TLE4999I3 User's Manual

Product Family: TLE4999I3

About this document

Scope and purpose

This document is valid for the TLE4999I3. It describes the digital programming interface and the programming flow to be used to configure the sensor IC. The configuration parameters of the TLE4999I3 are stored in an EEPROM. The specification for electrical and timing parameters given in this document are to be understood directly on the sensor pins. Additional effects relating to the external circuitry, the attached programming equipment or environmental influence are not considered.

The general behavior and a top-level block diagram of the TLE4999I3 are described in the TLE4999I3 data sheet.

Intended audience

This document is intended for anyone who needs to program and calibrate the TLE4999I3 programmable linear Hall sensor with PSI5 interface.

Table of Contents

1 TLE4999I3 Signal Processing

Both channels of the TLE4999I3 use a fully digital signal processing concept.

The analog values from the Hall probes are directly converted to digital signals by the Hall ADC and then are processed in the digital signal processing units (DSPs).

The DSPs are using configuration parameters stored in the EEPROM as well as temperature and stress data acquired by the corresponding temperature and stress sensing elements.

Configurable second-order user temperature polynomials are implemented for main and sub channel to compensate the thermal reduction of the remanent magnetic flux of a permanent magnet used in a position sensing application. Additionally, an application-specific output characteristic can be set by configuring the EEPROM parameters Gain and Zero Point.

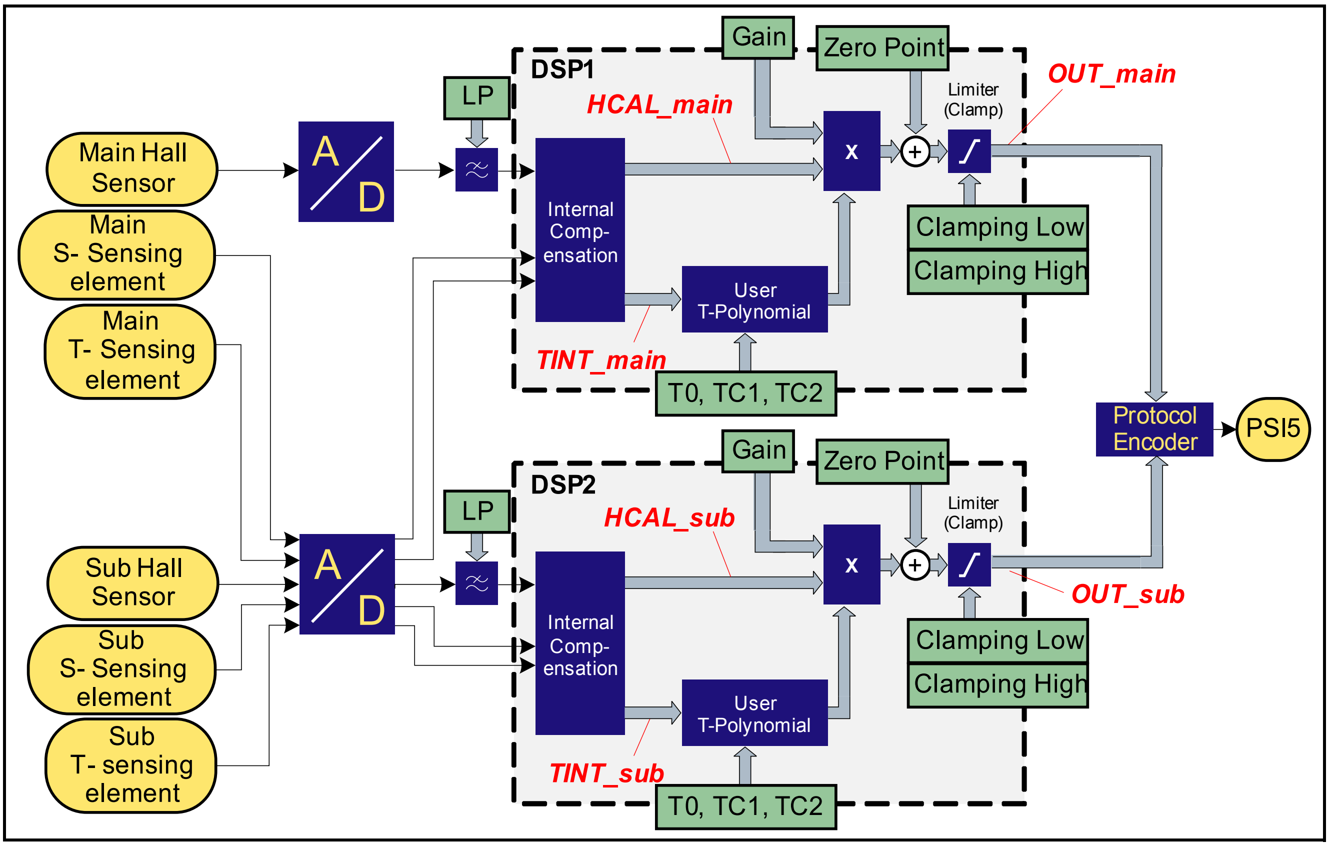

Figure 1 Simplified Signal Flow Diagram of the TLE4999I3.

Figure 1 shows the signal flow diagram for temperature compensation and output characteristic of the TLE4999I3.

The main ADC is used for conversion of the main Hall signal. The sub ADC is muliplexed for conversion of main and sub temperature and stress signals and sub Hall signal. The Hall signals are processed in the following sequence of steps:

1. The analog Hall signals are converted by the main and sub ADC.
2. The digital values are filtered by digital low-pass filters, which operate at a configurable filter frequency given by the main and sub "LP filter"-setting.
3. The signals from the Hall ADCs are compensated internally for stress and temperature drifts in the respective DSPs. The compensated values are stored in the main and sub HCAL registers. Also, the converted signals from the temperature sensors are stored in the main and sub TINT registers.
4. The main and sub HCAL values are multiplied by the respective user gain settings stored in the EEPROM and the results of the main and sub user temperature compensation polynomials.
5. The main and sub zero point settings are added to the resulting Hall values.
6. The digital Hall values are clamped according to the configured upper and lower clamping limits for main and sub channel. The output values of the clamping stages are stored in the OUT_main and OUT_sub registers.
7. An output protocol is generated from the resulting OUT_main and OUT_sub values and transmitted on the PSI5 pin.

2 Programming

2.1 Programmer Connection

Figure 2 shows the connection of the TLE4999I3 to the programming equipment.

The external components Cx and Cy are set according to the TLE4999I3 data sheet. The line capacitance affects the maximum possible data rate of the programming interface. For high line capacitances, for example due to a long cable connection, a slow data rate shall be used to ensure robust transmission.

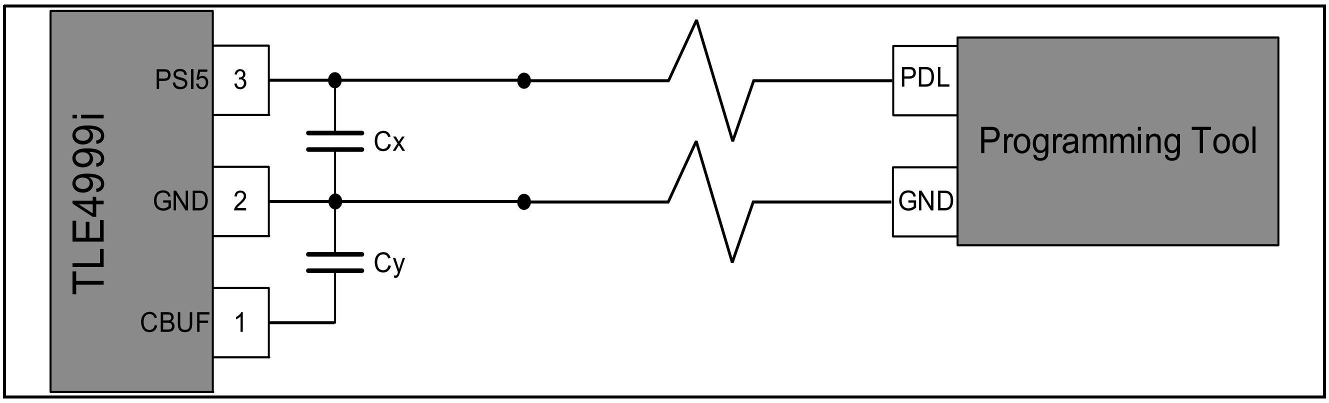

Figure 2 TLE4999I3 Circuitry for programming

2.2 Programming Interface

The TLE4999I3 sensor allows end-of-line programming of the EEPROM and read access to all internal registers via the SICI (**S**erial **I**nspection and **C**onfiguration **I**nterface) interface. The bidirectional communication mode can be entered during a limited time window directly after power on by sending the "activate programming mode" command.

