TLE4972

User manual

Scope and purpose

This is the user manual of the product family XENSIV™ TLE4972.

TLE4972 is a high precision miniature coreless magnetic current sensor for AC and DC measurements with analog interface and two fast over-current detection outputs. Infineon's well-established and robust monolithic Hall technology enables accurate and highly linear measurement of the magnetic field induced by currents flowing in an external conductor. With a full scale up to ±31mT it is possible to measure currents up to 2,000 ampere. All negative effects (e.g. saturation, hysteresis) commonly known from open loop sensors using flux concentration techniques are avoided.

The digitally assisted analog concept of TLE4972 offers superior stability over temperature and lifetime thanks to the Infineon proprietary mechanical stress and temperature compensation. The temperature drift of sensitivity is corrected at sensor level using a 3rd order polynom. The offset drift is corrected at sensor level using a 2nd order polynom. The drift performance specified in the product datasheet [1] is verified by extensive lab characterization and derived from AEC-Q100 qualification when applicable.

The sensor is an ISO 26262 Safety Element out of Context for safety requirements up to ASIL B and is equipped with internal self-diagnostics. Detailed information are available in the Safety Manual [2].

The user manual describes the output modes and sensing principle in Chapter 1 and the detailed technical aspects of the device required for integration in a system in Chapter 2. The internal block diagram and the typical application circuit are available in the product datasheet [1].

TLE4972 features an integrated EEPROM enabling high flexibility at system level. The document provides a description of the available interface commands in Chapter 3. Measurement range, as well as OCD thresholds and output mode can be programmed by the user. The full set of programmable settings is explained in Chapter 4.2.

Initial errors due to part to part variation and misalignment with respect to the current rail can be canceled out through a single point, room temperature calibration. Details about calibration concept and error components are reported in Chapter 6.

The device is intrinsically robust against stray fields thanks to the differential sensing technology, and crosstalk between nearby phases in multi-phase systems can be compensated at system level as explained in Chapter 7.

Deviation of behavior from datasheet specifications when the ratiometricity settings are re-programmed is explained in Chapter 8.

The devices to which this manual applies are listed in the table "related devices" below.

For the device's specification, please see the respective datasheet [1].

Intended audience

This user manual is written for experienced hardware and software engineers involved in the implementation of the device into a system. It is the responsibility of the system integrator to ensure that the product is suitable for the chosen application and that the procedures described within this user manual are correctly followed.

Related devices

Name	Ordering Code	Package
TLE4972-AE35D5	SP004914362	PG-TDSO-16
TLE4972-AE35S5	SP004914370	PG-VSON-6

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1 Sensing concept

In this chapter the signal naming convention is explained. In addition, the output modes in which the sensor can be configured are described in the following sections. The detailed formulas for each output mode are reported in the product datasheet [1].

Note: The sensor features a ratiometric output mode. Parts without ratiometricity cannot be re-programmed in order to enable it and vice versa. Please check with your local sales representative whether ratiometric parts are available.

1.1 Sensing principle

In the figure below the sensor die is shown together with a sensing structure example realized on a conductor. The sensor features two Hall based sensing elements, or probes, enabling a differential sensing principle. The Hall probes are sensitive to the component of the magnetic field orthogonal to the conductor. The magnetic field lines are generated so that the orthogonal component of the magnetic field has opposite directions on the two sensing elements.

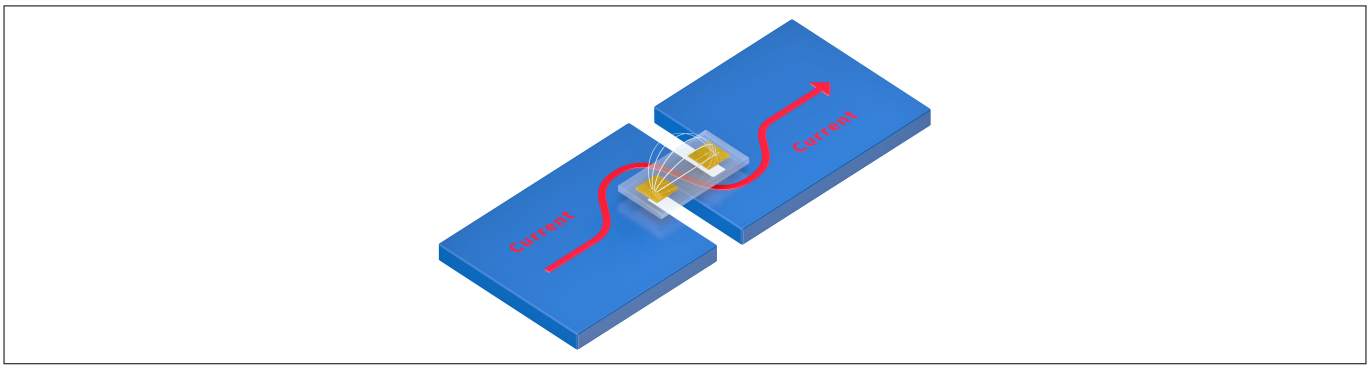

Figure 1 Magnetic field on sensing elements with core-less differential current sensor

B_{DIFF} is the average differential magnetic field at the Hall probes location, respectively B_{H1} and B_{H2}:

$$B_{DIFF} = \frac{B_{H1} - B_{H2}}{2} \quad (1)$$

Guidelines about sensing structure design are given in the dedicated application note [3].

1.2 Sensitivity and transfer factor

The sensor features an analog output, which is used to provide the information of the measured current. The analog measurement result is available as the differential output voltage V_O.

Being S_X the sensitivity in [mV/mT] and V_{OQ} the quiescent voltage of the sensor in [V], in all output modes except fully-differential, the differential output voltage V_O can be expressed as:

$$V_O = V(AOUT) - V(VREF) = S_X \times B_{DIFF} \quad (2)$$

In fully-differential mode, the differential output voltage V_O can be expressed as:

$$V_O = V(AOUT) - V(VREF) = 2 \times S_X \times B_{DIFF} \quad (3)$$

The sensitivity *S*, whose dimension is [V/A], is defined as:

$$S = S_X \times TF \tag{4}$$

where S_X is the sensitivity in [mV/mT] linked to the measurement range programmed in the EEPROM and *TF* is the current rail transfer factor in [T/A] associated to the sensing structure, defined as B_{DIFF} [T] divided by I [A]. The configurable values for S_X (S_X=S_1,...,S_6) are reported in the product datasheet [1].

The current rail transfer factor *TF* indicates the magnetic coupling between sensor and sensing structure. This value is usually expressed as its nominal value for a DC current, when the sensor is in the nominal position with respect to the current rail.

It will be directly influenced by:

- Displacement of sensor in the 3 directions of space, due to e.g. soldering tolerances, mechanical vibrations or material expansion/contraction over temperature and lifetime;
- Manufacturing tolerances of bus-bars and PCB traces;
- Skin effect and eddy current effect in the conductor, when an AC current flows through it;
- Presence of magnetic parts in the system, or of heatsinks/conductor nearby the sensor; eddy currents can be induced in any conductor, also on an aluminum heatsink, and they can hence influence the frequency response of the current measurement system.

Further details about desired sensitivity and target sensitivity for calibration are reported in Chapter 6.

1.3 Fully-differential output mode

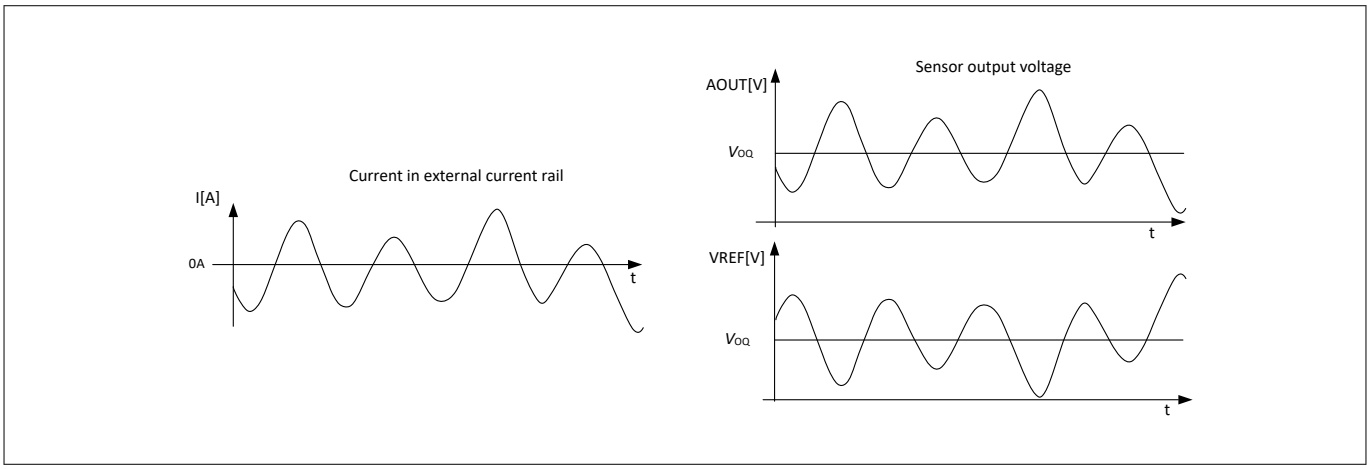

Figure 2 Sensor output for fully-differential mode

1.4 Semi-differential output mode

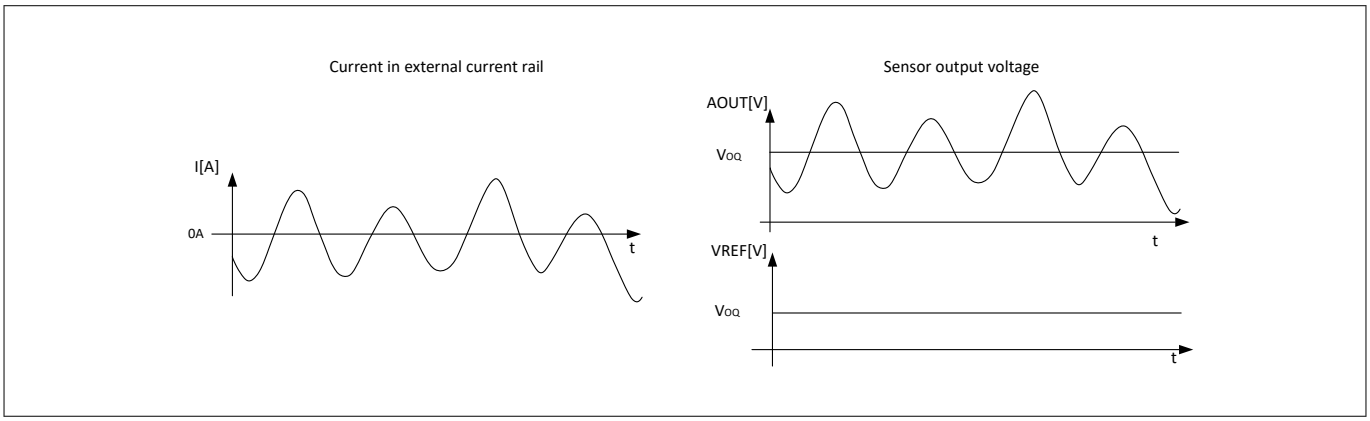

Figure 3 Sensor output for semi-differential mode

1.5 Single-ended output mode

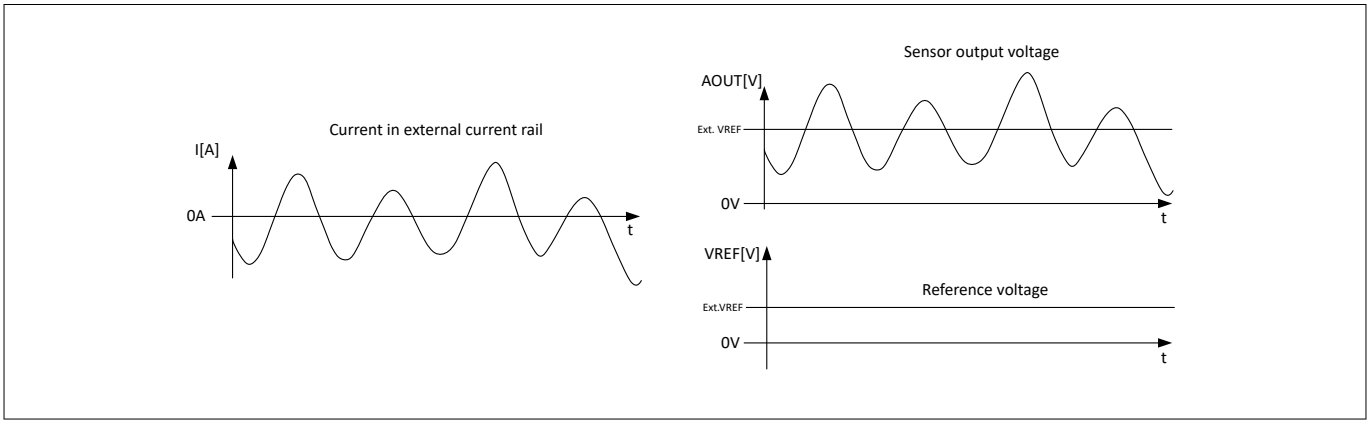

Figure 4 Sensor output for single-ended mode

2 System integration

The sensor works with 3.3 V typical voltage power supply to follow the trend of reduced power supply voltage. However, it can also fit in 5 V systems. This chapter explains how the sensor shall be connected to both 3.3 V and 5 V systems.

2.1 3.3 V domain integration

This section describes how to connect the sensor to the microcontroller in a 3.3 V system in the different operating modes.

2.1.1 Application circuit in fully-differential output mode (3.3 V)

The following figure shows a sketch of application diagram in fully-differential mode. For the detailed application circuit please refer to the product datasheet [1].

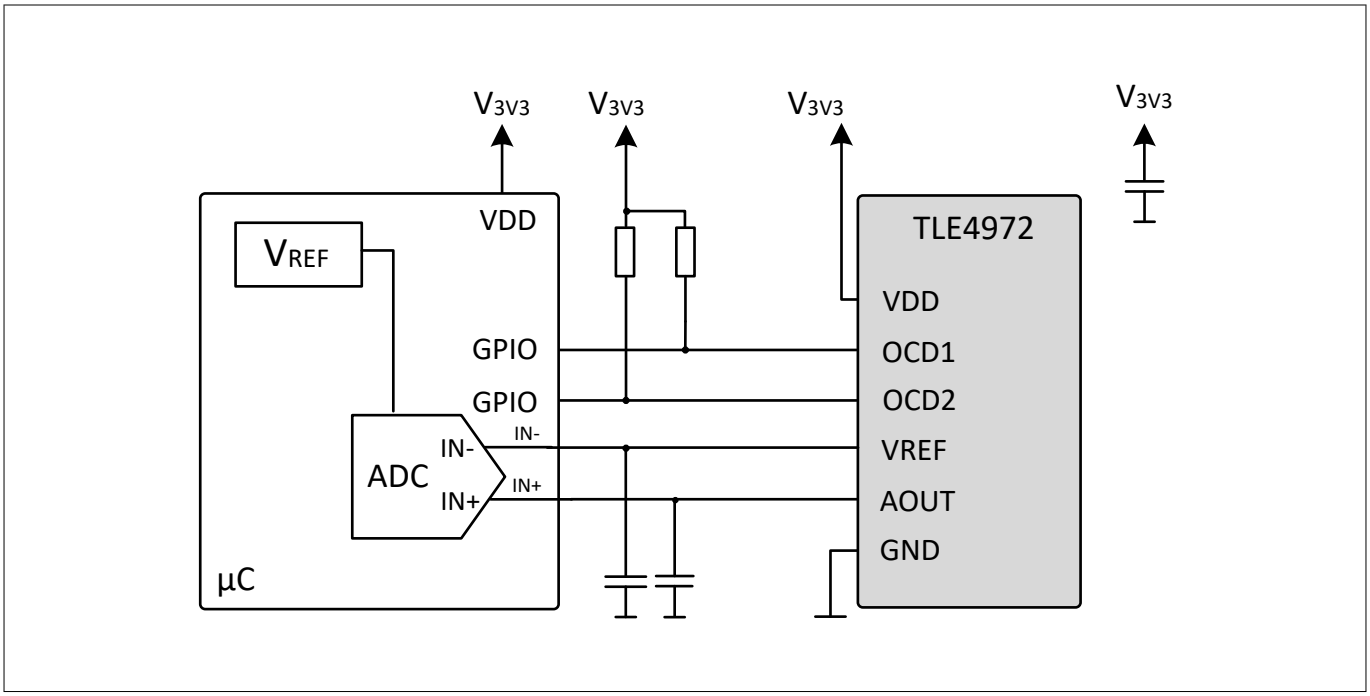

Figure 5 Application circuit in fully-differential mode

2.1.2 Application circuit in semi-differential output mode (3.3 V)

The following figure shows a sketch of application diagram in semi-differential mode. For the detailed application circuit please refer to the product datasheet [1].

