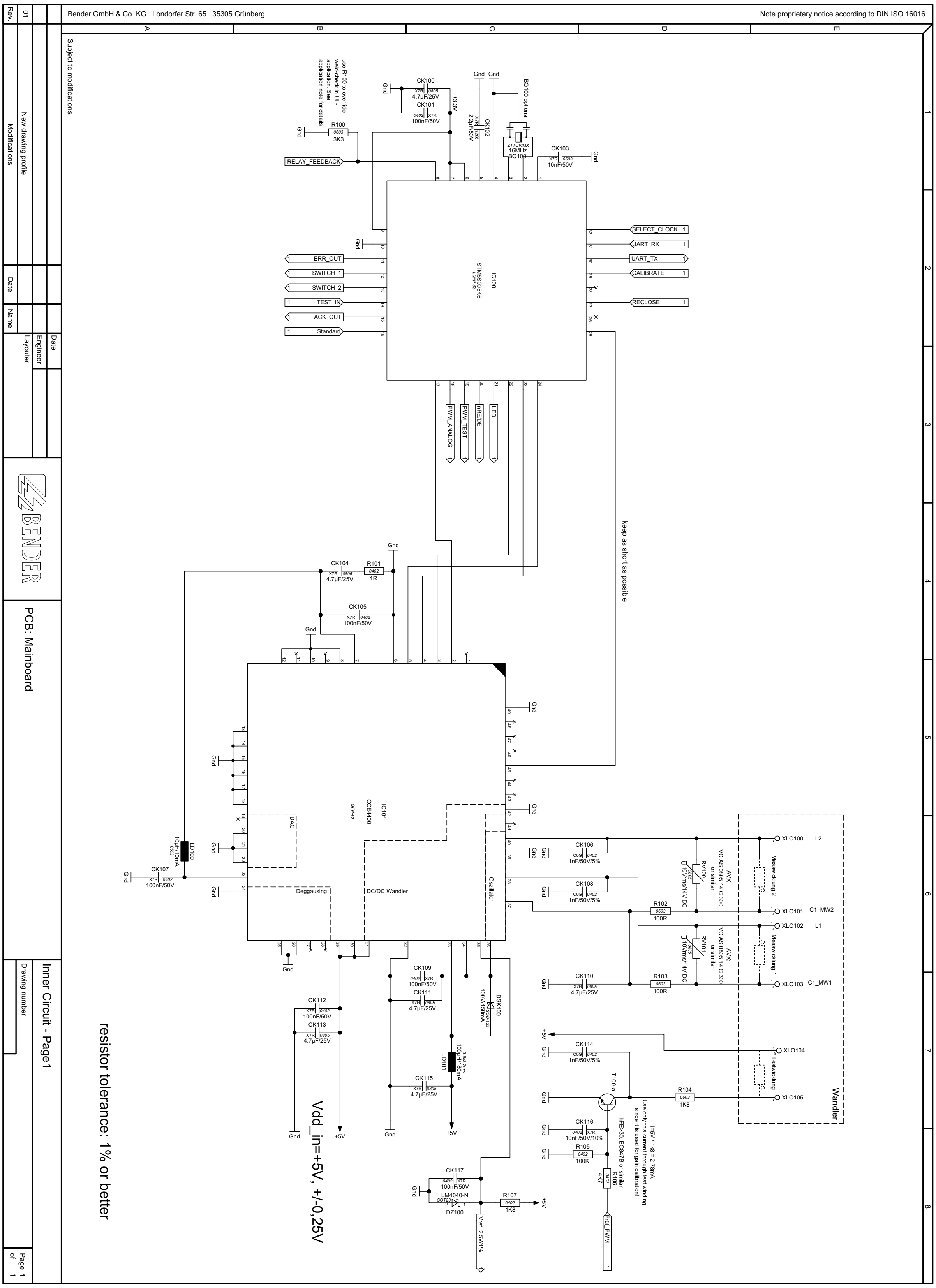
UL2231-2 and **CSA C22.2 No. 281.2**, The Standard for Personnel Protection Systems for electric Vehicle (EV) Supply Circuits: Particular Requirements for Protection Devices for Use in Charging Systems.
UL991, The Standard for Safety for Tests For Safety-Related Controls employing Solid-State Devices.
ANSI/UL 1998, The Standard for Safety for Software in Programmable Components.

11. Revision history

Date	Document version	State/Changes
03.2024	00	Initial release

12. Schematic

See next page.


Bender GmbH & Co. KG Londorfer Str. 65 35305 Grünberg
Note proprietary notice according to DIN ISO 16016
Subject to modifications
New drawing profile
Modifications
PCB: Mainboard
Inner Circuit - Page1
resistor tolerance: 1% or better
Vdd_in=+5V, +/-0,25V
keep as short as possible
IC100
STM8S005K6
IC101
CCE4400
DC/DC Wandler
Deggausing
Oszillator
DAC
Wandler
RELAY_FEEDBACK
ERR_OUT
SWITCH_1
SWITCH_2
TEST_IN
ACK_OUT
Standard
SELECT_CLOCK
UART_RX
UART_TX
CALIBRATE
RECLOSE
PWM_ANALOG
PWM_TEST
nRE/DE
LED
Vref_2,5V/1%
Prüf_PWM

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