2.2.1 Bit Encoding

The communication via the SICI interface is based on transmitting a single bit to the sensor and immediately receiving a bit. This makes the interface bit-synchronous, robust and very flexible in timing. The programmer initiates the communication by sending one bit as a voltage pulse on the PDL line, then the sensor answers one bit by sending a current pulse thereafter.

Bits from the programmer are encoded as the difference in duration of consecutive "high" and "low" voltage levels. To transmit a bit to the sensor, the programmer sends one single high/low PWM signal with a period T. The logic value of the bit is then encoded as the difference between "high" and "low" time:

- to transmit a "0" to the sensor, the programmer drives the line "high" for a short time t_{1_0}, then releases it to "low" for a long time $t_{2\_0} = T - t_{1\_0}$ (typically $t_{1\_0} = 0.3*T$)
- to transmit a "1" to the sensor, the programmer drives the line "high" for a long time t_{1_1}, then releases it to "low" for a short time $t_{2\_1} = T - t_{1\_1}$ (typically $t_{1\_1} = 0.7*T$)

After sending a bit, the programmer initiates an answer from the sensor by driving the line "high" again for a fixed time t_3 and then releasing it to "low" for a fixed time t_4. The sum of t_3 and t_4 has to be equal to the period T. The sensor recognizes the total bit-time interval T as the duration between two consecutive rising edges from the programmer.

After receiving one bit from the programmer, the sensor answers by transmitting one bit:

- the sensor transmits a "1" by drawing a current I_2 for a time $t_5 = 2 * | t_{2\_x} - t_{1\_x} | - t_3$
- the sensor transmits a "0" by not drawing additional current

To read the bit transmitted by the sensor, the programmer has to monitor the current consumption after the pulse defied by t_3. The bit encoding scheme is illustrated in **Figure 3**.

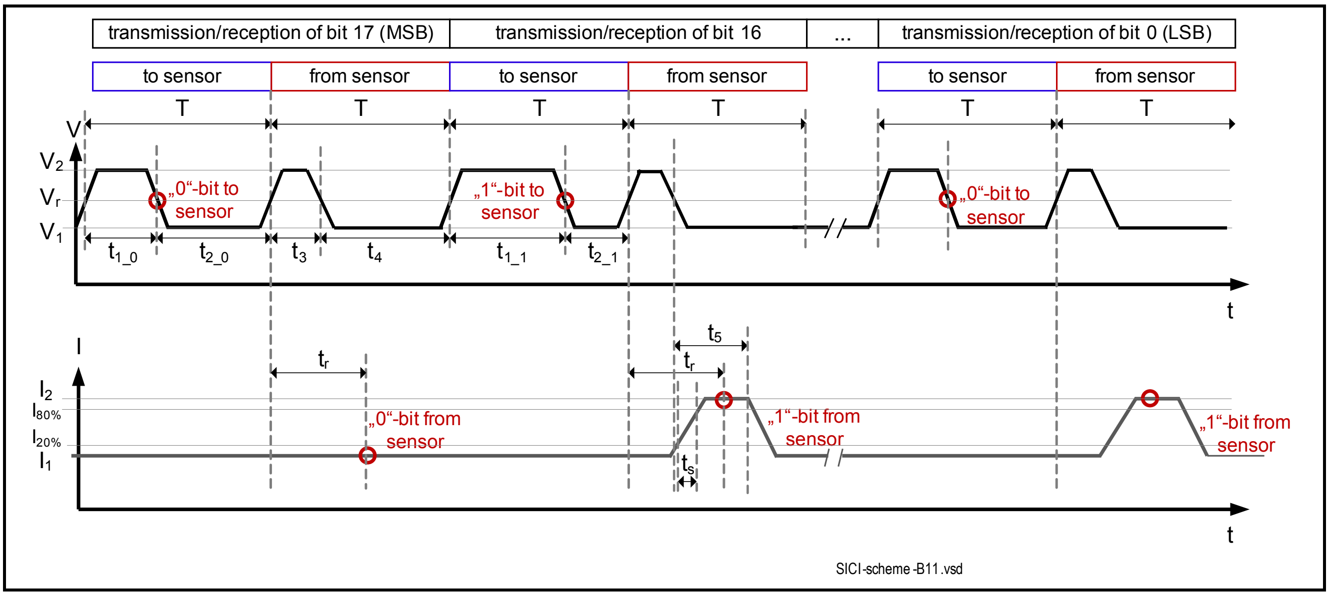

Figure 3 SICI interface bit encoding.

In the example in **Figure 3**, the programmer first sends a "0" bit (30/70 duty cycle), then drives the line high again for the sensor to answer (second period T). The sensor does not draw an additional current pulse, so it responds with a "0" bit. Then, the programmer sends a "1" bit (70/30 duty cycle), then again drives the line high (fourth period T). During the fourth period, the sensor answers with a "1" bit by drawing a current pulse.

The transmission rate of the interface is determined by the width T of the PWM signal sent by the programmer. A maximum transmission speed of 50 kbit/s can be reached for T = 10 µs. Lowering the transmission rate generally increases the robustness of the communication in distorted environments and/or with high

capacitive loads on the line. The optimum communication speed thus depends on the application circuitry. The timing specification of the SICI interface is given in **Table 1**.

Table 1 SICI Interface electrical and timing characteristics

Parameter	Symbol	Values			Unit	Note or Test Condition
		Min.	Typ.	Max.		
Low voltage for transmission to sensor	V_1	5.5	–	7.0	V	
High voltage for transmission to sensor	V_2	10.0	–	11.5	V	
Sensor current draw during transmission	I_{draw}	–	–	35	mA	programmer shall be able to supply up to max. current
Low current for transmission from sensor	I_1	–	–	15	mA	
High current for transmission from sensor	I_2	20	–	40	mA	
SICI frame period	T	40	–	120	µs	
Interface bit rate		6 .25	12.5	50	kBit/s	
High time "0" bit to sensor	t_{1_0}	25	30	40	% of T	"0" bit is transferred as typ. 30/70 duty cycle (determined by programmer)
Low time "0" bit to sensor	t_{2_0}	60	70	75	% of T	
High time "1" bit to sensor	t_{1_1}	60	70	75	% of T	"1" bit is transferred as typ. 70/30 duty cycle (determined by programmer)
Low time "1" bit to sensor	t_{2_1}	25	30	40	% of T	
High time during sensor transmission	t_3	10	20	30	% of T	$t_3 \leq \|t_1 - t_2\|$ High pulse must be stable enough to ensure correct reception of current pulse response from sensor
Low time during sensor transmission	t_4	70	80	90	% of T	$t_4 \geq T - t_3$
Response pulse length from sensor	t_5	10	60	90	% of T	$t_5 = 2 * \| t_{1\_x} - t_{2\_x} \| - t_3$ determined by absolute difference of programmer high and low time
Low/High timeout	$t_{timeout}$	1.7	3.3	5.0	ms	any longer high or low phase will reset the interface and abort the current frame
Capture time for response pulse from sensor	t_r	(50% of t_5) + t_3	–	(80% of t_5) + t_3	% of T	current level on PDL line shall be read at this time to ensure stable readout of sensor response. See **Figure 3**
Rise/Fall time for voltage pulses	t_{rise}	0.4	–	1.2	µs	influence of cable and external circuitry has to be taken into account
Settling time for current pulses from sensor	t_s	0.3	–	1	µs	

2.2.2 Programming Protocol

One data frame of the SICI interface consists of 1 control bit, 16 data bits arranged MSB first and 1 parity bit (odd parity). The SICI communication is started by the programmer sending an "activate programming mode" command directly after power-up of the sensor. The sensor replies with a "1" at the parity bit . The control bit is "1" for command frames" and "0" for data frames. The sensor is ready for programming 300 µs after receiving the "activate programming mode" command.

After entering programming mode, the programmer can start transmitting one or multiple frames. Between two frames, the programmer has to pause for at least t_{pause}.

As described in **Chapter 2.2.1**, the SICI interface is bit-synchronous, so every voltage-encoded bit sent by the programmer is immediately responded by one current-encoded bit from the sensor.

To read data content from the sensors registers, the programmer can send a "read" command including the register address to read from. As the SICI interface is bit-synchronous, the "read" command from the programmer has to be followed by one or multiple "empty" data frames, that is frames containing all 0's. The sensor responds the read command by showing last valid command that it received, in case the last valid command was "activate programming mode" command the sensor will then reply wit an "1" at the parity bit, otherwise the sensor responds by repeating every bit of the last valid command it received. Then, it responds the empty data frame by sending the content of the addressed register.