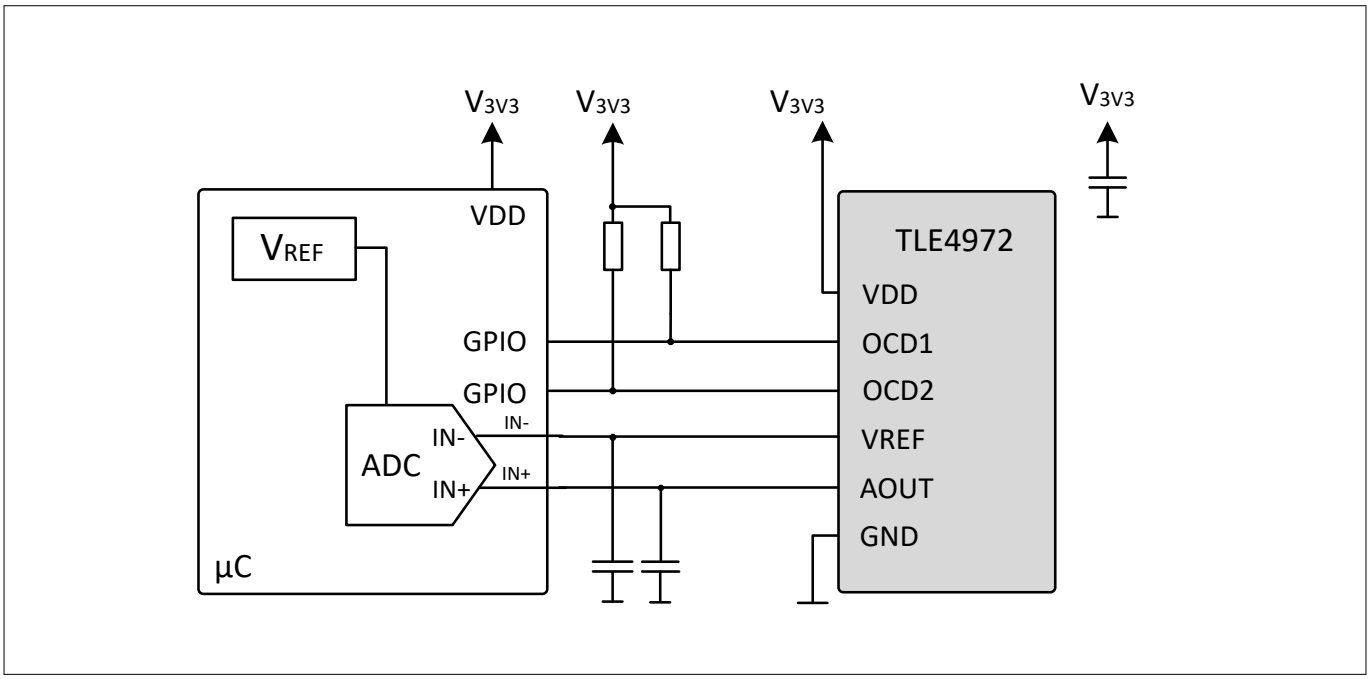

Figure 6 Application circuit in semi-differential mode

2.1.3 Application circuit in single-ended output mode (3.3 V)

The following figure shows a sketch of application diagram in single-ended mode. A resistive divider circuit is used to supply the reference voltage externally, when the VREF is derived from the ADC or µC reference voltage. For the detailed application circuit please refer to the product datasheet [1].

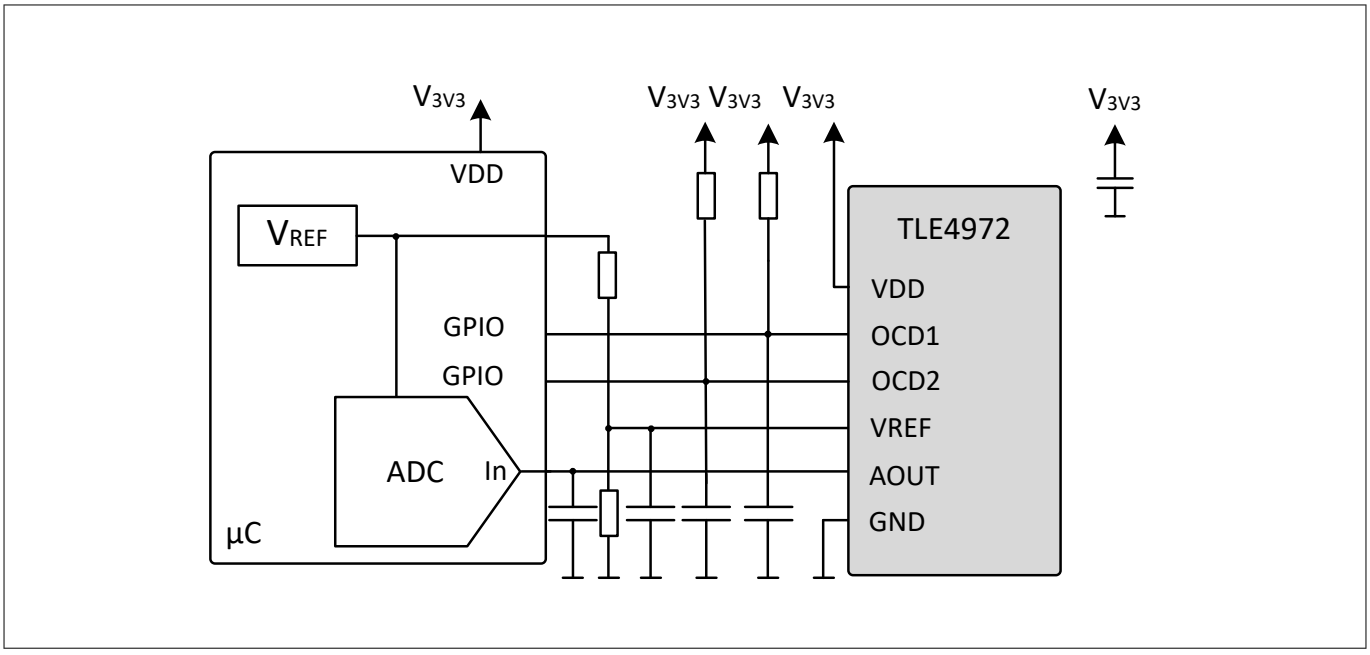

Figure 7 Application circuit in single-ended mode

2.1.4 Application circuit for in-system programming (3.3 V)

In case in-system programming is needed, the figure below shows the typical application circuit that enables in-system programming from microcontroller side in 3.3 V systems. In case an external programmer is used, in-system V_{IO_PRG} generation is not needed. Please refer to Chapter 3.1 for further details.

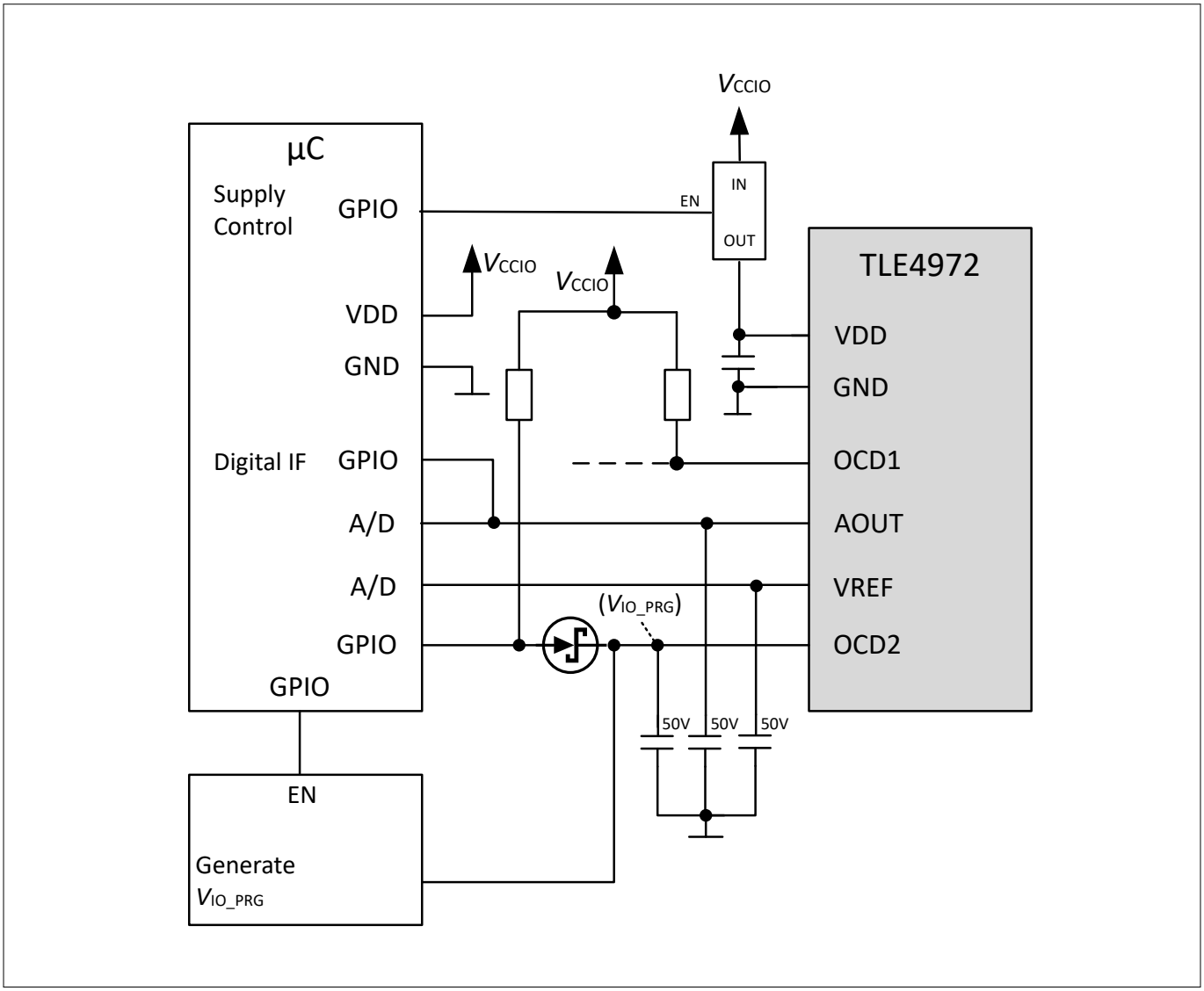

Figure 8 SICI Application circuit with Schottky diode

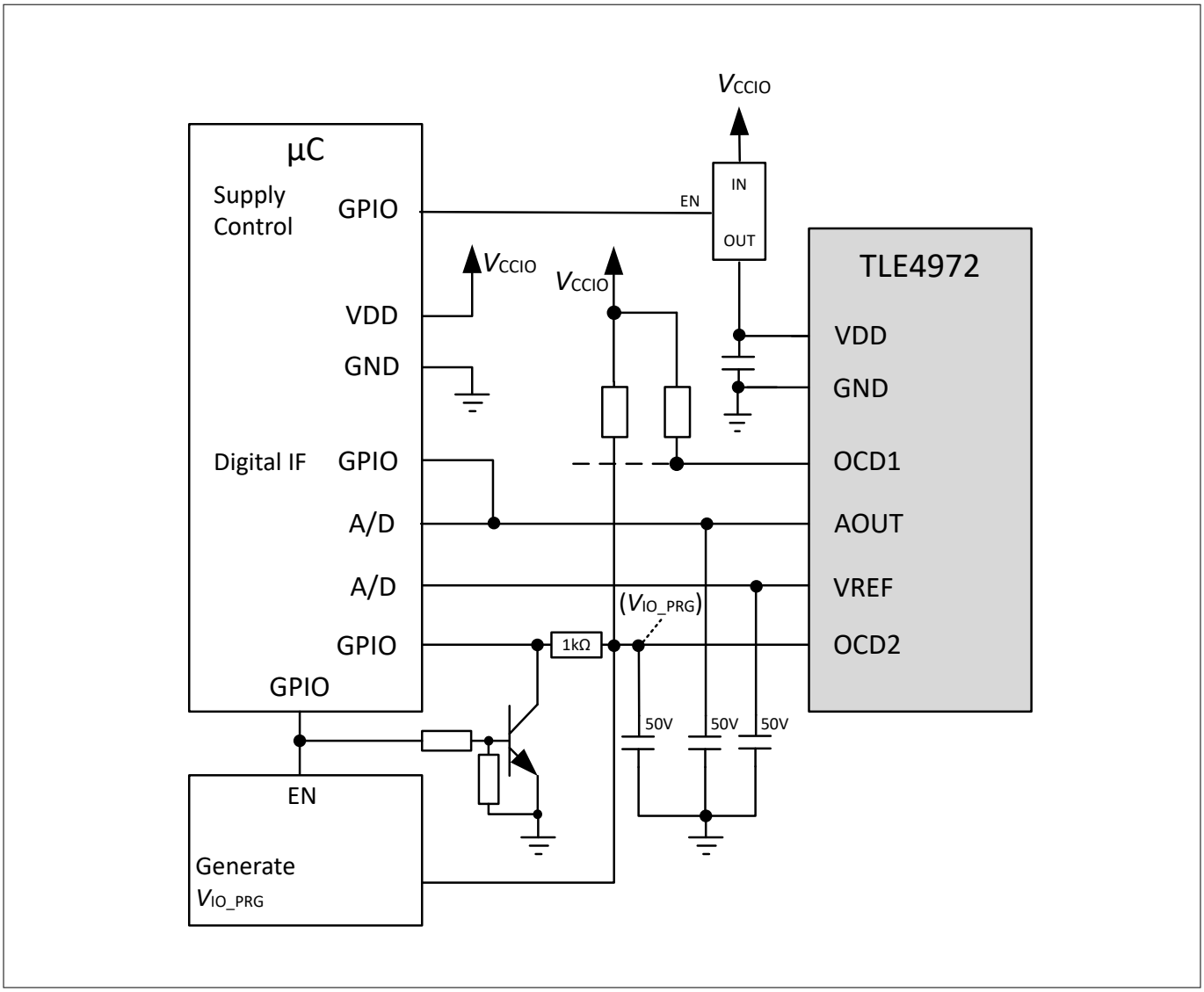

Figure 9 SICI Application circuit with pull-down transistor

Note: In order to protect the µC and other ICs connected to the OCD2 line a hardware protection scheme must be implemented. In the figure above the OCD2 line at microcontroller side is protected through a Schottky diode. This solution is simple, but doesn´t allow a fast pull-down of the OCD2 line from microcontroller side, that is needed for the diagnosis mode activation. Details about the diagnosis mode are provided in the Safety Manual [2]. An alternative is shown in the second proposed application circuit, where the OCD2 line at microcontroller side is pulled down through a 1 kΩ resistor. This solution allows a fast diagnosis mode activation from microcontroller.

Protecting the microcontroller from the programming voltage on OCD2 pin is not needed in case that the sensors lie on a separate PCB which is not connected to the system during programming phase.

Note: In order to allow in-system programming with an external programmer, the sensor pins VDD, GND, AOUT and OCD2 must be routed to the external programmer with a dedicated on-board connector. For end of line in-system calibration, also VREF must be routed to the external programmer in order to read the differential output voltage needed by the calibration routine.

Note: Do not connect OCD2 pins from different sensors together, if diagnosis mode is enabled in the EEPROM (default). If all OCD2s are tied together, the OCD2 fault indication of one sensor might unintentionally

activate the diagnosis mode on the other sensors by forcing the pin to ground. Details about the diagnosis mode are provided in the Safety Manual [2].

2.2 5 V domain integration

This chapter discusses a proposal to connect TLE4972 sensor with a 5 V microcontroller.

2.2.1 Converting from 5 V to 3.3 V

If the supply of the control system is 5 V and not 3.3 V, a step-down of the supply voltage is needed.

The simplest way to generate a 3.3 V supply from a 5 V supply is by using a resistive voltage divider. However, when using a resistive voltage divider one has to consider the following drawbacks:

- resistors have tolerances, hence in series-production the generated output supply may differ from the initially calculated value;
- the current flowing from the upper resistor to the sensor dissipates power. Please refer to product datasheet [1] for typical and maximum current consumption;
- the generated voltage is dependent on the current consumption of the sensor, hence it is not stable and may be subjected to variations.

Additionally, in order to reduce the effect of the load current on the voltage divider output voltage, the resistor cannot be too large. On the other hand, by using low resistor values the overall current flowing through the voltage divider to ground increases, and hence the power dissipated in the resistors also increases, leading to unnecessary power dissipation.

For the reasons mentioned above it is recommended to generate the 3.3 V using a voltage regulator. Indeed, the power dissipated in the voltage regulator is lower and the voltage is more stable since usually a control loop is implemented, including also active devices (e.g. BJT, MOSFET). Suitable devices could be Linear Voltage Regulators (LDO) from Infineon:https://www.infineon.com/cms/en/product/power/linear-voltage-regulator/

2.2.2 Interfacing AOUT and VREF to the microcontroller

In order to separate the 3.3 V and 5 V voltage domains and to adapt the signal dynamic from 3.3 V to 5 V, it is recommended to use operational amplifiers in non-inverting configuration.

The selected device shall have:

- Low offset to not add offset to the current sensing chain;
- Low noise to not add noise to the current sensing chain;
- Rail to rail capability to preserve the large linear range of the sensor;
- True single supply (0 - 5 V) to be compatible with the supply of the system;
- Good bandwidth sufficiently large to fit the application requirements.

2.2.3 Application circuit in fully-differential output mode (5 V)

The following figure shows a sketch of application diagram in fully-differential mode in a 5 V system. For the detailed application circuit please refer to the product datasheet [1].

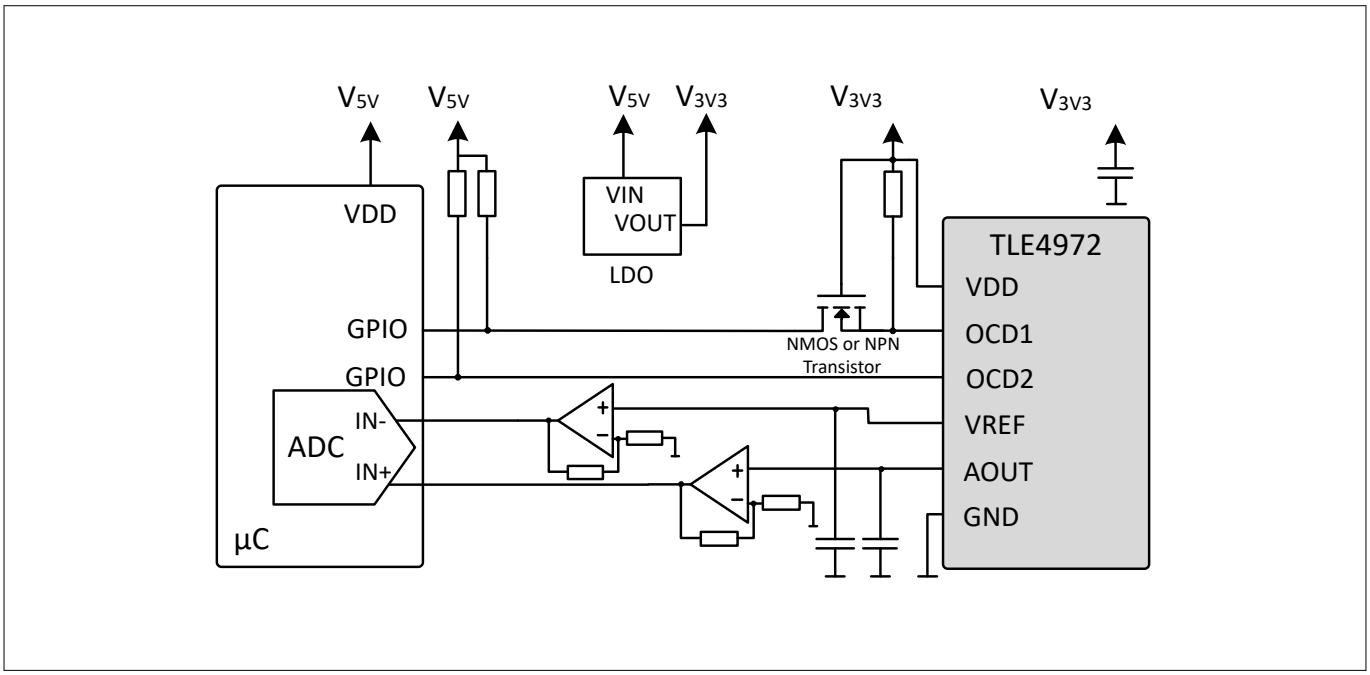

Figure 10 Application circuit in fully-differential mode for 5 V systems

2.2.4 Application circuit in semi-differential output mode (5 V)

The following figure shows a sketch of application diagram in semi-differential mode in a 5 V system. For the detailed application circuit please refer to the product datasheet [1].

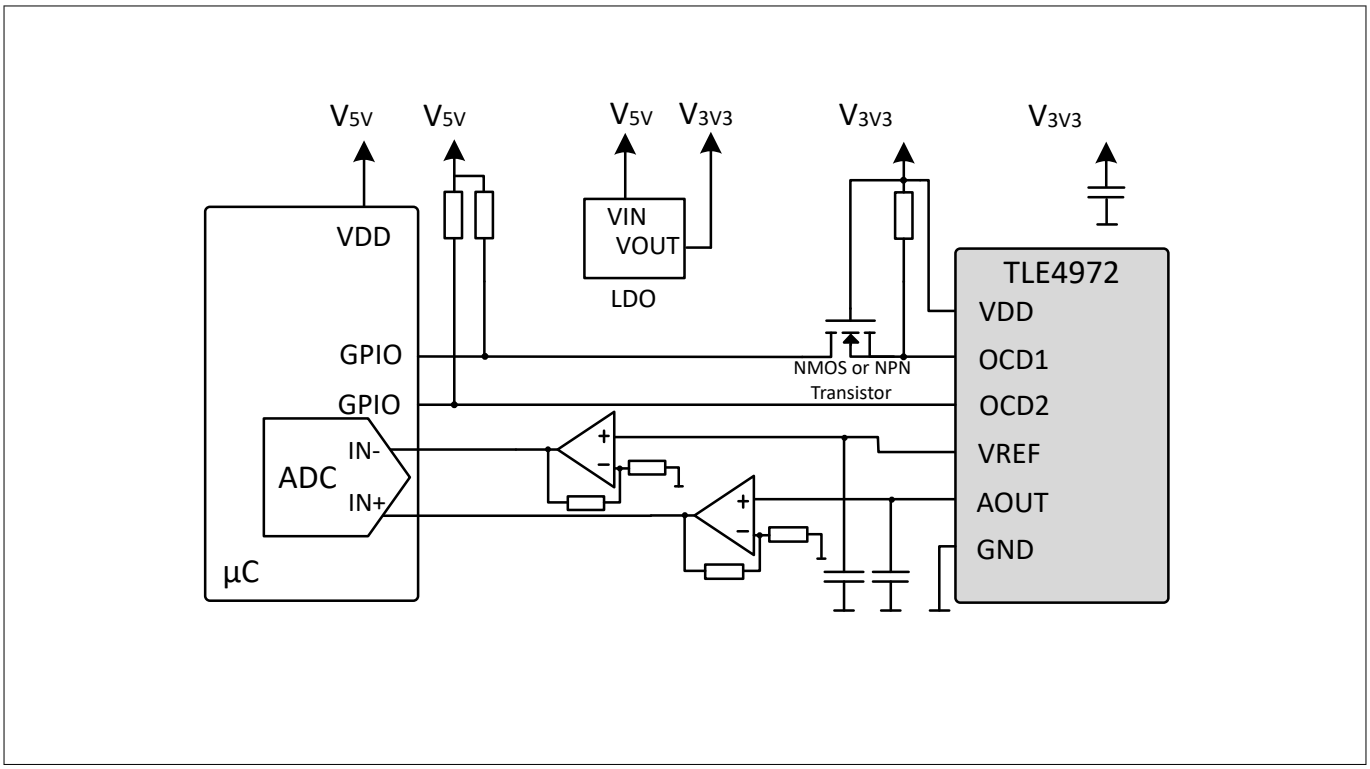

Figure 11 Application circuit in semi-differential mode for 5 V systems

2.2.5 Application circuit in single-ended output mode (5 V)

The following figure shows a sketch of application diagram in single-ended mode in a 5 V system. For the detailed application circuit please refer to the product datasheet [1].

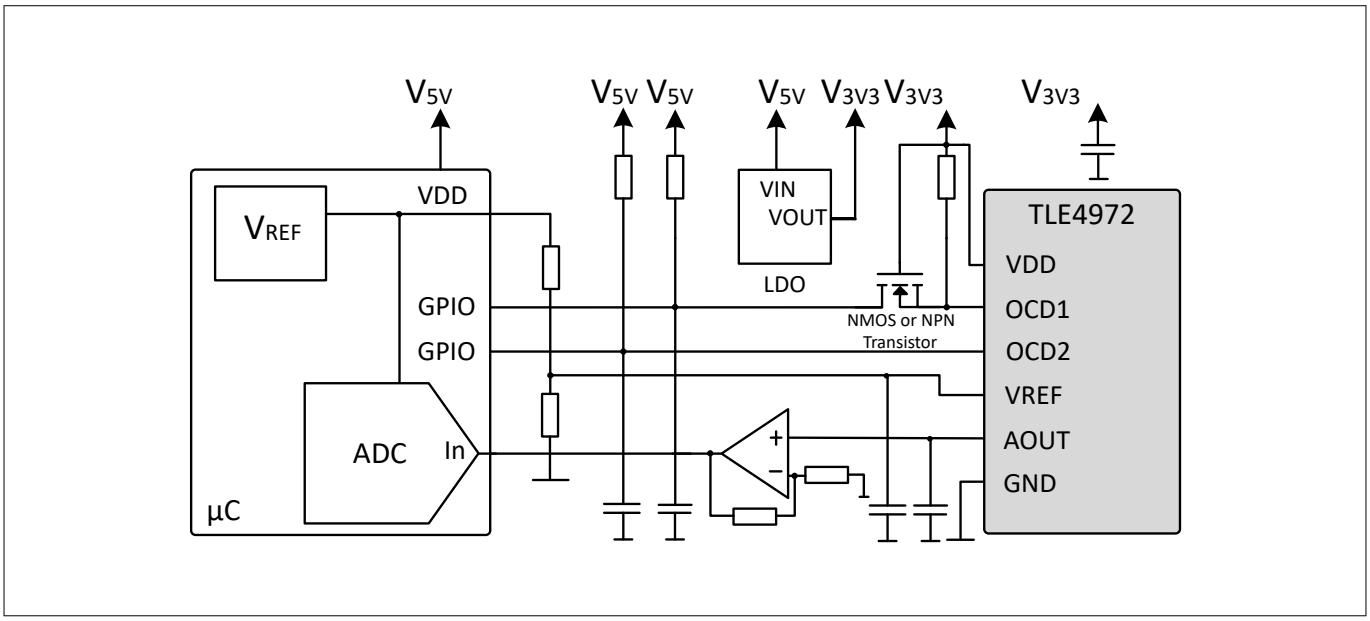

Figure 12 Application circuit in single-ended mode for 5 V systems

2.2.6 Application circuit for in-system programming (5 V)

In case of 5 V systems, programming is only possible through an external programmer connected to the 3.3 V sensor domain. Please refer to Chapter 3.1 for further details.

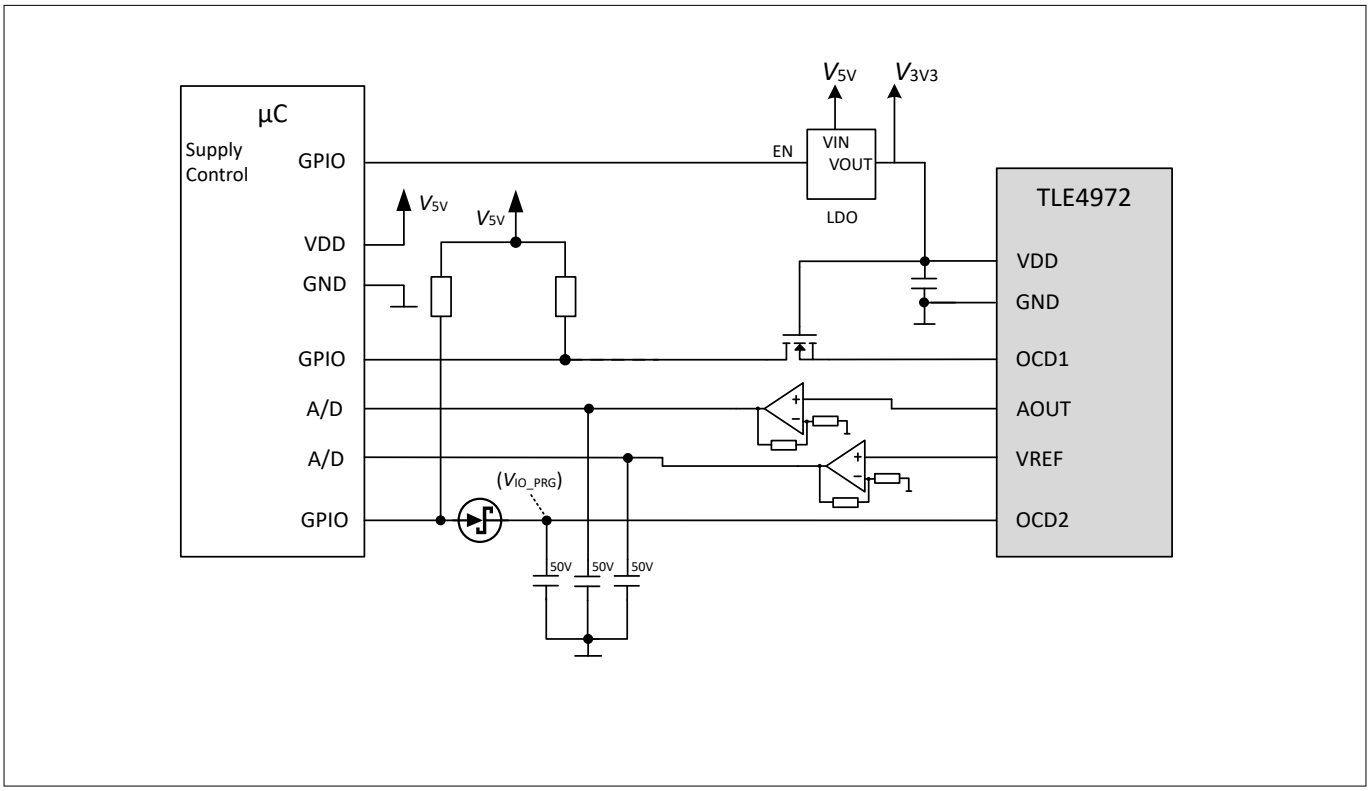

Figure 13 SICI Application circuit in 5 V systems with Schottky diode

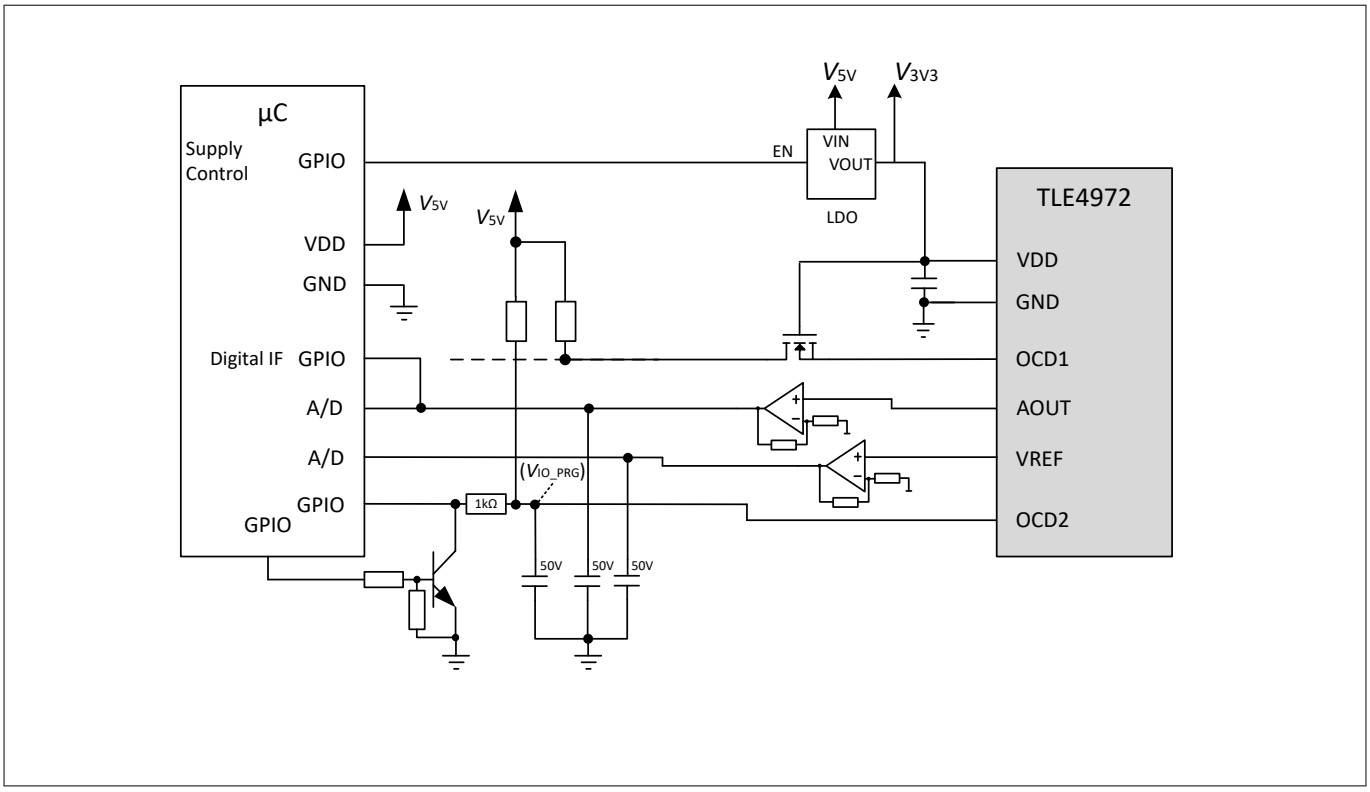

Figure 14 SICI Application circuit in 5 V systems with pull-down transistor

Note: In order to protect the µC and other ICs connected to the OCD2 line a hardware protection scheme must be implemented. In the figure above the OCD2 line at microcontroller side is protected through a Schottky diode. This solution is simple, but doesn´t allow a fast pull-down of the OCD2 line from microcontroller side, that is needed for the diagnosis mode activation. Details about the diagnosis mode are provided in the Safety Manual [2]. An alternative is shown in the second proposed application circuit, where the OCD2 line at microcontroller side is pulled down through a 1 kΩ resistor. This solution allows a fast diagnosis mode activation from microcontroller.

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Note: Do not connect OCD2 pins from different sensors together, if diagnosis mode is enabled in the EEPROM (default). If all OCD2s are tied together, the OCD2 fault indication of one sensor might unintentionally activate the diagnosis mode on the other sensors by forcing the pin to ground. Details about the diagnosis mode are provided in the Safety Manual [2].

2.3 External programmer

An external programmer can be used to avoid the implementation of the SICI hardware layer. An evaluation programmer is available for pre-production activities [4].

For productive in circuit programming Infineon recommends to use a verified programmer which has been a coproduction development between Infineon and CGS. For further documentation please refer to CGS – Computer Gesteuerte Systeme GmbH (cgs-gruppe.de).

3 Serial Inspection and Configuration Interface (SICI)

3.1 SICI hardware layer and voltage ratings

The sensor provides a 16 bits bidirectional one wire digital interface to access the internal EEPROM and internal registers. The application circuits for in-system programming in case of 3.3 V and 5 V systems and the needed system level precautions are described in Chapter 2.1.4 and Chapter 2.2.6. The AOUT pin is connected to a GPIO port in order to establish the communication between the sensor and the microcontroller. The communication is based on transmitting a bitstream from microcontroller to the sensor. The AOUT pin is used as an I/O pin to read and write on the SICI bus by forcing the pin to low/high with a defined timing. The EEPROM is effectively programmed by applying the V_{IO_PRG} voltage to the OCD2 pin.

Table 1 SICI operating parameters

Parameter	Symbol	Min.	Typ.	Max.	Unit	Note
Voltage level for SICI – High	V_{SICI_HIGH}	1.6	3.3	-	V	High state (transition from low to high).
Voltage level for SICI – Low	V_{SICI_LOW}	-	0	1.3	V	Low state (transition from high to low).

3.2 Internal State Machine (ISM)

The TLE4972 features a digital signal conditioning concept. The Internal State Machine (ISM) optimizes in real time the output stage performance, providing stable sensor behavior over temperature and lifetime. The ISM has to be disabled during programming, in order to avoid write conflicts to internal registers. The reactivation of the ISM happens through power cycle of the device, or by setting the corresponding bit in the internal bitmap. Please refer to Chapter 4.1.

3.3 SICI timing specifications

A single bit information sent by the microcontroller is encoded as a PWM waveform for which the duty-cycle is defined as follows:

- Logic "0" is sent as a short low ($0.3*T_{BIT}$) and long high ($0.7*T_{BIT}$) PWM pulse;
- Logic "1" is sent as a long low ($0.7*T_{BIT}$) and short high ($0.3*T_{BIT}$) PWM pulse.

The typical threshold level to detect a logic "0" during a high to low transition and for logic "1" during low to high transition are shown in Table 1.

An example of a 1 bit transmission sending a logic "0" to the device by receiving a logic "1" can be seen in the following figure. The initial pulse length is defined by t_{1_0} and t_{2_0}. When sending a logic "0" to the device the low time t_{1_0} has to be shorter than the high time t_{2_0}. The response time t_4 is depending on the low time t_{1_0} and high time t_{2_0} as described in the following table. The grey square marks the time window when reading shall be performed by the microcontroller. Read access shall be performed starting at half of the t_4 time window, as specified by the reading time t_R. During the reading time t_R, the master shall not drive the AOUT pin. All parameters are described in the following table.