Multiple consecutive registers can be read with one read command by sending more than one empty frame after the "read" command. The sensor then automatically increments the register address with every received empty frame and responds by sending the content of the consecutive registers (see **Figure 4**).

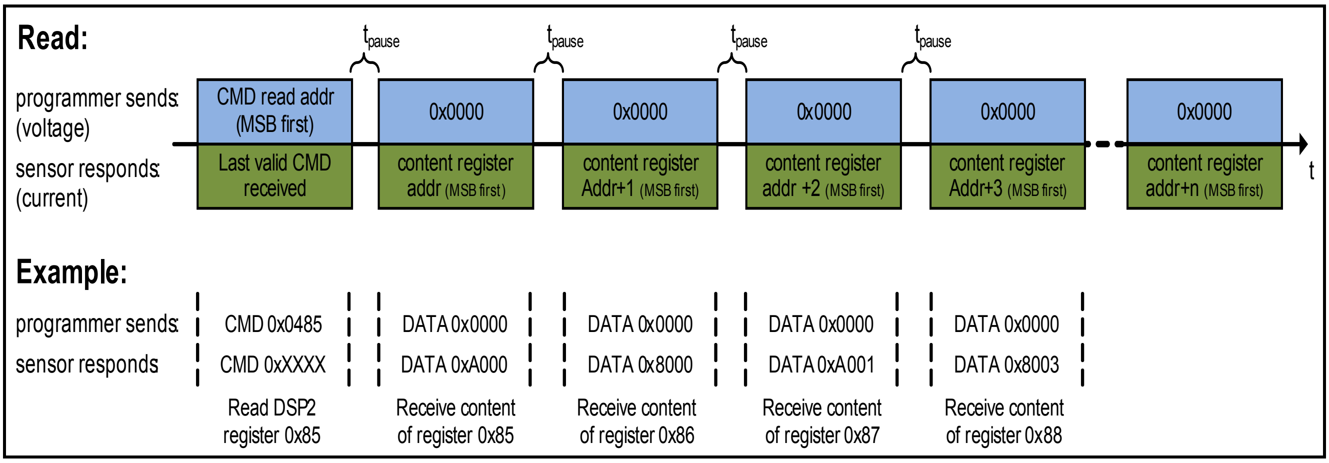

Figure 4 Frame order for read commands

To write data to registers, the programmer can send a "write" command including the register address to write to, followed by a data frame containing the data which shall be written to the addressed register. The sensor responds to the write command by showing last valid command that it received, in case the last valid command was "activate programming mode" command the sensor will then reply with an "1" at the parity bit, otherwise the sensor responds by repeating every bit of the last valid command it received, and it responds to the data frame by repeating the write command again.

Multiple consecutive registers can be written with one command by sending more than one data frame after the "write" command. The sensor automatically increments the address, so the content of the sent data frames from the programmer is written into consecutive registers. The sensor responds every data frame by repeating the write command including the (incrementing) address that is written to (see **Figure 5**).

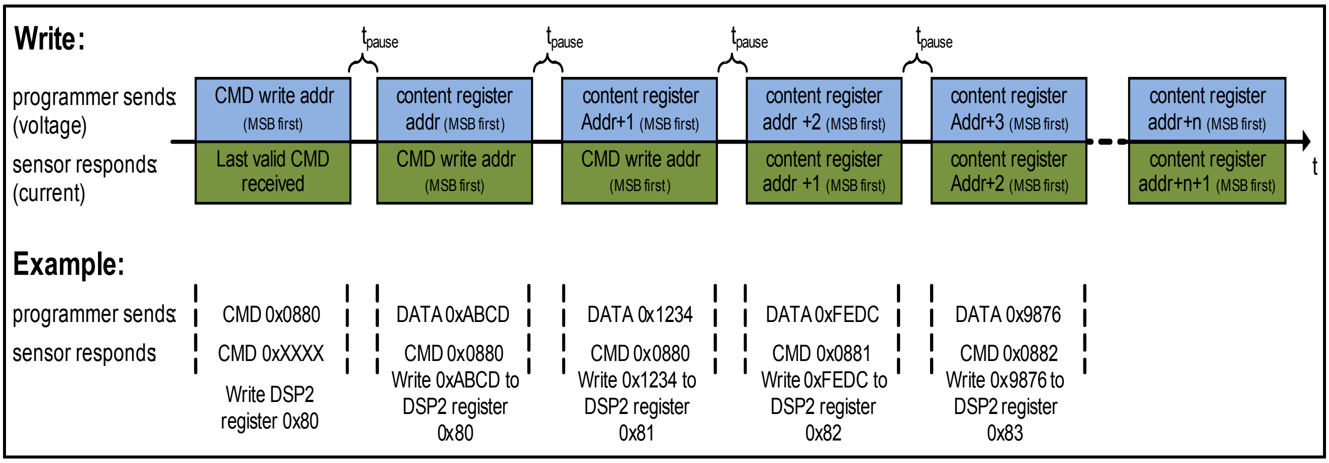

Figure 5 Frame order for write commands

The possible commands that can be sent by the programmer are listed in **Table 2**. The two signal processing units of the TLE4999I3, DSP1 and DSP2, have separate sets of working registers. Read and write access to these registers is done via the corresponding read and write commands for DSP1 and DSP2, respectively.

*Note: Wrong SICI commands (that is any bit patterns not covered by **Table 2**), are ignored by the sensor.*

Table 2 SICI commands

Command	Bits (MSB...LSB)	Description
Activate programming mode	$E478_H$	After receiving this command, the sensor enters programming mode. Programming mode can be exited by an external supply voltage reset or with the corresponding interface command ($AB00_H$).
DSP1 Read	$01xx_H$	Read data frame(s) from DSP1 register address xx_H
DSP1 Write	$02xx_H$	Write data frame(s) to DSP1 register address xx_H
DSP1 Algorithm trigger	3400_H	Trigger DSP1 Algorithm
DSP2 Read	$04xx_H$	Read data frame(s) from DSP2 register address xx_H
DSP2 Write	$08xx_H$	Write data frame(s) to DSP2 register address xx_H
DSP2 Algorithm trigger	6800_H	Trigger DSP2 Algorithm
EEP Refresh Page	$D00x_H$	Refresh EEPROM page; EEPROM page x_H lines 0_H to 7_H are mapped to DSP2 register range $C8_H$ to CF_H
EEP Program	$430x_H$	Start programming sequence for EEPROM page x_H
EEP Automatic Margin Check	$86xx_H$	Perform automatic margin check for all EEPROM pages at once, xx specifies a delay for activation of the auto margin check (32µs steps).
EEP Lock	$0D00_H$	Lock entire EEPROM
Exit programming mode	$AB00_H$	Exit programming mode

Table 3 summarizes the timings for programming mode.

Table 3 Timing specification for frame pause and programming mode activation

Parameter	Symbol	Values			Unit	Note or Test Condition
		Min.	Typ.	Max.		
Pause between frames	t_{pause}	30	–	–	µs	gap between frames to ensure correct processing
Pause after programming mode activation	t_{act_pause}	300			µs	
Time window for activation of programming interface	$t_{activate}$	2	–	5	ms	time after power-up of the sensor during which the "activate programming mode" command is accepted by the sensor
Pause after programming pulse	$t_{prog\ pause}$	1	–	–	ms	

Figure 6 shows an example frame with the programmer communication (voltage levels) and the corresponding sensor response (current levels).

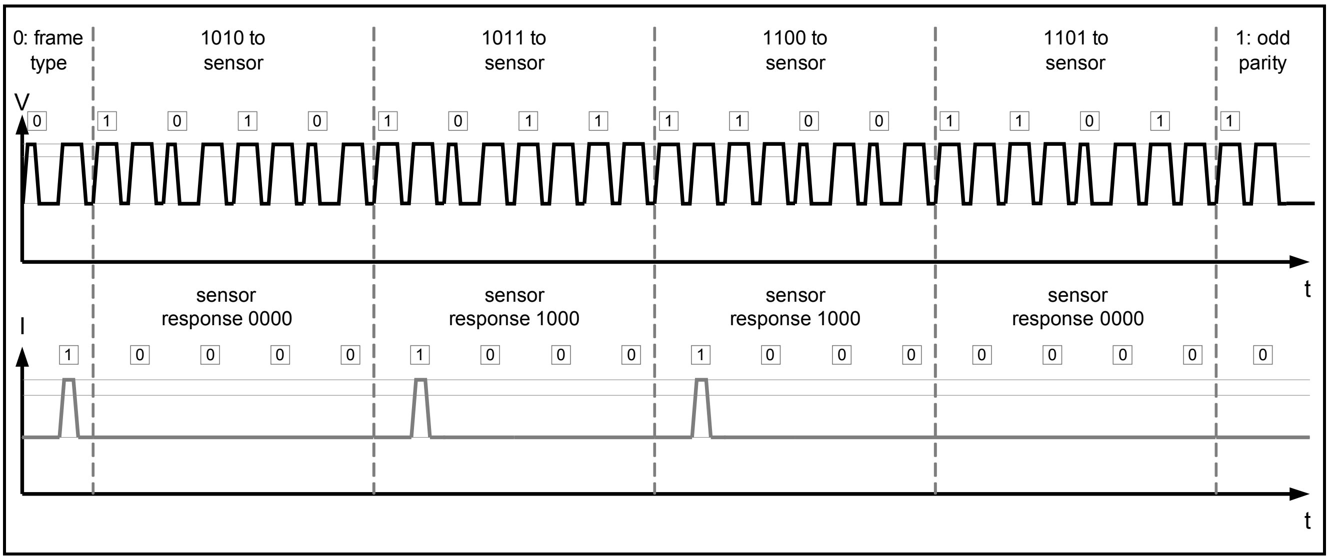

Figure 6 Example SICI frame with programmer command (voltage) and sensor response (current)