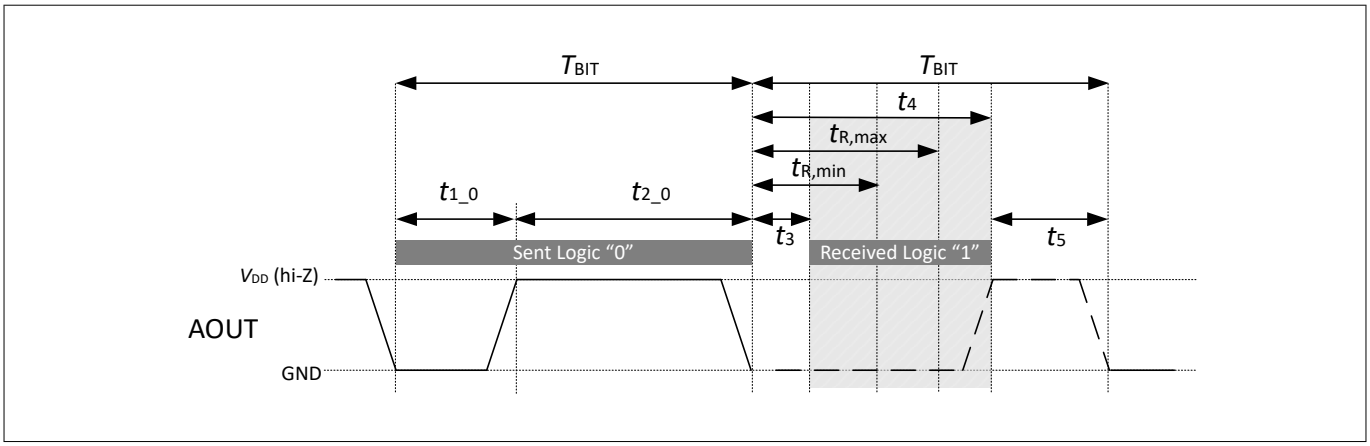


Figure 15 Logic "0" Duty Cycle Waveform

The following figure shows an example of a 1 bit transmission sending logic "1" to the device by receiving logic "0".

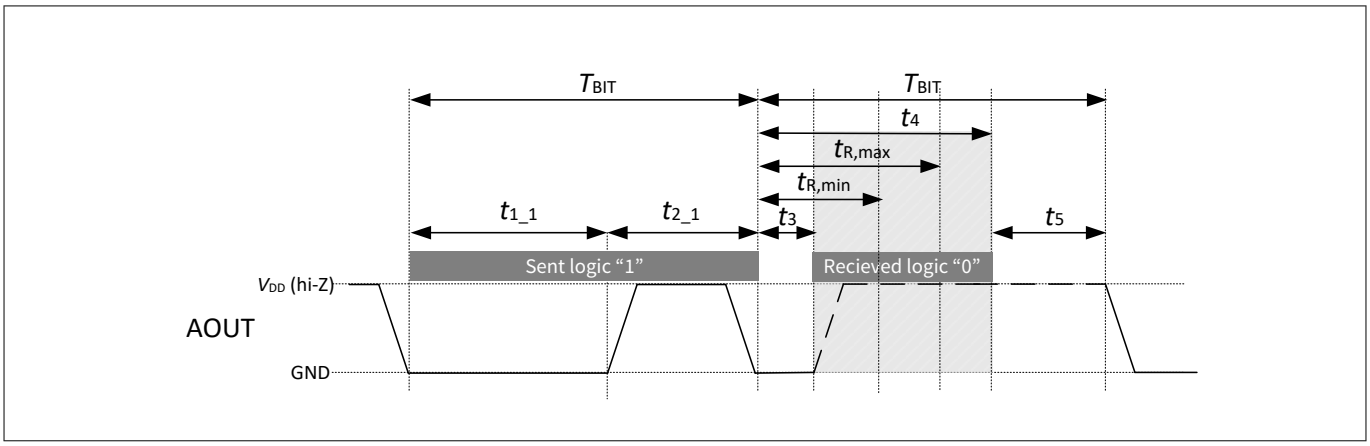


Figure 16 Logic "1" Duty Cycle Waveform

Table 2 SICI interface timings

Parameter	Symbol	Min.	Typ.	Max.	Unit	Note
Interface pre-enable time	t_{PRE_IFEN}	-	-	100	µs	The user can start forcing AOUT to GND during this time window.
Interface enable time	t_{IFEN}	300	-	-	µs	AOUT must be forced to GND before the end of this time window in order to enter the SICI interface.
Period time of 1 bit	T_{BIT}	40	-	7500	µs	It defines the time to transmit 1 bit between the device and a microcontroller.

(table continues...)

Table 2 (continued) SICI interface timings

Parameter	Symbol	Min.	Typ.	Max.	Unit	Note
Low time sending 0	t_{1_0}	28	33	38	% of T_{BIT}	It defines the first low time of a bit. The low time has to be shorter than the next high time to send a logic 0 bit to the device. Every bit has to start with a low time.
Low time sending 1	t_{1_1}	62	67	72	% of T_{BIT}	It defines the first low time of a bit. The low time has to be longer than the next high time to send a logic 1 bit to the device. Every bit has to start with a low time.
High time sending 0	t_{2_0}	-	T_{BIT} -t_{1_0}	-	µs	It defines the first high time after the low time of a single bit. In order to send a logic 0 to the device the high time has to be longer than the previous low time.
High time sending 1	t_{2_1}	-	T_{BIT} -t_{1_1}	-	µs	It defines the first high time after the low time of a single bit. In order to send a logic 1 to the device the high time has to be shorter than the previous low time.
Low time before read	t_3	10	-	30	% of t_4	Increase of this time will reduce sensor response time t_4. Therefore t_R has to be set accordingly. The AOUT pin has to be forced to GND after the first high time of a transmitted bit to initiate the response sequence.
Reading time	t_R	50	-	80	% of t_4	The device drives AOUT to V_{DD} by default. Set the external controller in tri-state.

(table continues...)

Table 2 (continued) SICI interface timings

Parameter	Symbol	Min.	Typ.	Max.	Unit	Note
Response time	t_4	2 * ABS(t_{1_x} - t_{2_x})	-	-	µs	During this time, the AOUT pin is driven from the device. Therefore, the master shall not drive the AOUT pin. The device drives the AOUT either to GND or V_{DD} .The master shall sample/read the AOUT pin level for the response within the defined time window specified by parameter t_R.
Time between 2 bits	t_5	1	T_{BIT}-t_4	5400	µs	The maximum high time between two bits is limited by the maximum allowed high time. By exceeding the maximum high time, the interface is deactivated and can only be entered after restarting the device.
Max high time	t_{HIGH}	1	-	5400	µs	Only valid for a single bit high time. There is no restriction in timing between two commands. If AOUT stays at V_{DD} longer than the defined max high time thigh, the SICI communication is closed and the sensor starts working in the defined operating mode. To start a new communication the sensor shall be powered off and on again.
Min low time	t_{LOW}	1	-	5400	µs	If AOUT stays at GND longer than the defined max of minimum low time the SICI communication is closed and the sensor starts working in the defined operating mode. To start a new communication the sensor shall be powered off and on again.

(table continues...)

Table 2 (continued) SICI interface timings

Parameter	Symbol	Min.	Typ.	Max.	Unit	Note
ISM settling time	$T_{ISM\_SETTLING}$	-	-	100	µs	Time needed after ISM reactivation for AOUT voltage to settle.

3.4 SICI activation

The AOUT pin must be driven using a specific timing to ensure the correct enabling of the SICI communication between the sensor and microcontroller. The external microcontroller must be able to control the sensor supply voltage in order to meet the correct timing and successfully activate the interface. The steps for correctly entering the SICI are the following; in the figure below, the green highlighted squares indicate the received bits, while the blue highlighted squares indicate the bits sent by the sensor:

- The output buffer of the sensor (open drain with internal pull-up) keeps the AOUT pin to V_{DD} during the high impedance state of the GPIO pin of the external microcontroller, within the first 400 µs after supplying the device;
- The AOUT pin has to be driven by the external microcontroller to GND for t_{LOW} time within the defined time window of t_{IFEN}. The GPIO pin of the external microcontroller must support tri-state configuration to allow the sensor to reply. This low state is only necessary after startup to allow the device to be prepared to receive the 16 bits enter-interface command (password). The activation will also work if the AOUT stays at GND from the beginning onwards. There is no need to set the AOUT to V_{DD} before forcing it to GND;
- After releasing the AOUT back to V_{DD} send the 16 bits enter-interface command with LSB first from the microcontroller. While sending the SICI enter-interface command, the device answers to each sent bit with logic "0";
- After a correct enter-interface command has been sent, the AOUT pin will remain at V_{DD} being in open-drain mode. Otherwise, the AOUT pin will reflect the quiescent voltage if the interface activation is unsuccessful.

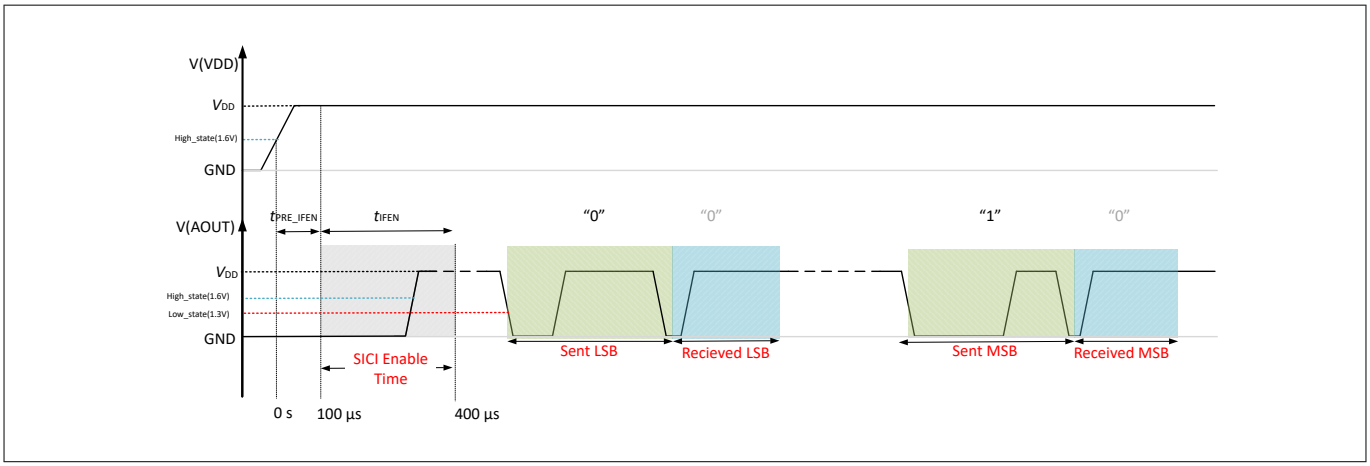


Figure 17 Enabling SICI after device startup

The figure below shows the real time oscilloscope figure which describes the interface activation by modulating the AOUT after startup. The modulation of the first two password bits can be seen in the oscilloscope picture. The user must make sure that microcontroller does not drive the AOUT pin to high during the sensor reply, i.e. Read LSB bit "0" in the figure below, to avoid the AOUT pin drawing an excessive amount of current.

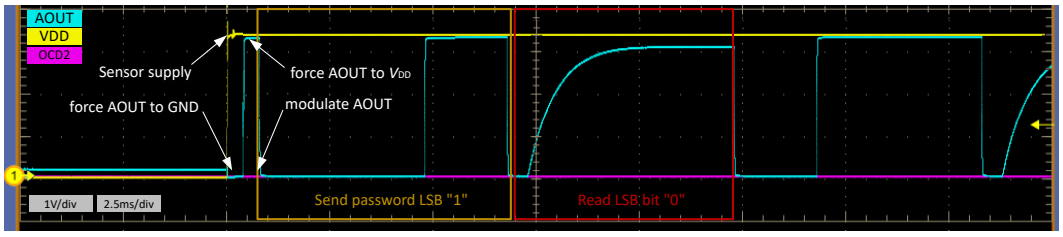


Figure 18 SICI enter interface sequence

The figure below shows the oscilloscope picture of the complete 16 bits command which is necessary to activate the sensor interface. The PWM modulation of each sent bit followed by the answer bits are visible. After sending the enter-interface command, the next falling edge of the AOUT will start the subsequent 16 bits commands.

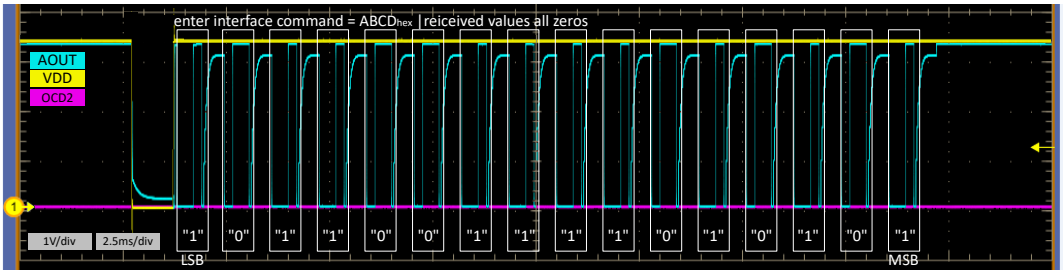


Figure 19 SICI enter-interface command

3.5 SICI standard commands

A typical SICI communication consists of multiple input commands transmitted over AOUT via the same voltage modulation as used for the enter-interface command, followed by a command including the access information and address. The sensor replies with the data of a previous command. The sent data stream is initiated by the microcontroller starting with the LSB first and the receiving sequence is driven by the device. The reply data stream sent by the device starts with the LSB first.

The following three tables describe the microcontroller command frame bit and the standard interface commands.

Table 3 Microcontroller Command Frame

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
w/r	PR#	0			ADDR[6:0]							LEN[3:0]			

Table 4 Microcontroller Command Bit Description

Bits	Name	Description
3:0	LEN	These 4 bits define the burst length i.e. the number of data frames following the command frame for read and write accesses as LEN + 1. The burst length is important especially for write accesses, as all frames from the master are treated as data frames. The address is incremented automatically by the interface starting with the initial address in the command frame until the burst length has been reached.
10:4	ADDR	Initial 7 bits address used for read and write accesses. Note that the address will simply wrap around internally, if the access reaches the end of the address space (128 words), but the burst length is not reached yet.
13:11	-	These bits need to be set to "0", as they are used to identify NOP commands. Therefore, a NOP command with usually all bits set to "1" is ignored by the interface.
14	PR#	"0" means, the interface performs a read-out of the initially addressed register and sends back the current data while receiving the first write data frame. On successive write data frames, the new content of the previously written register address is send back to the master. To get all the new register content e.g. an additional NOP frame would have to be sent at last, as it is done for a read access. Note that these pre and post reads during a write access will also affect clear-on-read bits (e.g. status bits). Therefore, it is suggested to set this bit to "1", if in doubt. "1" means, pure write access to addressed registers.
15	w/r	"0" means read access. To receive the data requested for readout, NOP frames (frame content set to all ones) have to be send for the given burst length. A frame that does not have at least bits 13:11 set to "1" will be interpreted as a new command and thus can interrupt a read access. "1" means write access. All the following frames within the burst length will be treated as write data frames. Therefore, a write access cannot be interrupted.

Table 5 Commonly Used Commands

Command name	Address	Command / Data	Description
Enter-interface command	-	$ABCD_{hex}$	Activate communication.
Power down ISM	25_{hex}	8000_{hex}	Reserve if-access to the EEPROM data bus to avoid that ISM is blocking the data bus.

(table continues...)

Table 5 (continued) Commonly Used Commands

Command name	Address	Command / Data	Description
Disable failure indication	01_{hex}	0000_{hex}	Disabling internal safety mechanism reactions (except overvoltage).
Write command	40_{hex} to 42_{hex}	8402_{hex} / XYXY	Initialize write command to address 40_{hex}. Send data XYXY to previous addressed line where XYXY stand for 16 bits data placeholder.
Read command	40_{hex} to 51_{hex}	0400_{hex}	Initialize read command at address 40_{hex}.
Read command	41_{hex}	0410_{hex}	Initialize read command at address 41_{hex}. Read data from previous address 40_{hex}.
Read command	51_{hex}	0510_{hex}	Initialize read command at address 51_{hex}. Read data from previous address.
NOP	-	$FFFF_{hex}$	No operation command, to read former addressed values.
EEPROM set all zeros	$3E_{hex}$	0248_{hex}	Set all EEPROM bits to zero.
EEPROM set all ones	$3E_{hex}$	$024B_{hex}$	Set all EEPROM bits to one.
EEPROM refresh	$3E_{hex}$	$024C_{hex}$	Refresh all EEPROM lines.
EEPROM program zeros	$3E_{hex}$	$024E_{hex}$	Program all set zeros into EEPROM.
EEPROM program ones	$3E_{hex}$	$C3E0_{hex}$ / $024F_{hex}$	Program all set ones into EEPROM.

To each command the sensor replies with the previous addressed data except while sending the enter-interface command; in that case, the device replies with all zeros. That means, there is always a delay of one command between the requested command and the respective data. For example, if a new read command is sent to the sensor, then it replies with the data of the previous command.

Therefore a read sequence consists of the read command with the requested address followed by a second command to receive the previous addressed data. The second command can either be a read or write command to address the next line.

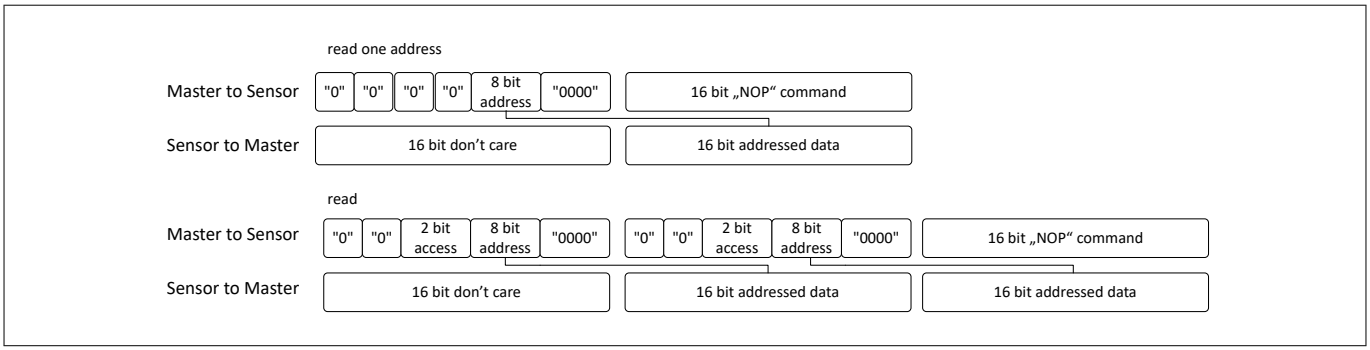


Figure 20 SICI Read Sequence

To perform a write command to a register, the MSB of the command has to be set to "1". A write sequence consists of two SICI frames of 16 bits. After each write command, the device is expecting further 16 bits of data.