2.2.3 DSP Registers

The following registers of the TLE4999I3's signal processing units, DSP1 and DSP2, can be accessed with the corresponding "DSP1/2 Read/Write" commands:

Table 4 DSP1 Registers

Address	Symbol	Function	R/W
$0B_H$	HCAL_main	16bit internal calibrated main Hall ADC value (signed)	read only
$0E_H$	TINT_main	16bit internal calibrated main temperature value (signed)	read only
10_H	SCAL_main	16bit internal calibrated main stress value (signed)	read only
$0A_H$ (12...0)	OUT_main	13bit main Hall PSI5 output value (unsigned)	read only

Table 5 DSP2 Registers

Address	Symbol	Function	R/W
00_H	HW_STATUS	Hardware Status	read only
11_H	HCAL_sub	16bit internal calibrated sub Hall ADC value (signed)	read only
14_H	TINT_sub	16bit internal calibrated sub temperature value (signed)	read only
17_H	SCAL_sub	16bit internal calibrated sub stress value (signed)	read only
10_H (12...0)	OUT_sub	13bit sub Hall PSI5 output value (unsigned)	read only
35_H	HW_ID	Hardware ID	read only
$7F_H$	EEP_STAT	EEPROM Status	read only
$C8_H$	EEP_AB_DATA_0	EEPROM mapping register - line 0	read only
$C9_H$	EEP_AB_DATA_1	EEPROM mapping register - line 1	read/write
CA_H	EEP_AB_DATA_2	EEPROM mapping register - line 2	read/write
CB_H	EEP_AB_DATA_3	EEPROM mapping register - line 3	read/write
CC_H	EEP_AB_DATA_4	EEPROM mapping register - line 4	read/write
CD_H	EEP_AB_DATA_5	EEPROM mapping register - line 5	read/write
CE_H	EEP_AB_DATA_6	EEPROM mapping register - line 6	read/write
CF_H	EEP_AB_DATA_7	EEPROM mapping register - line 7	read/write

The registers HCAL_main/sub, TINT_main/sub, and SCAL_main/sub provide a readout of the main and sub path Hall, temperature, and stress measurements during programming interface access. They are employed for the user calibration procedure described in **Chapter 3**.

The register HW_ID contains the hardware ID of the TLE4999I3, which is "0010_B" for productive parts.

The registers EEP_WORD0 to EEP_WORD7 are mapping registers for read and write access to the EEPROM. After receiving an "EEP Refresh Page" command $D0xx_H$, the sensor maps the content of EEPROM page xx_H to these registers.

2.2.3.1 HW_STATUS

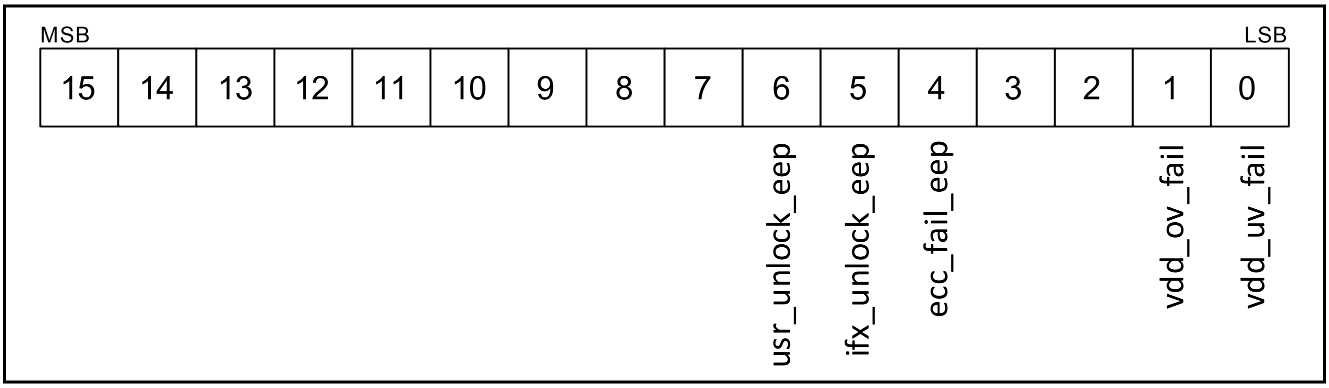

Figure 7 Hardware Status Register

- vdd_uv_fail is "1" in case an external supply undervoltage is detected.
- vdd_ov_fail is "1" in case an external supply overvoltage is detected.
- ecc_fail_eep is "1" if at least one multi-bit error was detected by the ECC.
- ifx_unlock_eep is "1" if the lock to the Infineon area of the EEPROM is not applied.
- usr_unlock_eep is "1" if the lock to the user area of the EEPROM is not applied.

2.2.3.2 EEP_STAT

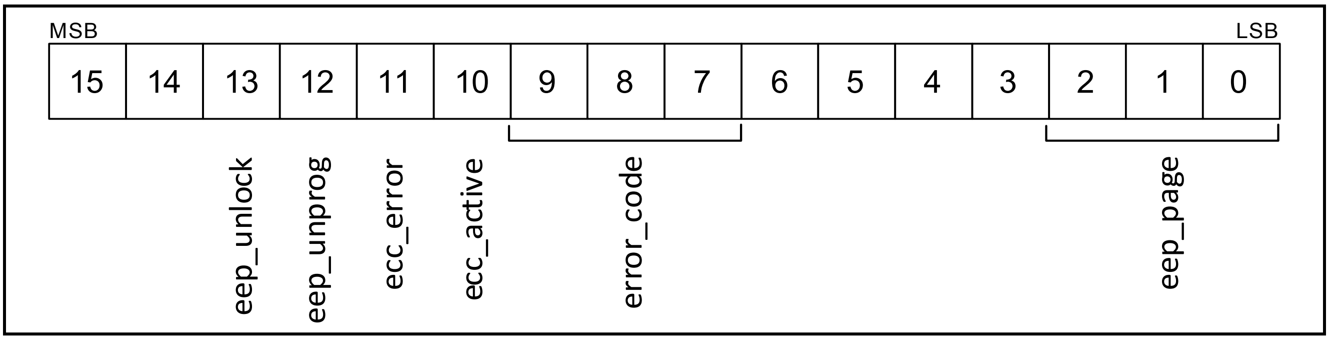

Figure 8 EEPROM Status Register

- eep_page contains the active EEPROM page which has been selected with the last "EEPROM Refresh Page" command.
- error_code contains the error code of a detected EEPROM error. If no error is present, this field is "000_B".
- ecc_active is "1" if at least one single-bit error was detected and automatically corrected by the ECC mechanism.
- ecc_error is "1" if at least one multi-bit error was detected by the ECC (error correction code).
- eep_unprog is "1" in case the EEPROM configuration was not programmed. In this case, the PSI5 output remains disabled.
- eep_unlock is "1" as long as the EEPROM is unlocked. After locking, it is "0".

2.3 EEPROM

2.3.1 EEPROM Map

The EEPROM contains data for configuration, calibration and temperature compensation. It is organized in different pages, each page consists of 8 lines with 16 data bits per line. It is only possible to access one EEPROM page at a time for read / write operation. An overview of the user configurable range of the EEPROM is shown in **Figure 9**.

Each EEPROM line is protected by 6 additional ECC bits which provide detection and correction of flipped bits. The ECC can detect and automatically correct one flipped bit within a data line during operation of the sensor. If two bits within a data line flip, the ECC detects an error but cannot automatically correct it. In this case, the sensor indicates an error by disabling the sensor’s PSI5 interface. The ECC bits are handled by the EEPROM controller internally and cannot be accessed manually.

In the EEPROM, the Infineon lock and user lock sections are on separate pages. The Infineon lock section is already locked at delivery and cannot be changed in the user programming. The user lock area shall be locked after the user calibration and configuration is complete.