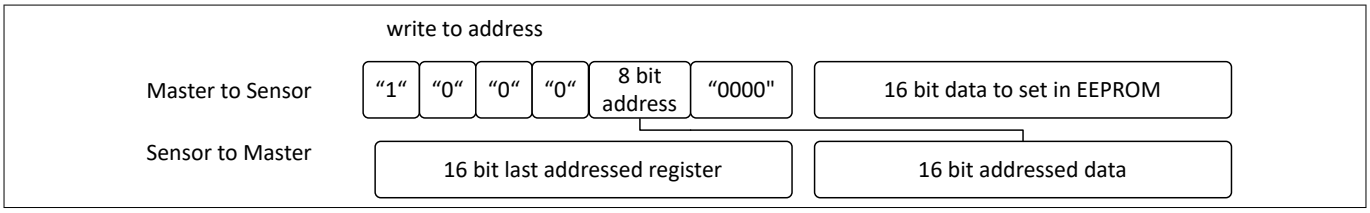


Figure 21 SICI Write Sequence

3.6 Internal temperature readout example

The temperature value can be read via the SICI interface. The following example describes the required command sequence to enter the interface and read out the 16 bits temperature value. In the following table, the commands with the correct timing order and the required minimum time are listed. The temperature measurement sensitivity is 16 LSB/°C. The ADC value corresponding to 25 °C is 1408_{dec}. The following formula describes how to calculate the temperature depending on the 16 bits value.

$$Temperature\ \left[°C\right] = \frac{ADC_{VALUE} - 2048}{16} + 65 \quad (5)$$

Table 6 Command sequence example to read out the internal 16 bits temperature value

Command / Data	Minimum frame time	Description
$ABCD_{hex}$	0.64 ms	Enter-interface command (send user password).
Write command to address 25_{hex}	0.64 ms	Power down ISM (write command).
8000_{hex}	0.64 ms	Power down ISM (data).
Read command at address 18_{hex}	0.64 ms	Sending the address to read the temperature value.
$FFFF_{hex}$	0.64 ms	Reading the data by sending the next command or sending the NOP command.

Power cycle the device to activate normal operating mode. Alternatively set the device in normal operating mode by sending the following commands.

(table continues...)

Table 6 (continued) Command sequence example to read out the internal 16 bits temperature value

Write command to address 25_{hex}	0.64 ms	Power on ISM (write command).
0000_{hex}	0.64 ms	Power on ISM (data).
Wait until the AOUT settles back into calibrated mode. This can take up to $T_{ISM\_SETTLING}$. In calibrated mode, the AOUT reflects the voltage level of the VREF pin, assuming that no current flows through the primary current rail of the device.		

4 Internal registers and EEPROM content

4.1 Internal registers

Apart from the EEPROM content, the user may need to fetch from and/or write into the following registers. The register address lines that correspond to Gain Code Word, Offset Code Word, internal temperature and diagnosis mode amplitude are shown in the following tables. Each address line consists of 16 bits.

Table 7 Internal temperature register. Address 18_{hex}

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
T_{INT}															

Before accessing the internal temperature register, the user needs to disable the ISM.

Table 8 Gain Code Word register. Address 20_{hex}

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
					Gain_CW										

Before accessing the Gain Code Word register, the user needs to disable the ISM.

Table 9 Offset Code Word register. Address 21_{hex}

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
								Offset_CW							

Before accessing the Offset Code Word register, the user needs to disable the ISM. The value is stored in sign-magnitude representation.

Table 10 SICI bypass register. Address 25_{hex}

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
test_pd_ism			SICI_mode_dis												

Set the 15th bit to "1" to power down the ISM for undisturbed access to all registers through interface. Note that ISM will be deactivated almost immediately, but reactivation and return to normal firmware execution can take up to $T_{ISM\_SETTLING}$. Please refer to the timing specifications in Table 2.Set the 12th bit to "1" to put the AOUT buffer in normal operating mode, if the device is in SICI interface mode. Note that the SICI interface is not available anymore after setting this bit. To restart the SICI, enter the SICI enter-interface command after chip reset.

Table 11 Diagnosis mode amplitude register. Address 16_{hex}

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Diag_mode_amp															

Set the 15th bit to "0" to reduce the amplitude of analog signal and OCD thresholds during the diagnosis mode execution with respect to default values.

Note: For writing into internal registers, the user has to enter the SICI interface by using the trimming password "$DCBA_{hex}$".

4.2 EEPROM content

This chapter gives an overview of the programmable content of the current sensor. The sensor's nonvolatile memory (EEPROM) is organized in 16 bits registers which can be addressed individually. The storage space is separated into two areas, user area with read/write access and the read only area (can actually be written, but it is not programmable). Address lines indicated in green are accessible for the user and can be set according to individual application requirements. Addresses from $4B_{hex}$ to 51_{hex} are usually not to be changed by the user.

When the EEPROM content is reprogrammed a CRC check register has to be updated. The user has to calculate the new CRC value by reading the entire EEPROM content, which corresponds to 18 lines. An incorrect CRC value leads to an error detection by an internal safety mechanism of the device. In case of a CRC error, the OCD open drain outputs are set to GND. A detailed description of the user accessible content and the CRC calculation procedure explained in Chapter 5.2.

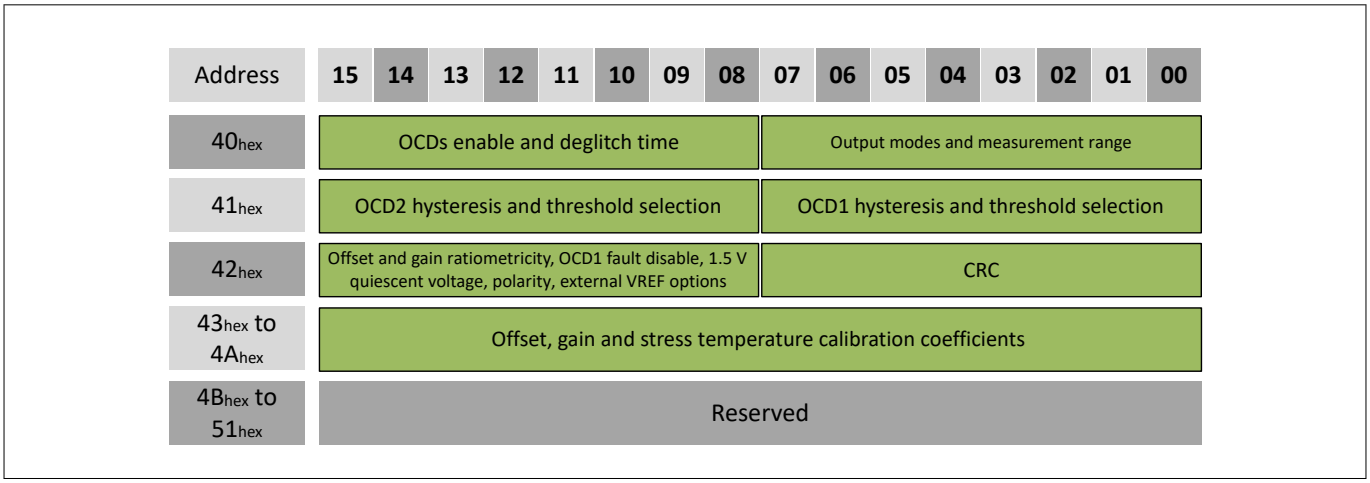


Figure 22 EEPROM Overview

Table 12 Functional description of address line 40_{hex}

Bit field name	Bit	Type	Bit field description
$MEAS_{RNG}$	4:0	rw	The measurement range bits define the mV/mT sensitivity according to the values reported in the product datasheet [1]. Further information are listed in Table 21. The standard setting is S3.
OP_{MODE}	6:5	rw	The output mode can be set according to Table 21. The standard setting is the semi-differential mode.
$OCD1_{DEGLITCH}$	9:7	rw	The deglitching time of the OCD1 can be set according to Table 21. The standard setting is 0 (no additional delay).
$OCD2_{DEGLITCH}$	13:10	rw	The deglitching time of the OCD2 can be set according to Table 21. The standard setting is 0 (no additional delay).
$OCD1_{EN}$	14	rw	This setting does not influence the error indication for an internal fault response or of the firmware based safety mechanisms, but only the over-current detection. The standard setting is 1, that means enabled.

(table continues...)

Table 12 (continued) Functional description of address line 40_{hex}

$OCD2_{EN}$	15	rw	This setting does not influence the error indication for an internal fault response or of the firmware based safety mechanisms, but only the over-current detection. The standard setting is 1, that means enabled.

Table 13 Functional description of address line 41_{hex}

Bit field name	Bit	Type	Bit field description
$OCD1_{HYST}$	1:0	rw	The hysteresis level of the over-current detection channel 1 shall be set according to the full scale in Table 21. The standard setting is 3_{hex}.
$OCD1_{THRSH}$	7:2	rw	6 bits value. Over-current detection threshold calculation formulas are reported in product datasheet [1]. The standard setting is C_{hex}.
$OCD2_{HYST}$	9:8	rw	The hysteresis level of the OCD2 shall be set according to the full scale in Table 21. The standard setting is 3_{hex}.
$OCD2_{THRSH}$	15:10	rw	6 bits value. Over-current detection threshold calculation formulas are reported in product datasheet [1]. The standard setting is F_{hex} for VSON variant, 10_{hex} for TDSO variant.

Table 14 Functional description of address line 42_{hex}

Bit field name	Bit	Type	Bit field description
CRC	7:0	rw	CRC checksum over whole EEPROM content.
$VREF_{EXT}$	10:8	rw	The external V_{REF} bits have to be set according to the external applied reference voltage on the V_{REF} pin. The standard setting is 1.65 V. This only applies in single-ended mode.
$Polarity_{INV}$	11	rw	Output polarity inversion: 0 = disable (default polarity), 1 = enable (inverted polarity). The standard setting is 0.
QV_{1V5SD}	12	rw	Semi-differential bidirectional and fully differential mode only. 1.5 V quiescent voltage enable: 0 = disabled, 1 = enable. The standard setting is 0.
$OCD1_{FONLY}$	13	rw	OCD1 fault signal disable: 0 = fault signal on both OCDs, 1 = no fault signal on OCD1. Internal undervoltage and overvoltage events are signaled in any case because they influence the reliability of OCD indication. The standard setting is 0.
$RATIO_{GAIN}$	14	rw	Gain ratiometricity option: 0 = disable, 1 = enable. The standard setting is 0.

(table continues...)

Table 14 (continued) Functional description of address line 42_{hex}

$RATIO_{OFF}$	15	rw	The ratiometric offset behavior of the quiescent voltage is activated if the bit is set to one. 0 = disable, 1 = enable. The standard setting is 0.

Table 15 Functional description of address line 43_{hex}

Bit field name	Bit	Type	Bit field description
g_base_3_0	3:0	rw	Base gain compensation factor: 4 lowest significant bits of the 11 bits value.
g_tc_tl	15:4	rw	Gain temperature coefficient linear (signed).

Table 16 Functional description of address line 44_{hex}

Bit field name	Bit	Type	Bit field description
g_base_9_4	5:0	rw	Base gain compensation factor: 6 intermediate/middle significant bits of the 11 bits value.
g_tc_tq	15:6	rw	Gain temperature coefficient quadratic (signed).

Table 17 Functional description of address line 45_{hex}

Bit field name	Bit	Type	Bit field description
s_base_3_0	3:0	rw	Stress base value: 4 lower significant bits of the 12 bits value.
g_base_10	4	rw	Base gain compensation factor: single most significant bit of the 11 bits value.
g_tc_tt	15:5	rw	Gain temperature coefficient cubic (signed).

Table 18 Functional description of address line 48_{hex}

Bit field name	Bit	Type	Bit field description
o_base	7:0	rw	Base offset compensation factor (signed).
epk_base	15:8	rw	EPK stress base value (signed).

Table 19 Functional description of address line 49_{hex}

Bit field name	Bit	Type	Bit field description
o_tc_tl	7:0	rw	Offset temperature coefficient linear (signed).
epk_tc_tl	15:8	rw	EPK stress temperature coefficient linear (signed).

Table 20 Functional description of address line $4A_{hex}$

Bit field name	Bit	Type	Bit field description
o_tc_tq	7:0	rw	Offset temperature coefficient quadratic (signed).
epk_tc_tq	15:8	rw	EPK stress temperature coefficient quadratic (signed).

Table 21 EEPROM parameters description

Bit field parameter name	Description
$MEAS_{RNG}$	• 05_{hex} = S1; • 06_{hex} = S2; • 08_{hex} = S3; • $0C_{hex}$ = S4; • 10_{hex} = S5; • 18_{hex} = S6.
OP_{MODE}	• 0_{hex} = SD_{BID} (Semi-differential bidirectional); • 1_{hex} = FD (Fully-differential); • 2_{hex} = SD_{UNI} (Semi-differential unidirectional); • 3_{hex} = SE (Single-ended).
$OCD1_{DEGLITCH}$	• 0_{hex} = 0 ns; • 1_{hex} = 500 ns; • 2_{hex} = 1000 ns; • 3_{hex} = 1500 ns; • 4_{hex} = 2000 ns; • 5_{hex} = 2500 ns; • 6_{hex} = 3000 ns; • 7_{hex} = 3500 ns.
$OCD2_{DEGLITCH}$	• 0_{hex} = 0 ns; • 1_{hex} = 500 ns; • 2_{hex} = 1000 ns; • 3_{hex} = 1500 ns; • 4_{hex} = 2000 ns; • 5_{hex} = 2500 ns; • 6_{hex} = 3000 ns; • 7_{hex} = 3500 ns; • 8_{hex} = 4000 ns; • 9_{hex} = 4500 ns; • A_{hex} = 5000 ns; • B_{hex} = 5500 ns; • C_{hex} = 6000 ns; • D_{hex} = 6500 ns; • E_{hex} = 7000 ns; • F_{hex} = 7500 ns.
$OCD1_{THRSH}$	6 bits value. Over-current detection threshold calculation formulas are reported in product datasheet [1].
$OCD2_{THRSH}$	6 bits value. Over-current detection threshold calculation formulas are reported in product datasheet [1].

(table continues...)

Table 21 (continued) EEPROM parameters description

Bit field parameter name	Description
$VREF_{EXT}$	• 0_{hex} = 1.65 V; • 2_{hex} = 1.5 V; • 3_{hex} = 1.8 V.
$OCDX_{HYST}$	• 0_{hex} = 0 * FS; • 1_{hex} = 0.0625 * FS; • 2_{hex} = 0.125 * FS; • 3_{hex} = 0.25 * FS.

5 EEPROM programming

5.1 EEPROM programming instructions

This chapter gives instructions about how to modify the EPPROM content. The table below will guide the user through a complete programming sequence by just following the listed commands line by line:

- The first command which has to be sent after power-up is the enter-interface command;
- The ISM is then disabled to avoid conflicts during EEPROM programming;
- In order to avoid unintended high current consumption during the programming voltage at the OCD2 pin, the error indication has to be disabled by writing the disable failure indication command to the device;
- Since the device is doing a cyclic redundancy check, the new CRC value has to be calculated when the values are modified. The EEPROM content should be read before the values are modified. Once the values are modified, the CRC has to be calculated using the modified EEPROM content;
- After reading the full EEPROM content, the EEPROM set all zeros command must be sent;
- The zeros are then programmed in the EEPROM through the EEPROM program zeros command;
- The programming voltage has to be applied for $t_{EEPVPROG}$. This programs effectively the zeroes in the EEPROM;
- After calculating the new CRC write all EEPROM registers using a write command to the respective address lines;
- The ones are then programmed in the EEPROM through the EEPROM program ones command;
- The programming voltage has to be applied again for $t_{EEPVPROG}$. This programs effectively the ones in the EEPROM;
- The EEPROM refresh command has then to be executed;
- Reset the device through a power cycle to restore normal operation.

Note: If a common OCD2 line is used for different sensors, in order to prevent unintended high current consumption on OCD2 pin, the error indication has to be disabled for all of them before applying the programming voltage.

Table 22 EEPROM programming parameters

Parameter	Symbol	Min	Typ	Max	Unit	note
EEPROM Programming time	$t_{EEPVPROG}$	30	-	-	ms	Time to apply programming voltage V_{IO_PRG} on OCD2 pin.
EEPROM wait time	$t_{EEPWAIT}$	100	-	-	µs	Wait time after EEPROM refresh command.
Number of programming cycles	N_{PROG}	-	-	100	-	Maximum number of programming cycles.

Table 23 EEPROM programming example

Command Name	Address	Data / Command	Description
Enter Interface	-	$ABCD_{hex}$	Enter interface using the enter-interface command.
Power down ISM	25_{hex}	8250_{hex}	Write command.
	-	8000_{hex}	Set data.
Disable failure indication	01_{hex}	8010_{hex}	Write command.
	-	0000_{hex}	Set data.
Read all register			Read original EEPROM data; needed since the CRC is calculated on all registers and not only on the modified registers.
Read command	40_{hex}	0400_{hex}	Read command at EEPROM line 0.
Read command	n	XXXX	Read command for address "n". Receive previous addressed data.
Read command	51_{hex}	0510_{hex}	Read last line in EEPROM. Receive previous addressed data.
NOP	-	$FFFF_{hex}$	Read values from previous address without initializing a new command. The data can also be read with the next write command instead of using the NOP command.
EEPROM set all zeros	$3E_{hex}$	$83E0_{hex}$	Write command.
		0248_{hex}	Set data.
EEPROM program zeros	$3E_{hex}$	$83E0_{hex}$	Write command.
	-	$024E_{hex}$	Set data.
Programming voltage application			Applying the programming voltage at OCD2 pin for $t_{EEPVPROG}$.
Write data			Calculate new CRC, write all EEPROM registers, write the new CRC to respective field.
EEPROM program ones	$3E_{hex}$	$83E0_{hex}$	Write command.
	-	$024F_{hex}$	Set data.