<table>
<tr><th></th><th></th><th>(MSB)</th><th></th><th></th><th></th><th></th><th></th><th></th><th></th><th></th><th></th><th></th><th></th><th></th><th></th><th></th><th>(LSB)</th></tr>
<tr><th>Page</th><th>Line</th><th>15</th><th>14</th><th>13</th><th>12</th><th>11</th><th>10</th><th>09</th><th>08</th><th>07</th><th>06</th><th>05</th><th>04</th><th>03</th><th>02</th><th>01</th><th>00</th></tr>
<tr><td rowspan="8">0</td><td>0</td><td colspan="16">User ID1 (15...0)</td></tr>
<tr><td>1</td><td colspan="13">Clamping Low Main (12...0) - CLM</td><td colspan="3">reserved</td></tr>
<tr><td>2</td><td colspan="13">Clamping High Main (12...0) - CHM</td><td colspan="3">reserved</td></tr>
<tr><td>3</td><td colspan="2">reserved</td><td colspan="4">LPM (3...0)</td><td colspan="10">Linear Temperature Coefficient Main (9...0) - TC1M</td></tr>
<tr><td>4</td><td colspan="7">Ref. Temp. Main (6...0) - T0M</td><td colspan="9">Quad. Temp. Coefficient Main (8...0) - TC2M</td></tr>
<tr><td>5</td><td colspan="14">Gain Main (13...0) - GM</td><td colspan="2">reserved</td></tr>
<tr><td>6</td><td colspan="13">Zero Point Main (12...0) - ZM</td><td colspan="2">reserved</td><td>RM</td></tr>
<tr><td>7</td><td colspan="8">reserved</td><td colspan="8">Block CRC main (7...0)</td></tr>
<tr><td rowspan="8">1</td><td>1</td><td>res.</td><td>Slew</td><td colspan="4">LPS (3...0)</td><td colspan="10">Linear Temperature Coefficient Sub (9...0) - TC1S</td></tr>
<tr><td>2</td><td colspan="7">Ref. Temp. Sub (6...0) - T0S</td><td colspan="9">Quad. Temp. Coefficient Sub (8...0) - TC2S</td></tr>
<tr><td>3</td><td colspan="14">Gain Sub (13...0) - GS</td><td colspan="2">reserved</td></tr>
<tr><td>4</td><td colspan="13">Zero Point Sub (12...0) - ZS</td><td>res.</td><td>ID</td><td>RS</td></tr>
<tr><td>5</td><td colspan="16">User ID2 (15...0)</td></tr>
<tr><td>6</td><td colspan="13">Clamping Low Sub (12...0) - CLS</td><td colspan="3">reserved</td></tr>
<tr><td>7</td><td colspan="13">Clamping High Sub (12...0) - CHS</td><td colspan="3">reserved</td></tr>
<tr><td>8</td><td colspan="8">Protocol Delay (7...0) - PD</td><td colspan="8">Block CRC sub (7...0)</td></tr>
</table>

Figure 9 Page structure and addressing scheme of the user range of the EEPROM

2.3.2 EEPROM Block CRC

Both pages of the EEPROM user lock section are protected by separate 8 bit block CRCs (cyclic redundancy checks). The block checksums are calculated from lines 00 to the first 8 bits of line 07 of the corresponding page using the following polynomial: $\mathbf{x^8 + x^4 + x^3 + x^2 + 1}$

and the seed value: $\mathbf{10101010_B}$.

When changing the content of an EEPROM page, the block checksum has to be re-calculated from the new page content and written into the corresponding CRC field in line 07.

In case the checksum value stored in the CRC field does not match the page content, the TLE4999I3 detects a CRC error and disables the PSI5 output.

2.3.3 EEPROM Configuration Parameters

2.3.3.1 Magnetic Field Range - RM, RS

The range parameters RM (range main channel) and RS (range sub channel) can be configured independently.

The working range of the magnetic field defines the input range of the A/D converter. It is always symmetrical around the zero field point. Any two points in the magnetic field range can be selected to be the end points of the output value. The output value is represented within the range between the two points.

In the case of fields higher than the range values, the output signal may be distorted.

Table 6 Range Setting Main/Sub

Parameter RM, RS	Range	Nominal Range in mT
1	Fine	±12.5
0	Regular	±25

2.3.3.2 Gain Setting - GM, GS

The gain parameters Gain main and Gain sub can be configured independently.

The overall sensitivity of each measurement channel is defined by the range and the gain setting. The compensated Hall measurement value is multiplied by the Gain value. The multiplication factor is given by:

$$\mathrm{Gain}_{\mathrm{main}} = \frac{\mathrm{GM}}{1510} \tag{2.1}$$

$$\mathrm{Gain}_{\mathrm{sub}} = \frac{\mathrm{GS}}{1510} \tag{2.2}$$

Table 7 Gain Setting Main/Sub

Parameter GM,GS	Value	Description
Range	-8192...8191	corresponds to gain factor -5.43 ... 5.42
Quantization step	662 ppm	
Default[1)]	1510	corresponds to gain factor 1.0

1) In 25mT range, a gain value of +1.0 corresponds to a nominal sensitivity of 147.5 LSB13/mT.

Note: The main and sub channel of the TLE4999I3 show by default (both Gain settings 1.0) inverse output slopes.

2.3.3.3 Zero Point Setting - ZM, ZS

The zero point values correspond to the channel output values with zero magnetic field at the sensor. They can be configured independently for main and sub channel.

Table 8 Zero Point Setting Main/Sub

Parameter GM,GS	Value	Description
Range	0 ... 8191	corresponds to zero point at 0 LSB13 ... 8191 LSB13
Quantization step	1 LSB13	
Default	4095	corresponds to nominal zero point[1)] at 4095 LSB13 (= 50% of full output range)

1) Subject to specified initial zero point specification.

2.3.3.4 Low-Pass Filter Setting - LPM, LPS

Configurable digital low-pass filters are implemented in the signal paths of the main and sub channels. The possible settings, together with the corresponding phase and step-response delays are shown in **Table 9**. **Figure 10** shows a Bode plot of the filter settings, and **Figure 10** illustrates the phase delay and step response. The filter setting can be configured independently for main and sub channel.

Table 9 Low Pass Filter Setting Main/Sub

Parameter LP	Nominal cutoff frequency in Hz (-3 dB point)	Nominal Phase Delay of 100 Hz Signal in µs	Nominal Step-Response (90%) Time in µs
0	Off[1)]	122	244
1	80	1530	4770
2	160	992	2430
3	200	838	1970
4	240	726	1630
5	320	576	1280
6	400	481	1002
7	470	416	864
8	500	391	800
9	650	319	618
10	870	250	480

Table 9 Low Pass Filter Setting Main/Sub

Parameter LP	Nominal cutoff frequency in Hz (-3 dB point)	Nominal Phase Delay of 100 Hz Signal in µs	Nominal Step-Response (90%) Time in µs
11	980	226	416
12	1070	207	384
13	1270	177	320
14	1380	161	288
15	1530	144	256

1) Set programmable low pass filter off, inherent filter of ADC stays on

Note: The delays given in ***Table 9*** *are internal delays. In order to calculate the total latency in a specific configuration, the PSI5 interface transmission time has to be added.*