(table continues...)

Table 23 (continued) EEPROM programming example

Command Name	Address	Data / Command	Description
Programming voltage application			Applying the programming voltage at OCD2 pin for $t_{EEPVPROG}$.
EEPROM refresh	$3E_{hex}$	$83E0_{hex}$	Write to EEPROM command line.
	-	$024C_{hex}$	Set EEPROM command refresh.
Wait after EEPROM refresh			Wait for $t_{EEPWAIT}$.
Power cycle the device to return in normal operating mode.			

5.2 EEPROM CRC calculation

To detect accidental changes of the EEPROM content the data in the EEPROM are protected with a cyclic redundancy check (CRC). The CRC calculation is based on the polynomial x8+x4+x3+x2+1. The figure below describes the CRC calculation specification. The seed word is defined as AA_{hex}. The CRC calculation of the EEPROM is performed byte by byte; starting from the EEPROM line three (address 43_{hex}). After reaching the end of the EEPROM, the calculation continues with the high byte of address line 40_{hex} till the high byte of address line 42_{hex} and is completed with inverting the CRC result to get the final CRC checksum.

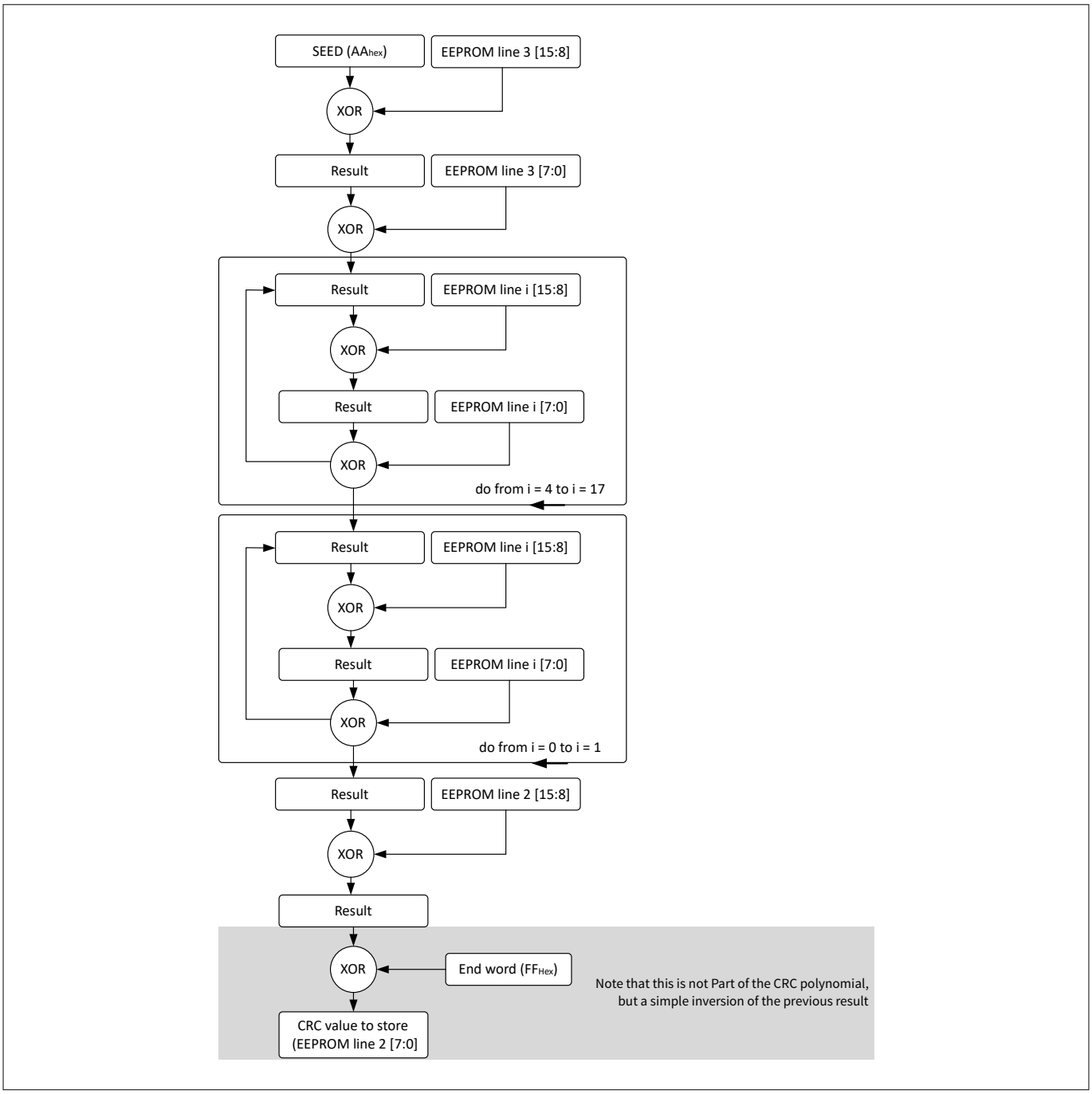


Figure 23 CRC calculation flowchart

5.3 EEPROM CRC calculation example

```
//CRC 8 (SAE - J1850) CRC polynomial: x^8 + x^4 + x^3 + x^2 + 1 // len = 18 (EEPROM line 0-17)
#define CRC_POLYNOMIAL 0x1D #define CRC_SEED 0xAA

//check CRC bool checkCRC (uint16_t* data, int len) {
uint8_t checkSum = data[2]&0xFF;//CRC lower byte in EEPROM line2 return checkSum == crcCalc(data, len);
}

//read data beginning in EEPROM line 3 to line 17, append line 0 to line 2 uint8_t crcCalc(uint16_t* data, int len)
{
uint8_t crcData8[len*2]; for(int i = 0; i < len; i++) {
crcData8[i*2] = ( data[(i+3)%18] >>8 ) & 0xFF;//read upper 8 bit crcData8[i*2+1] = ( data[(i+3)%18] ) & 0xFF;//read
lower 8 bit
}
return crc8(crcData8, len*2-1); //do not include last byte (line 2 lower byte)
}

// CRC calculation uint8_t crc8(uint8_t *data, uint8_t length) {
uint32_t crc; int16_t i, bit; crc = CRC_SEED; for (i = 0; i < length; i++) {
crc ^= data[i]; for (bit = 0; bit < 8; bit++) {
if ((crc & 0x80) != 0) {
crc <<= 1; crc ^= CRC_POLYNOMIAL;
} else {
crc <<= 1;
}
}
}
return ~crc; // ~crc = crc^0xFF;
}
```

6 Calibration

For optimum accuracy at system level it is necessary to perform the calibration of sensitivity [V/A] and offset [V] at room temperature when the sensor is integrated in a system. This calibration is usually performed at end of line.

The sensitivity needs to be calibrated in order to compensate the errors due to displacement of the sensor during mounting and soldering (which will affect the transfer factor *TF*), as well as the initial sensitivity error of the sensor [V/T] due to part to part variation.

The offset needs to be calibrated in order to compensate the offset introduced by the interface between sensor and microcontroller, as well as the initial offset error of the sensor due to part to part variation.

Once the user executes a sensitivity and offset calibration at room temperature (or at any other single temperature), only the drift over temperature and lifetime of offset and sensitivity will contribute to the current total error.

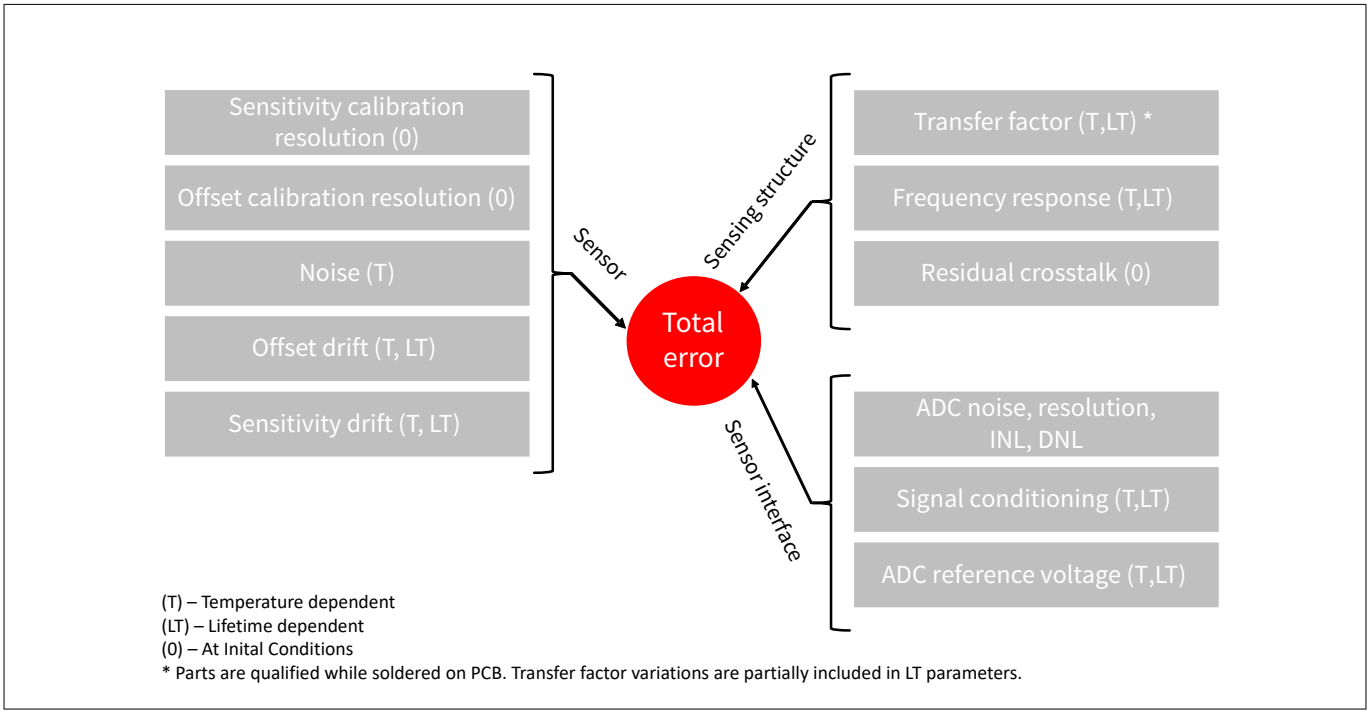


Figure 24 Error sources in external current rail sensing

The total measurement error can be reduced through a single point end of line in-system calibration. This can be performed in the sensor or in the microcontroller:

- Microcontroller calibration: the correction factors for sensitivity and offset are measured at end of line for each system and stored in the microcontroller memory instead of sensor EEPROM. This method might require more computational effort on microcontroller side for the sensitivity and offset correction during operation;
- Sensor calibration: the calibration parameters are measured and stored directly in the sensor EEPROM at end of line. This method requires on-board programming hardware in order to be able to communicate and program the sensor from the microcontroller, or a dedicated connector for an external programmer. Please refer to Chapter 2 for additional information.

6.1 Transfer factor estimation

In order to set the correct measurement range and sensitivity for the application the transfer factor *TF*, that represents the coupling between sensor and sensing structure, and its maximum variations need to be known. The sensor calibration can compensate up to 15% of the *TF* variation, among all other error components. It is possible to estimate the *TF* value by reading the content of the Gain_CW internal register at room temperature through the SICI interface (refer to Chapter 4.1) and performing a sensitivity measurement.

Given the internal Gain_CW register content at room temperature, the value of the EEPROM setting $MEAS_{RNG}$ and the measured sensitivity [V/A], the transfer factor T_R [µT/A] can be estimated as:

$$TF = \frac{Sensitivity[mV/A]}{15 \times 2^{13}} \times \frac{300000 \times \left(Gain\_CW + 2^9\right)}{0.2 \times MEAS_{RNG} \times 82.0966} \quad (6)$$

Note: In order to obtain a precise estimation of the TF, it is suggested to measure it through the method explained above on multiple systems (more than 10) and to consider the average value.

6.2 Desired sensitivity

Given the target current full scale I_{FS} for the application the desired sensitivity can be calculated. Independently of the measurement range, the differential output full scale voltage is 1.2 V. This value of V_O will be achieved when the full scale magnetic field in respect to the selected measurement range (*S1*,...,*S6*) is applied. Thus the desired sensitivity in [V/A] can be easily calculated by dividing 1.2 by I_{FS}. For example: if I_{FS} = 500 A, the desired sensitivity is 2.4 mV/A.

It is not possible to achieve exactly the desired sensitivity. The target sensitivity for the calibration must instead be one of the six possible sensitivity values fixed through the measurement range selection.

Note: In case fully differential output mode is used, the differential output voltage V_O will have doubled voltage swing. That means, the full scale will be in correspondence of 2.4 V instead of 1.2 V. The desired sensitivity must be doubled with respect to the other operating modes.

6.3 Target sensitivity

The target sensitivity is the closest nominal sensitivity in [mV/A] to the desired one that is achievable by setting the measurement range to one of the six available options *S1*,...,*S6.* It should not be higher than the desired one, otherwise the target full scale would be smaller than the desired full scale.

The sensitivity in [mV/A] obtained by setting the measurement range to one of the available options will depend on the value of the transfer factor *TF*:

$$target \quad sensitivity[mV/A] = S_X[mV/mT] \times TF[\,\mu\, T/A] \div 1000 \quad (7)$$

For example: if *TF* = 40 µT/A, in measurement range *S3* = 62 mV/mT the target sensitivity for the calibration will be 2.48 mV/A.

Note: Choosing a different sensitivity than the nominal one will reduce the available buffer for the compensation of the error components. In other words, part of the calibration capability of the sensor will be used to shift the nominal sensitivity. Since the same result can be obtained by changing the value of TF, this is the recommended way to proceed.

6.4 Sensitivity and offset measurement

It is possible to measure sensitivity and offset using the internal ADC of the microcontroller, or with an external programmer and measurement instruments. In the latter case, it is crucial that the accuracy of the measurement instruments is high enough so that the error introduced by the measurement itself is much lower than the total residual error the user wants to achieve. For that purpose, it is important to measure V(AOUT) and V(VREF) always by averaging the measurement on at least hundred samples, or by introducing a low pass filter. All non-DC components can be filtered out, since the calibration is performed in DC.

In order to measure the offset of the sensor, the user needs to:

- Control the current in the sensing structure to zero;
- Measure the differential output of the sensor V_O = V(AOUT) - V(VREF) in correspondence of zero current; the measured value corresponds to the offset.

In order to measure the sensitivity of the sensor, the user needs to:

- Inject a test current I_{TEST} in the sensing structure. I_{TEST} should be at least 10% of the target full scale current I_{FS} in order to achieve low noise in the sensitivity measurement and it should be low enough to prevent a high temperature rise of the device during calibration;
- Measure the differential output of the sensor V_O = V(AOUT) - V(VREF) in correspondence of the I_{TEST}, and when no current is flowing in order to measure the offset;
- Measure the I_{TEST} itself using a calibrated current source, a shunt combined with a multimeter or any other precise current measurement device.

The sensitivity is then calculated as:

$$Sensitivity = \frac{V_{O|I_{TEST}} - V_{O|I=0}}{I_{TEST}} \quad (8)$$

In case the part is ratiometric with respect to V_{DD}, a correction factor for the sensitivity has to be implemented:

- In addition to the previous measurement steps, measure V_{DD};
- Correct the measured sensitivity and measured offset using the formulas below.

$$Sensitivity_{RATIOMETRIC} = Sensitivity \times \frac{3.3\ V}{V_{DD}} \quad (9)$$

6.5 Microcontroller level calibration

The calibration done in the microcontroller at end of line allows to compensate all error components, including the ones related to ADC and sensor interface. Moreover, it doesn´t require additional circuitry needed for the in-system programming, or an external programmer. Sensitivity and offset can be measured by the ADC itself respectively in [LSB/A] and LSB. Given the target sensitivity, a correction factor can be calculated, stored and used to compensate the sensitivity mismatch directly at ADC level. The measured offset in [LSB] can be stored and subtracted to the current measurement at ADC level in order to compensate the offset.

6.6 Sensor level calibration

6.6.1 Calibration concept

In order to account for mis-alignment errors and part to part variation, the user can perform a single point, in-system calibration at room temperature at sensor level. The procedure leads to the re-calculation of all EEPROM calibration coefficients, including temperature related ones for the gain. It is not needed to re-calculate the offset calibration coefficients over temperature, but just the order zero coefficient (o_base). The original EEPROM calibration coefficients are calculated in production line for each device, during the calibration over temperature.

The single point in-system calibration at room temperature is achieved at sensor level by controlling the value of two internal sensor registers to pre-determined values, and measuring the corresponding change in sensitivity [mV/A] and offset [V]. The two registers are the "Gain CW" (Gain Code Word) and "Offset CW" (Offset Code Word) registers. They are described in Chapter 4.1. The Gain CW is directly affecting the internal sensor gain, while the Offset CW is connected to the internal offset correction circuit and changing it leads to a change of the output offset.

The main aim is to calculate the target Gain CW and target Offset CW needed to achieve the target sensitivity [mV/A] and offset [V] values (null offset). The two code words are related to the EEPROM calibration parameters. Starting from the room temperature calculation of the target Gain CW and target Offset CW, the new calibration parameters can be re-calculated and then stored in the EEPROM.

Note: In order to access the internal registers, the programming hardware has to be implemented in the system, or an external programmer has to be used. Please refer to Chapter 3.1 for further information.

The typical offset and sensitivity programming resolution are reported below.

Table 24 Typical calibration resolution

Parameter	Resolution
Offset	13.5 [µT]
Sensitivity	0.12% of sensitivity [mV/mT]

The typical resolution represents the ideal calibration resolution that is achievable. The final accuracy will depend on the hardware and algorithms used for the calibration.

The sensitivity calibration resolution is not costant with the calibration code (Gain_CW). 0.12% represents the typical value for default Gain_CW, as shown in the figure below.