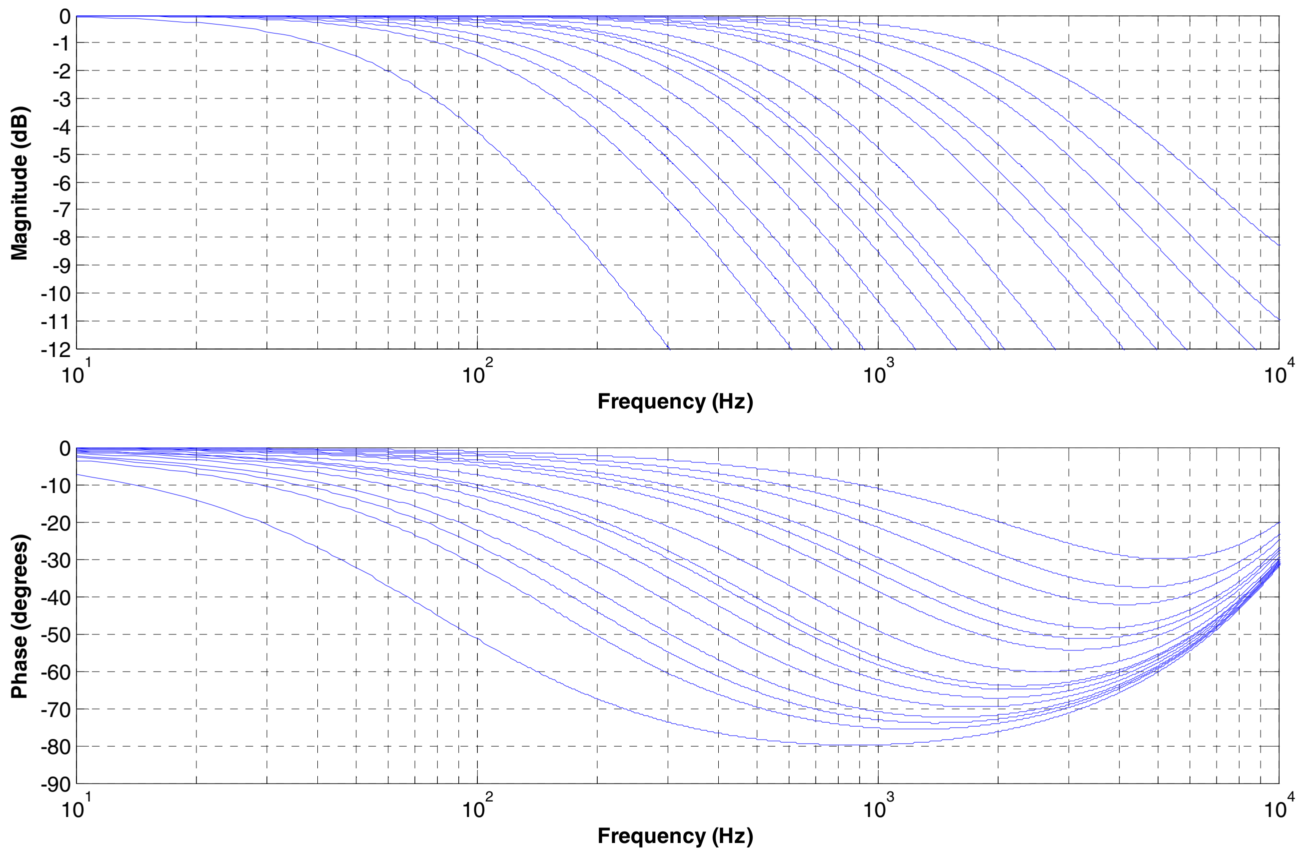

Figure 10 Bode Plot of TLE4999I3 Low-Pass Filter Settings 80 Hz to 3600 Hz (bottom to top graph).

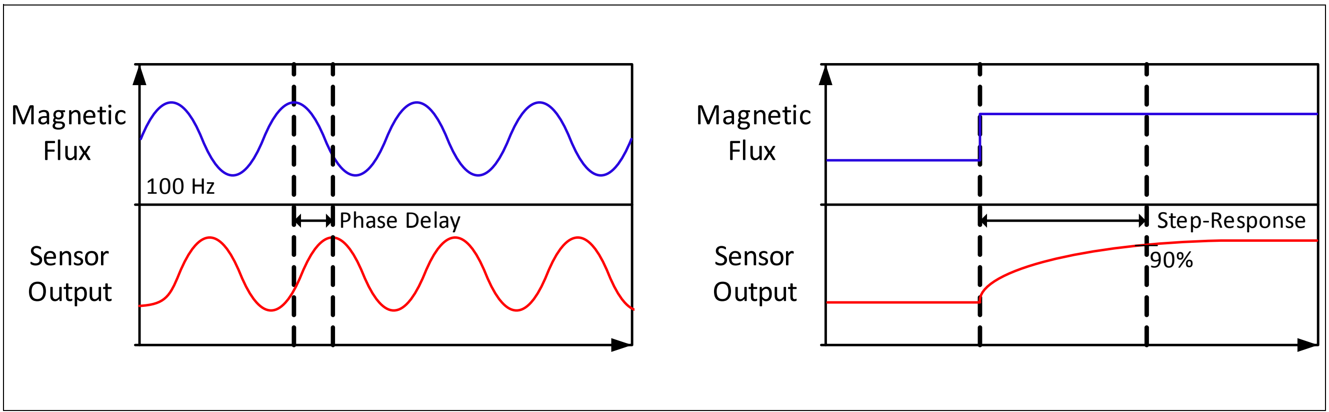

Figure 11 Illustration of Phase Delay and Step-Response.

2.3.3.5 Clamping - CHM, CLM, CHS, CLS

The clamping function is useful for separating the output range into an operating range and error ranges. If the magnetic field is exceeding the selected measurement range, the output value is limited to the clamping values. Any value in the error range is to be interpreted as an error by the receiver.

The high and low clamping levels can be configured independently for main and sub channel.

Figure 12 shows the default output curve in which the magnetic field range between -25 mT and 25 mT is mapped to 5% and 95% of the full 13bit output range.

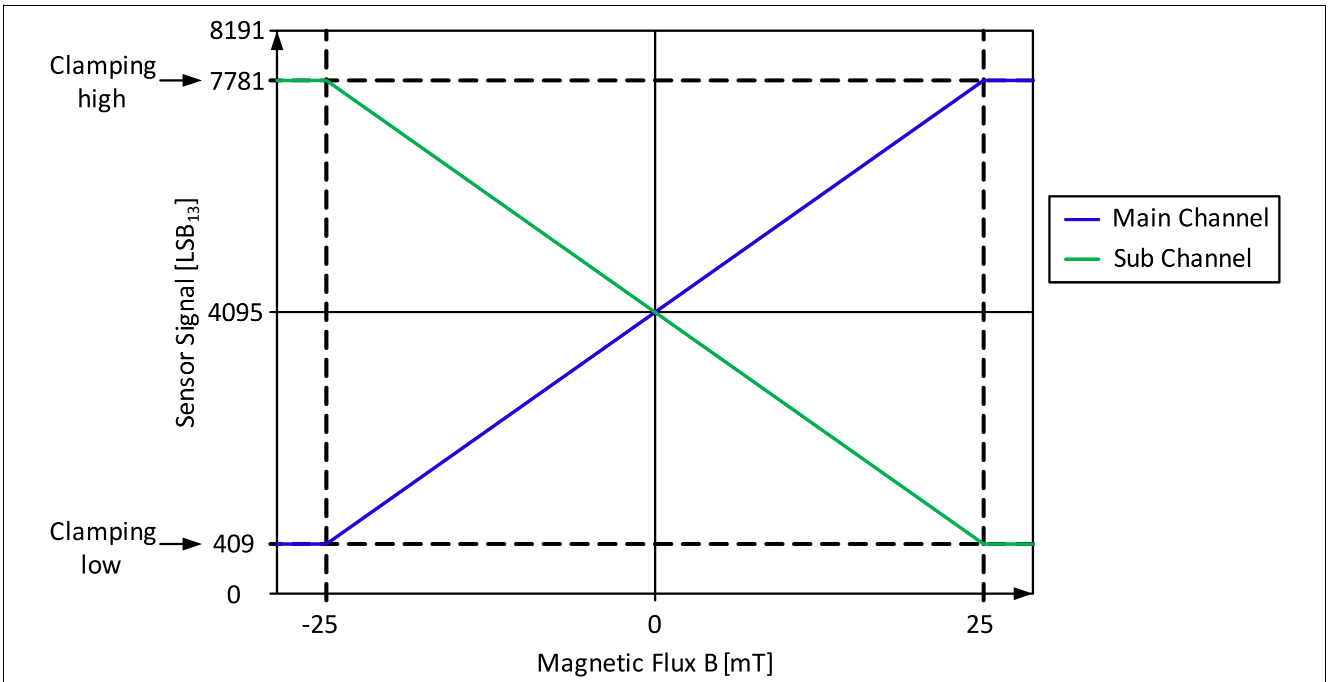

Figure 12 Clamping Example

Table 10 Clamping High/Low Settings for Main/Sub

Parameter CHM,CLM,CHS,CLS	Value	Description
Range	0 ... 8191	corresponds to upper/lower clamping at 0 LSB13 ... 8191 LSB13
Quantization step	1 LSB13	
Default	CLM, CLS: 409 CHM, CHS: 7781	corresponds to clamping at 5% and 95% of full 13bit output range

2.3.3.6 Temperature Compensation - T0M, T0S, TC1M, TC1S, TC2M, TC2S

Both channels of the Programmable Linear Hall Sensor with PSI5 Interface have a user-configurable second-order temperature compensation, which can be used to compensate the thermal reduction of the remanent magnetic flux of a permanent magnet used in a position sensing application.

Three parameters are used for the application temperature compensation:

- Reference temperature T_0
- A linear coefficient (1^{st} order) TC_1
- A quadratic coefficient (2^{nd} order) TC_2

The temperature compensation parameters for main and sub channel are stored in separate pages in the EEPROM.