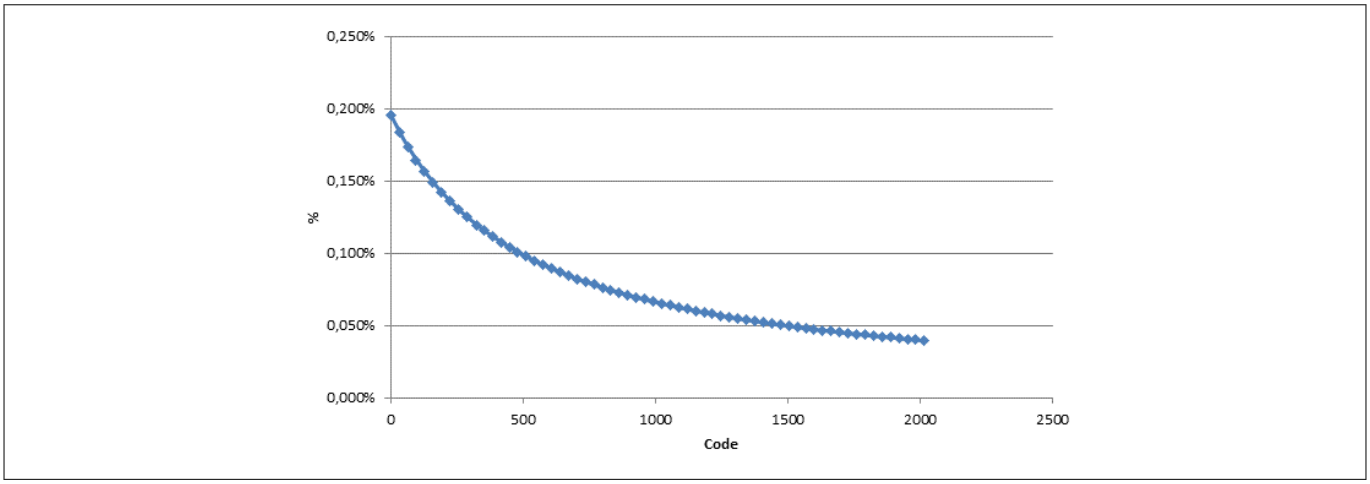


Figure 25 Sensitivity resolution in percentage with trimming code

6.6.2 Double code word calibration

The Double Code Word method takes advantage of the linear relationship of Offset_CW and offset as well as Gain_CW and inverse sensitivity. The target Gain_CW and target Offset_CW can thus be found by using linear interpolation of inverse sensitivity and offset in respect to pre-determined values for Gain_CW and Offset_CW. Once the values of $Sensitivity_1$, $Sensitivity_2$, $Offset_1$ and $Offset_2$ have been measured following the instructions in Chapter 6.6.2.1, it is possible to calculate the target values for Gain_CW and Offset_CW (Gain_CW_target, Offset_CW_target) as follows:

$$Offset_{AVG} = \frac{Offset_1 + Offset_2}{2}; \quad Offset_{RATIO} = \frac{Offset_2 - Offset_1}{Offset\_CW_2 - Offset\_CW_1};$$
$$Offset\_CW\_target = -\frac{Offset_{AVG}}{Offset_{RATIO}} \tag{10}$$

where $Offset\_CW_1$ = -40 and $Offset\_CW_2$ = 40.

$$Sensitivity_{RATIO} = \frac{\frac{1}{Target\ \ Sensitivity} - \frac{1}{Sensitivity_1}}{\frac{1}{Sensitivity_2} - \frac{1}{Sensitivity_1}}; \tag{11}$$

$$Gain\_CW\_target = Gain\_CW_1 + Sensitivity_{RATIO} \times (Gain\_CW_2 - Gain\_CW_1)$$

where $Gain\_CW_1 = 210$ and $Gain\_CW_2 = 570$.

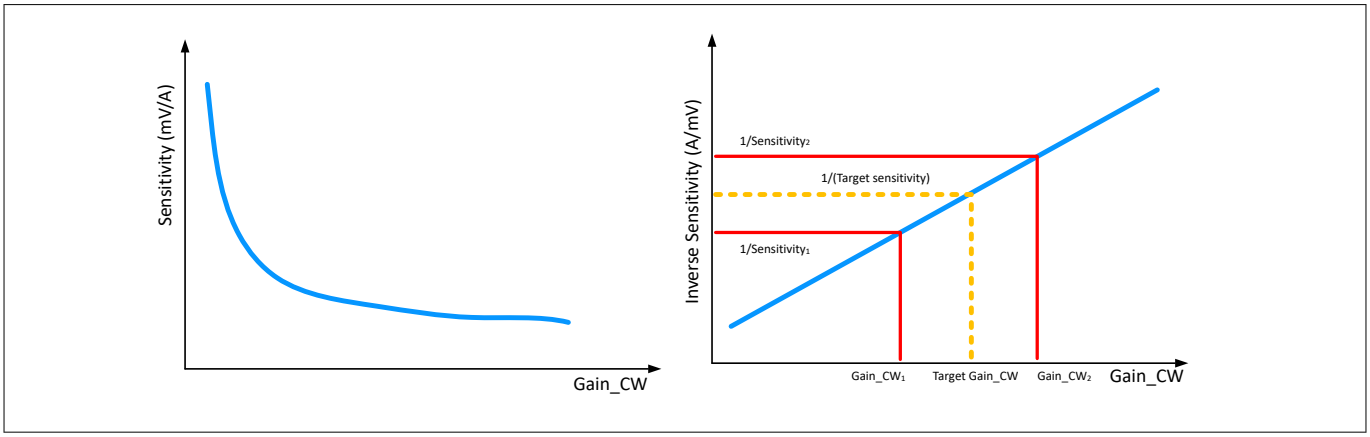


Figure 26 Target Gain CW calculation with Double Code Word method

Once the Gain_CW and target Offset_CW have been calculated at room temperature, the new EEPROM calibration coefficients, including the gain calibration coefficients over temperature, can be calculated and stored in the EEPROM. It is not needed to re-calculate the offset calibration coefficients over temperature, but just the order zero coefficient (o_base).

The complete Double Code Word method is explained in the flowchart hereafter. In the subsequent paragraph, the analytic calculation method of the new EEPROM calibration coefficients is explained.

6.6.2.1 Double Code Word method procedure

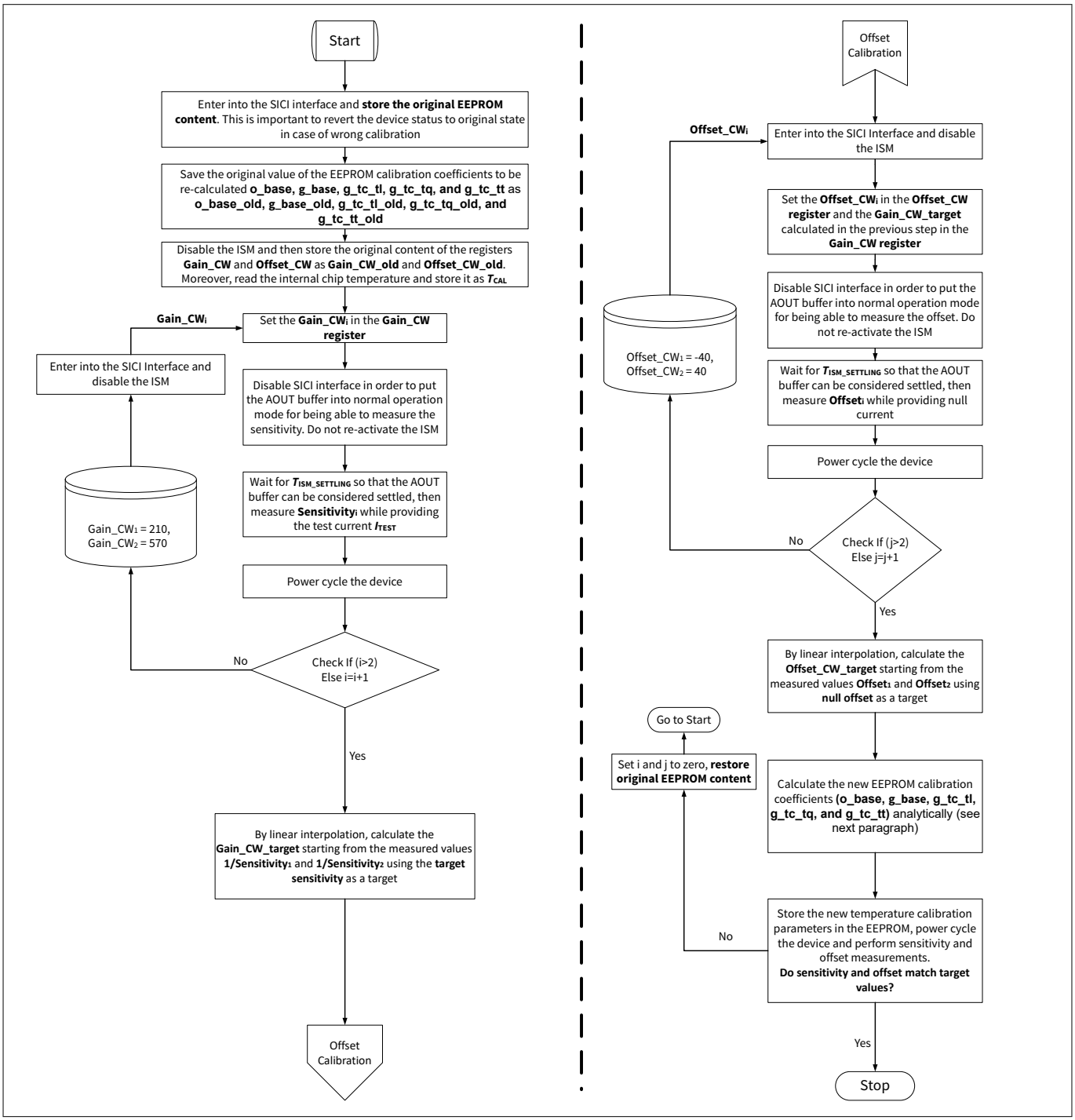


Figure 27 Double Code Word method flowchart

6.6.2.2 Calculation of new EEPROM calibration coefficients

The following equations can be used to analytically calculate the new EEPROM calibration coefficients (o_base_new, g_base_new, g_tc_tl_new, g_tc_tq_new, and g_tc_tt_new). The required inputs are:

- Original value of the EEPROM calibration coefficients (o_base_old, g_base_old, g_tc_tl_old, g_tc_tq_old, and g_tc_tt_old). They must be stored before any calibration attempt;
- Initial values of the Gain_CW and Offset_CW (Gain_CW_old, Offset_CW_old). They must be read from the Gain_CW and Offset_CW registers before any calibration attempt, after disabling the ISM;
- New target values of the Gain_CW and Offset_CW (Gain_CW_target, Offset_CW_target). They must be calculated as explained in Chapter 6.6.2.1.

The new o_base (o_base_new) can be calculated as:

$$o\_base\_new = o\_base\_old + (Offset\_CW\_target - Offset\_CW\_old) \tag{12}$$

The remaining coefficients can be calculated as follows. In all formula, the temperature "T" has to be expressed as the internal device temperature code through the formula:

$$T = (T[°C] - 65) \times 16 + 2048 \tag{13}$$

The calibration room temperature T_{CAL} is the internal chip temperature read at the beginning of the calibration procedure through the SICI interface.

Calculate the old internal sensor gain at T_{CAL}, Gain_old(T_{CAL}), by substituting Gain_CW_old(T_{CAL}) = Gain_CW_old in the following formula, where Gain_CW_old has been read at the beginning of the calibration procedure from the Gain_CW register:

$$Gain\_old(T) = \frac{15 \times 2^{13}}{300 \times (Gain\_CW\_old(T) + 512)} \tag{14}$$

Calculate the new internal sensor gain at T_{CAL}, Gain_new(T_{CAL}), by substituting Gain_CW_new(T_{CAL}) = Gain_CW_target in the following formula, where Gain_CW_target is the result of the Double Code Word method procedure:

$$Gain\_new(T) = \frac{15 \times 2^{13}}{300 \times (Gain\_CW\_new(T) + 512)} \tag{15}$$

Calculate the gain correction factor (Gain_CF) as:

$$Gain\_CF = \frac{Gain\_new(T_{CAL})}{Gain\_old(T_{CAL})} \tag{16}$$

It is possible to use this correction factor to determine the new target internal gain at all temperatures, and hence the new calibration coefficients. To do so, first, calculate the old temperature coefficients (BASE_old, TL_old, TQ_old, TT_old) from the old EEPROM calibration coefficients (g_base_old, g_tc_tl_old, g_tc_tq_old, and g_tc_tt_old):

$$\begin{aligned} BASE\_old &= g\_base\_old \\ TL\_old &= \frac{g\_tc\_tl\_old}{2^{11}} \\ TQ\_old &= \frac{g\_tc\_tq\_old}{2^{22}} \\ TT\_old &= \frac{g\_tc\_tt\_old}{2^{35}} \end{aligned} \tag{17}$$

Calculate then the old Gain_CW as function of T, Gain_CW_old(T), using the old temperature coefficients (BASE_old, TL_old, TQ_old, TT_old) in the following formula:

$$Gain\_CW\_old(T) = ROUND\left(BASE\_old + TL\_old \times T + TQ\_old \times T^2 + TT\_old \times T^3\right) \tag{18}$$

Calculate the old internal sensor gain as function of T, Gain_old(T), substituting the old Gain_CW as function of T (Gain_CW_old(T)) in the following formula:

$$Gain\_old(T) = \frac{15 \times 2^{13}}{300 \times (Gain\_CW\_old(T) \quad + \quad 512)} \tag{19}$$

The new gain at all temperatures, Gain_new(T), can be calculated as:

$$Gain\_new(T) = Gain\_old(T) \times Gain\_CF \tag{20}$$

Calculate the new Gain_CW_target as function of T, Gain_CW_target(T), as:

$$Gain\_CW\_target\left(T\right) = \frac{15 \times 2^{13}}{300 \times Gain\_new(T)} - 512 \tag{21}$$

Calculate then Gain_CW_target(-40°C), Gain_CW_target(100°C)
and Gain_CW_target(150°C). Gain_CW_target(T_{CAL}) is already known and equal to Gain_CW_target.
Approximate the coefficients (BASE_new, TL_new, TQ_new and TT_new) of the following cubic polynomial, using the four known values of Gain_CW_target(T) at the four temperature points (-40 °C, T_{CAL}, 100 °C and 150 °C):

$$Gain\_CW\_target(T) = BASE\_new + TL\_new \times T + TQ\_new \times T^2 + TT\_new \times T^3 \tag{22}$$

To do so, the user can perform a 3rd order interpolation. Thus, find the solution x = [BASE_new, TL_new, TQ_new, TT_new] for the linear system Ax = b:

$$A = \begin{bmatrix} 1 & T_{-40\,°C} & T_{-40\,°C}{}^2 & T_{-40\,°C}{}^3 \\ 1 & T_{CAL} & T_{CAL}{}^2 & T_{CAL}{}^3 \\ 1 & T_{100\,°C} & T_{100\,°C}{}^2 & T_{100\,°C}{}^3 \\ 1 & T_{150\,°C} & T_{150\,°C}{}^2 & T_{150\,°C}{}^3 \end{bmatrix}; \quad x = \begin{bmatrix} BASE\_new \\ TL\_new \\ TQ\_new \\ TT\_new \end{bmatrix}; \quad b = \begin{bmatrix} Gain\_CW\_target(-40 \quad °C) \\ Gain\_CW\_target(T_{CAL}) \\ Gain\_CW\_target(100 \quad °C) \\ Gain\_CW\_target(150 \quad °C) \end{bmatrix} \tag{23}$$

The solution is unique and can be found by means of the "linest" function in an Excel based test environment, or by means of a standard algorithm (e.g. Kramer's method).

Calculate the new EEPROM calibration coefficients (o_base_new, g_base_new, g_tc_tl_new, g_tc_tq_new, and g_tc_tt_new) using the new temperature coefficients (BASE_new, TL_new, TQ_new and TT_new):

$$\begin{aligned} g\_base\_new &= BASE\_new \\ g\_tc\_tl\_new &= TL\_new \times 2^{11} \\ g\_tc\_tq\_new &= TQ\_new \times 2^{22} \\ g\_tc\_tt\_new &= TT\_new \times 2^{35} \end{aligned} \tag{24}$$

Finally, program the new EEPROM calibration coefficients (o_base_new, g_base_new, g_tc_tl_new, g_tc_tq_new, and g_tc_tt_new) in the EEPROM.

6.7 OCD threshold calibration

The product datasheet [1] reports the formula for the calculation of the custom OCD thresholds for OCD1 and OCD2. The formula provide the value of the selected threshold in [A]. They require as input:

- the value of the transfer factor *TF*, that can be estimated as explained in Chapter 6.1;
- the value of the OCD threshold level set in the EEPROM ($OCD1_{THRLVL}$ or $OCD2_{THRLVL}$).

Using the mentioned formulas the user can calculate the expected OCD threshold in [A]. The effective threshold may differ in case of steep current slopes, due to skin effect and eddy current effects. The user can fine trim the threshold during system measurements by changing the the OCD threshold level set in the EEPROM.

7 Stray fields and crosstalk

The sensor features a differential sensing principle, as explained in Chapter 1. This ensures a high suppression to homogeneous stray fields (*BSR*). Nevertheless, the presence of current in a nearby conductor can introduce a crosstalk effect, that will introduce an error to the current measurement. In this chapter an explanation is given about how to compensate the crosstalk effect at system level.

7.1 Differential measurement principle

A differential measurement of the magnetic field caused by the current in the conductor is shown below. The two Hall probes are placed close to the current rail. Assuming that the current flows from the front side to the backside the left Hall probe detects a positive magnetic field and the right Hall probe measures a negative field.