The detailed procedure to derive the optimum TC1 and TC2 parameters for a a given magnet characteristic is described in **Chapter 2.4**.

Table 11 Reference Temperature Setting Main/Sub

Parameter T0M, T0S	Value	Description
Range	0...127	corresponds to 0...127°C
Quantization step	1°C	
Default	25	25°C

Table 12 Linear Temperature Coefficient Main/Sub

Parameter TC1M, TC1S	Value	Description
Range	0...1023	corresponds to -2400...5400 ppm/°C
Quantization step	7.629 ppm/°C	
Default	315	corresponds to 0 ppm/°C

Table 13 Quadratic Temperature Coefficient Setting Main/Sub

Parameter TC2M, TC2S	Value	Description
Range	0...511	corresponds to -30...30 ppm/°C^2
Quantization step	0.119 ppm/°C^2	
Default	256	corresponds to 0 ppm/°C^2

Attention: ***Even though the Programmable Linear Hall Sensor with PSI5 Interface has separate T0, TC1, and TC2 EEPROM registers for main and sub channel, these registers shall be programmed to exactly the same values for the two channels.***

2.3.3.7 Protocol Identification - ID

The PSI5 protocol of the TLE4999I3 has an ID bit which allows the identification of each individual sensor IC in a system that has two pieces of TLE4999I3 implemented. The value of this ID bit in the protocol is given by the setting of the ID bit in the TLE4999I3's EEPROM.

2.3.3.8 User ID1, ID2

The fields User ID1 and User ID2 in the TLE4999I3's EEPROM are free for use by the system integrator to store production specific information. They are not used in any way by the TLE4999I3's internal signal processing.

2.3.3.9 Protocol Rise/Fall Time - Slew

In order to tailor the interface behavior to application-specific requirements regarding transmission robustness and emission, the rise/fall time of the TLE4999I3's PSI5 interface can be configured:

- Slew = 1: Slow edge, low emission
- Slew = 0: Fast edge, higher emission

Table 14 Protocol Rise /Fall Time Settings

Parameter Rise/Fall Time ($t_{current\ slope}$)	Value	Description
Fast edge	0	corresponds typical 500 ns[1)2)]
Slow edge	1	corresponds to typical 700 ns[1)2)]
Default	0	corresponds to typical 500 ns[1)2)]

1) Interface timing variation not included
2) With recommended application circuit

2.3.3.10 Protocol Delay - PD

The nominal delay t_{PD} between the rising edge of the PSI5 synchronization pulse and the first data frame transmitted by the TLE4999I3 is configurable between 44 and 299 µs (see **Figure 13**).

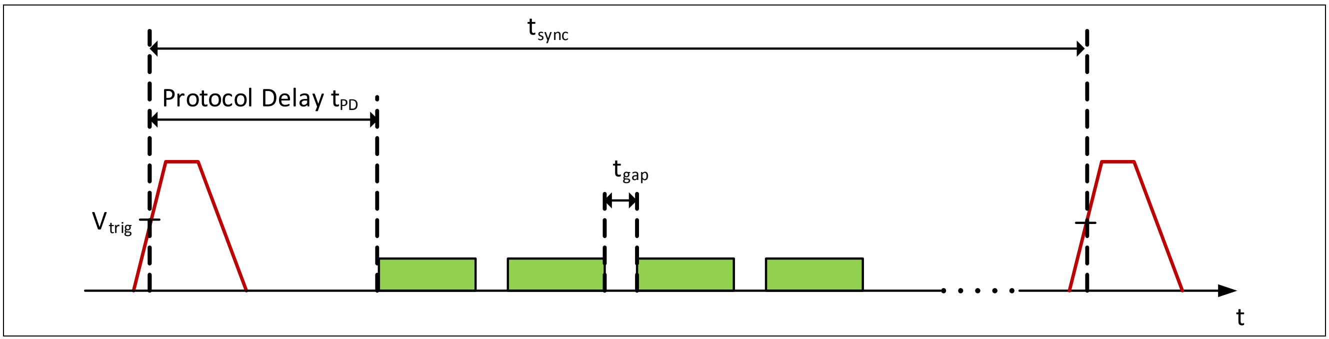

Figure 13 PSI5 Interface timing

Table 15 Protocol Delay Setting

Parameter PD (t_{PD})	Value	Description
Range	0...255	corresponds to nominal 44...299 µs[1)]
Quantization step	1 µs	
Default	16	corresponds to 60 µs[1)]

1) Interface timing variation not included

2.4 Programming Flow

The programming flow of the TLE4999I3 EEPROM is shown in **Figure 14** and **Figure 15**. To program the EEPROM, the sensor is brought into programming mode by sending the "Activate programming mode" command within the time window $t_{activate}$ after power-on. Write the data to be sent to the sensor. The desired page to write to is then selected by using the "Program Page" command. All the data to be written into the desired page is sent to the sensor, followed by the "Program Page" command and the application of a programming pulse. The procedure is repeated for all pages that need to be programmed.

After programming of all desired pages, the written data shall be read back by the programmer to ensure that the correct values are programmed.

Then, a margin check shall be executed by sending the "EEP Automatic Margin Check" command and applying a programming pulse (see also **Chapter 2.4.3**). The margin check ensures the reliable data retention of the programmed EEPROM cells.

Finally, the EEPROM shall be locked by sending the "EEPROM Lock" command and applying a programming pulse.