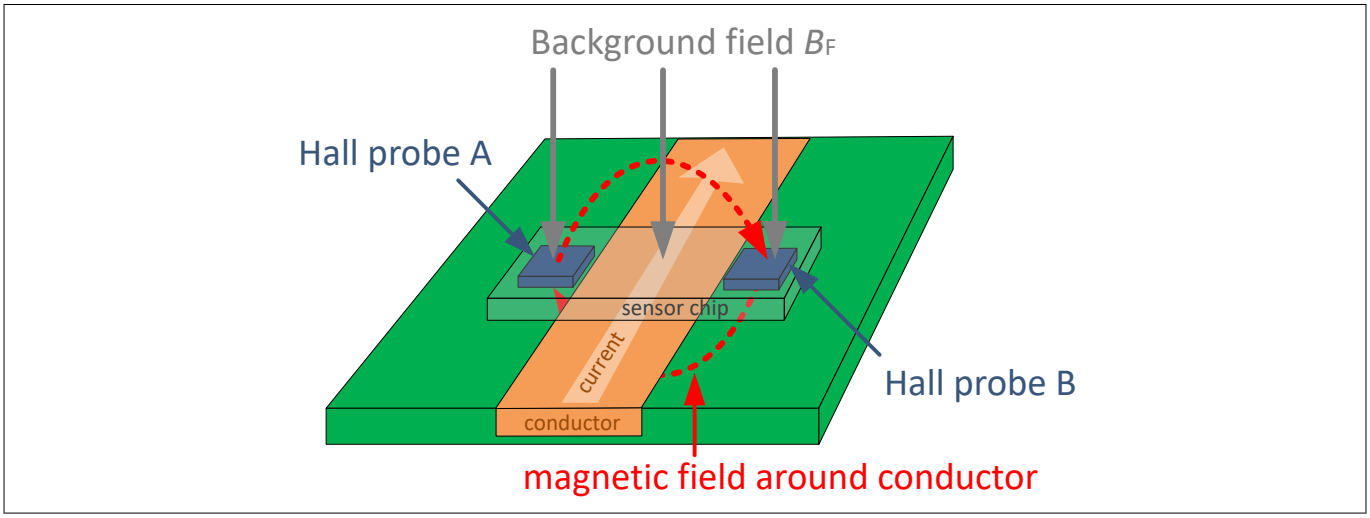


Figure 28 Differential measurement with background field cancellation

The following formula describes the differential signal calculation obtained by subtracting the right signal (B + B_F) from the left signal (A + B_F). Here, A and B represent the magnetic flux density in the left and right Hall probes respectively and B_F is the superimposed stray field.

$$V_O = f[(A + B_F) - (B + B_F)] = f(A - B) \tag{25}$$

The superimposed stray field cancels out since it has the same polarity on both Hall probes. A perfect cancellation of the homogeneous magnetic field is the result of the differential measurement principle.

7.2 Intrinsic crosstalk compensation

In a typical layout of multiple phase output system, the output phases are routed in parallel. Normally, the Hall probes are arranged perpendicular to the current path, in the so called Straight sensing structure configuration. In order to eliminate the crosstalk from neighboring phases, it is possible to arrange the Hall probes in parallel to the current path, in the so called S-bend sensing structure configuration. The figure below shows the magnetic field caused by the current in the V phase effecting the sensors on the U and W phases. Thanks to the parallel position of the Hall probes to the current rail, both Hall probes will detect the same magnitude of magnetic field since the gradient of the magnetic field has no influence on the single Hall probe. Therefore, the differential principle cancels the crosstalk in neighboring phases.

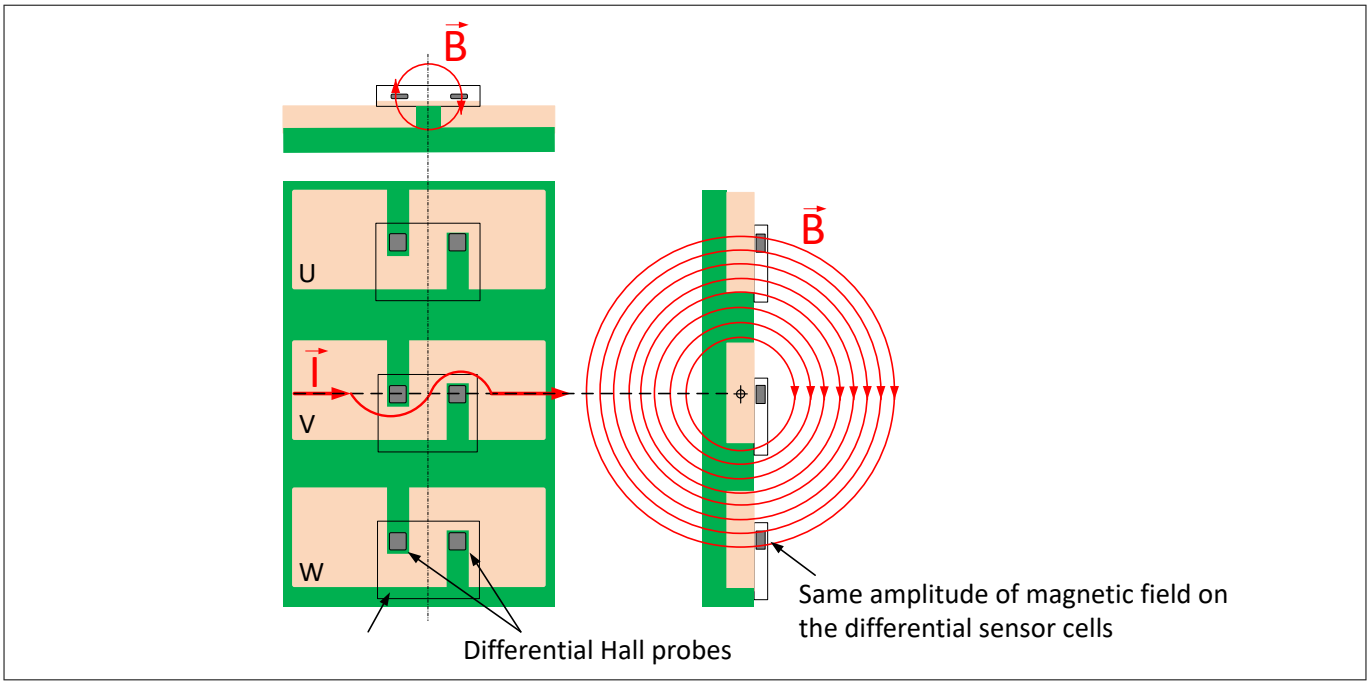


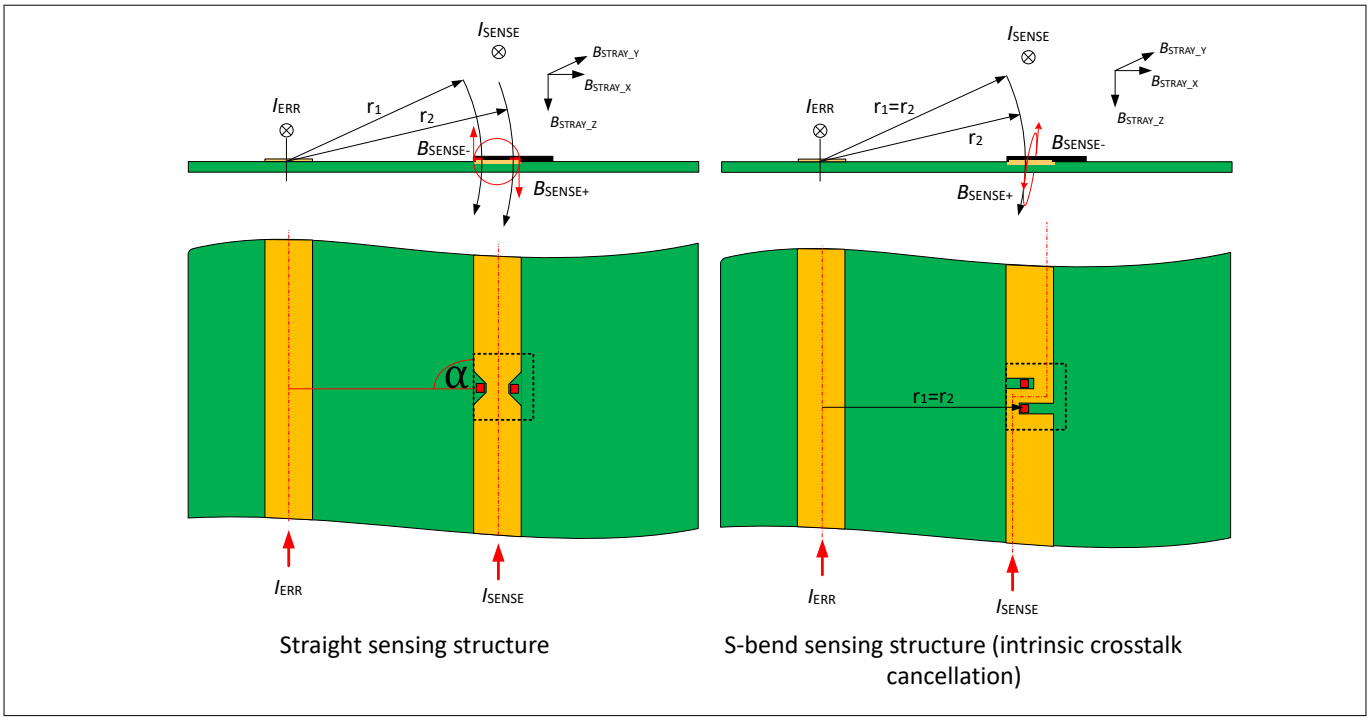
Figure 29 Intrinsic crosstalk cancelation in parallel wiring schema

The figure below describes in more details the case in which the Hall probes are arranged in a Straight or S-bend sensing structure. In the Straight sensing structure the two Hall cells are placed in X direction, therefore the crosstalk suppression is not nullified. Whereas, in

S-bend sensing structure the Hall probes are placed in Y direction, therefore the crosstalk suppression is very effective.

The following formula can be used to calculate the differential field:

$$B_{DIFF} = \mu_0 \frac{I_{ERR}}{I_{SENSE}} \left(\frac{1}{r_1} - \frac{1}{r_2} \right) \cos\alpha \quad (26)$$



Straight sensing structure

S-bend sensing structure (intrinsic crosstalk cancellation)

Figure 30 Straight and S-bend sensing structures

7.3 Crosstalk compensation matrix

Beyond utilizing a different sensor arrangement for crosstalk reduction, it is possible to calculate the crosstalk factors between phases of a multi-phase system and characterize the crosstalk phenomena through a crosstalk compensation matrix. This matrix, whose coefficients are stable over temperature and lifetime, can be used to correct actively the sensor output and cancel out the crosstalk between phases. The crosstalk matrix is defined as:

$$Crosstalk \quad matrix = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \tag{27}$$

The dimensions of the crosstalk coefficients is [V/A]. The a_{xx} coefficients, situated on the diagonal, are linked to the transfer factors TF_1, TF_2, TF_3 of the three phases of the multi phase system. The mutual crosstalk coefficient a_{xy} represent the cross coupling sensitivity on the sensor placed on the phase X due to a current flowing in the phase Y. All the coefficients of the crosstalk matrix can be calculated by injecting a test current in a phase, and measuring the sensor output on a different phase.

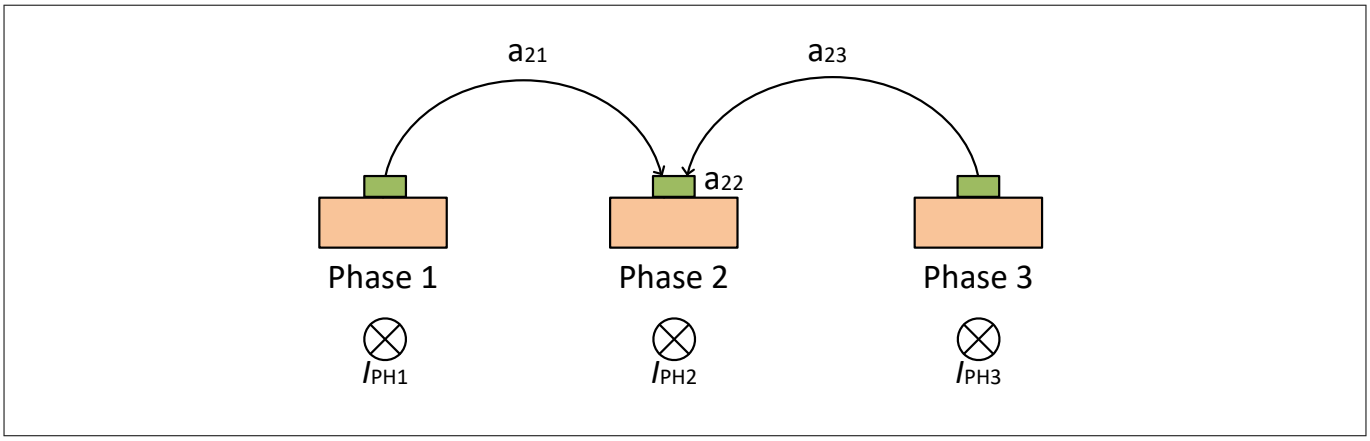


Figure 31 Crosstalk compensation matrix calculation

Once all coefficients of the crosstalk compensation matrix are known, the user can calculate the corrected sensor output voltages [V_{O1}, V_{O2}, V_{O3}] starting from the measured current at the three phases [I_{PH1}, I_{PH2}, I_{PH3}]:

$$\begin{bmatrix} V_{O1} \\ V_{O2} \\ V_{O3} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \times \begin{bmatrix} I_{PH1} \\ I_{PH2} \\ I_{PH3} \end{bmatrix} \quad (28)$$

8 Ratiometricity OFF/ON setting

The figure below shows an example of the sensitivity variation over the temperature when the ratiometricity is turned ON in a device whose standard setting is OFF. In a large population a portion of the devices might have sensitivity drift over temperature out of datasheet limit; the user is made aware of the degraded performance over temperature in case the setting is modified. This happens because internally to the sensor, the ratiometricity function introduces its own error contribution to the signal processing path gain which can be seen only when the function is activated. If the sensor is calibrated in production with ratiometricity OFF, and then the ratiometricity is switched ON, this contribution is obviously not calibrated.

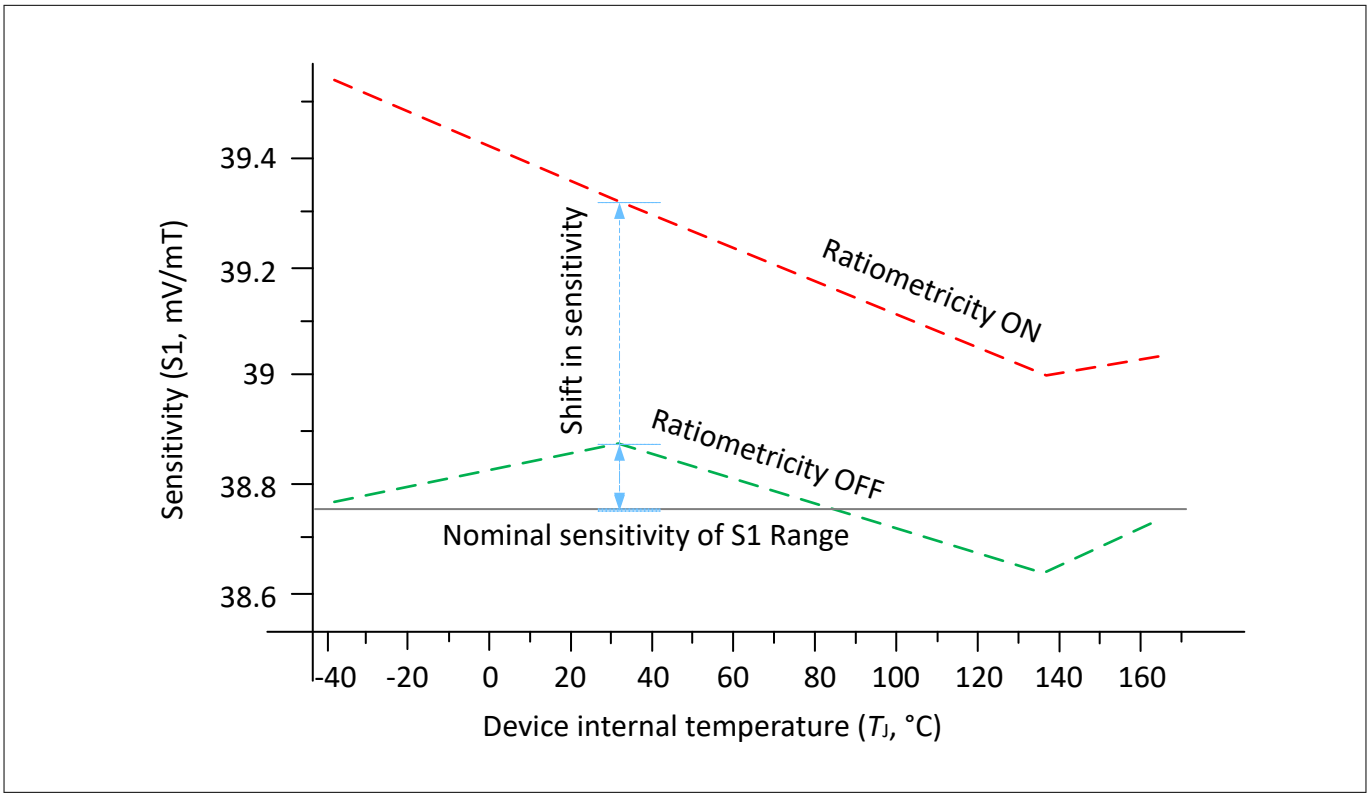


Figure 32 Ratiometricity setting influence on sensitivity drift over temperature

9 Glossary

Notation	Description
TF	Transfer Factor.
FS	Full Scale.
SICI	Serial Inspection and Configuration Interface.
EEPROM	Electrically Erasable Programmable Read-Only Memory.
EPK	Piezoelectric coefficient.
CRC	Cyclic Redundancy Check.
VDD	Supply voltage.
A/D	Analog Digital Converter Input.
ADC	Analog to Digital Converter.
ISM	Internal State Machine.
IFX	Infineon Technologies.
µC	Micro Controller.
LSB	Least Significant Bit.
MSB	Most Significant Bit.
NOP	No Operation.
PWM	Pulse Width Modulation.
I/O	Input / Output.
GND	Ground.
GPIO	General Purpose Input Output.
OCD	Over Current Detection.

10 References

[1] Infineon-TLE4972-AE35S5-DS-vxx_xx-EN.pdf; Infineon-TLE4972-AE35D5-DS-vxx_xx-EN.pdf
[2] Infineon-TLE4972-SM-vxx_xx-EN.pdf
[3] Infineon-TLE4972-Sensing_Structure_Design-AN-vxx_xx-EN
[4] Infineon-TLE4972-Current_Sensor_Programmer_User_guide-vxx_xx-EN

11 Revision History

Table 25 Revision History

Revision number	Date of release	Description of changes
1.01	2022-10-25	• Added sensitivity calculation information in case of ratiometric parts; • Clarified in EEPROM settings that internal undervoltage and overvoltage events are always signaled on OCD pin because they influence the reliability of OCD indication; • Added specification about maximum number of programming cycles; • Fixed error in register address 50_{hex}. The correct address is $4A_{hex}$; • Added reference to evaluation programmer and CGS programmer; • Updated EEPROM programming procedure; after "set all zeros" command, all EEPROM registers must be written in the EEPROM and not only the modified ones.
1.0	2022-02-08	Initial revision.

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