Programming

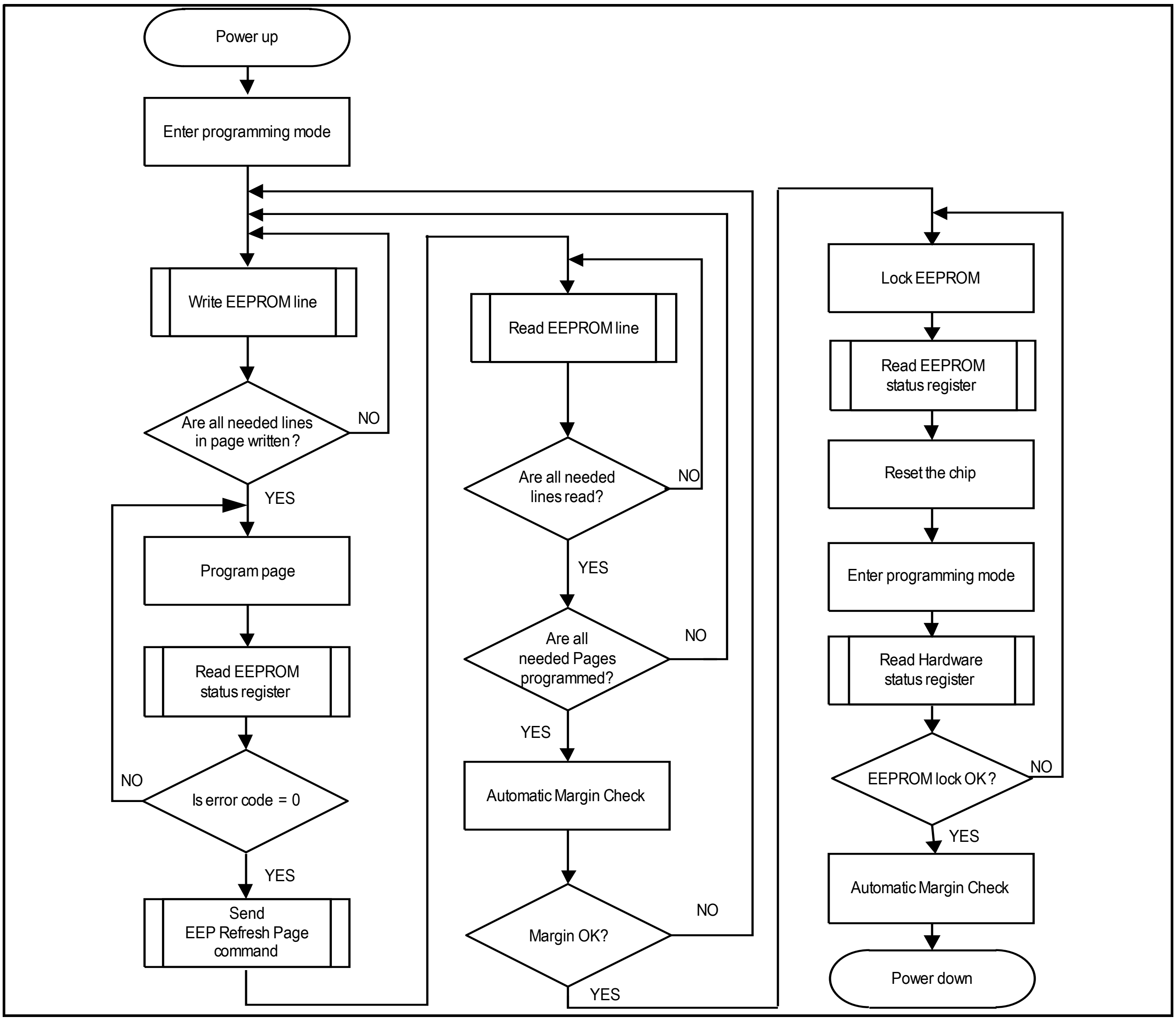

Figure 14 Overview EEPROM Programming

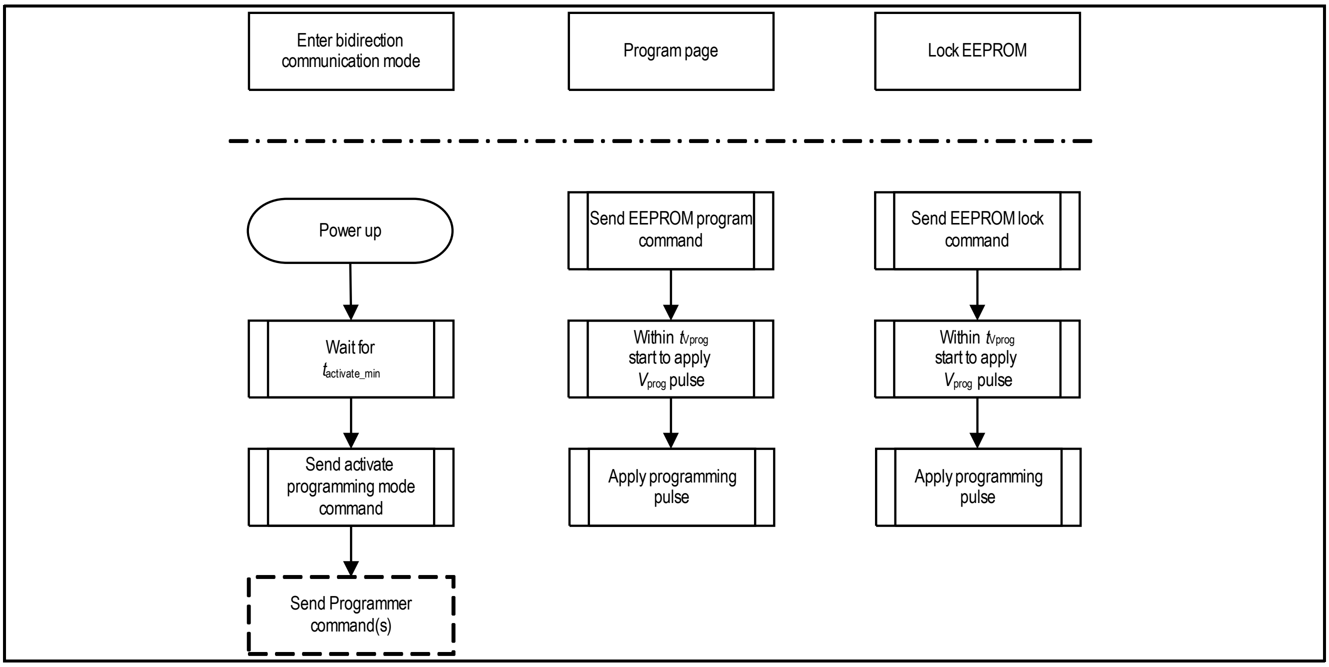

Figure 15 Subroutines of the EEPROM Programming

2.4.1 Defining the Content of the EEPROM

The EEPROM access of the TLE4999I3 in programming mode is handled by the DSP2. To program an EEPROM page, the corresponding page address is mapped to the EEP registers of DSP2 using the "Program Page " command . This command also loads the content of the registers into the EEPROM page. Therefore, all the lines will overwritten.

The desired content is written to the EEPROM registers by the "DSP2 Write" command. After the desired lines of the selected page are written, the content of the EEP registers is transfered into the selected EEPROM page using the "EEPROM program" command, followed by the application of a programming pulse (see **Figure 16**) that burns the data into the EEPROM cells. After the programming pulse, the programmer has to wait at least t_{prog_pause} before sending the next SICI frame. **Table 16** shows the specification of the programming pulse.

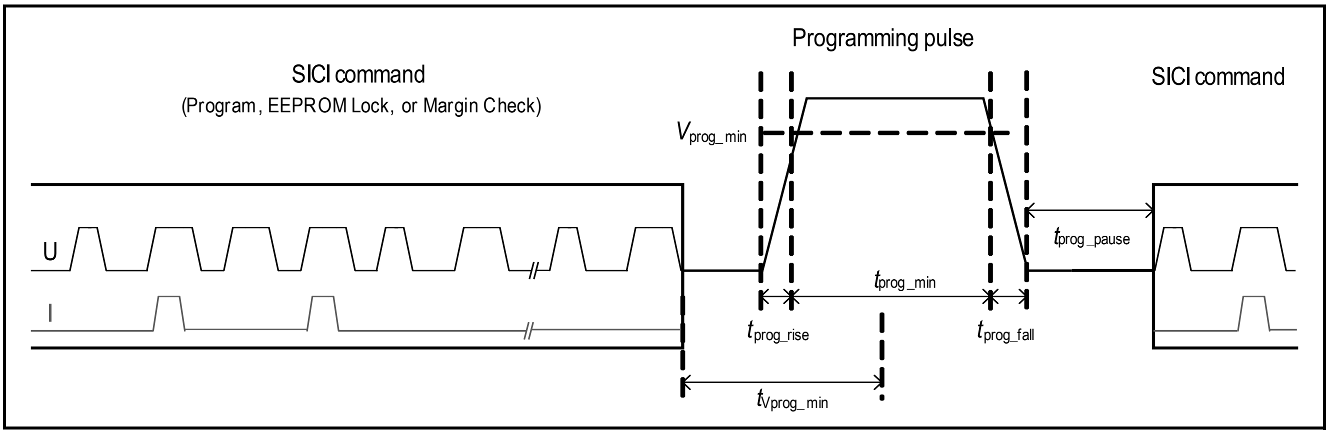

Figure 16 Detailed timing of applying the programming pulse

The EEPROM status register will indicate that the intelligent programming routine finished correctly. To verify that the correct content is written to the EEPROM cells, it is recommended to check this by reading back all EEPROM lines of the active page.

After all pages are programmed and checked, it is recommended to lock the EEPROM using the "EEP Lock" command. It is also recommended to verify the correct locking by reading back the EEPROM status register after the locking operation.

The programming mode is then exited by the "Exit programming mode" command.

Table 16 Timing and electrical characteristics for programming pulse

Parameter	Symbol	Values			Unit	Note or Test Condition
		Min.	Typ.	Max.		
Programming pulse voltage	V_{prog}	15.8	–	16.4	V	valid for EEPROM page programming, and EEPROM lock
Margin test pulse voltage	–	15.8	–	16.4	V	valid for EEPROM margin test
Duration of programming pulse for EEPROM page programming	t_{prog}	400	–	–	ms	measured after $V_{prog,min}$ is reached
Duration of rising/falling edge of programming pulse	t_{prog_rise} t_{prog_fall}	–	–	400	µs	influence of cable and external circuitry has to be taken into account
Duration of programming pulse for EEPROM margin test	$t_{prog\ MT}$	7	–	–	ms	measured after $V_{prog,min}$ is reached
Duration of programming pulse for EEPROM lock	$t_{prog\ lock}$	135	–	–	ms	measured after $V_{prog,min}$ is reached
Programming cycles per page	n_{prog}	–	–	10		a programming cycle is defined as applying the programming pulse once in order to change the state of at least one EEPROM cell. each page can be programmed n_{prog} times
Programming temperature	T_{prog}	10	–	60	°C	
Time window to start the programming pulse	t_{Vprog}	0	–	20	ms	measured from reaching the low level after the last SICI frame

2.4.2 Memory Lock

It is recommended to lock the EEPROM after the programming is finished. This is done by sending the EEPROM lock command and applying the programming pulse for a time $t_{prog\ lock}$. The same voltage level and start time window as used for a normal EEPROM programming operation are valid (V_{prog_min} and t_{Vprog}).

The EEPROM is separated in two areas. The first area is the customer lock area (EEPROM pages 0 and 1). The second area is the Infineon lock area. The Infineon lock area is already locked at delivery so that it cannot be changed anymore.

The correctness of the locking operation can be verified by reading the EEPROM status register. Once the EEPROM is locked there is no possibility to rewrite the EEPROM again.

2.4.3 Margin Check

After programming, a margin check is necessary to get confirmation about the stored charge inside the EEPROM cells and therewith check the quality of the EEPROM programming. The TLE4999I3 uses intelligent programming, which continuously monitors the actual margin while the programming voltage is applied and stops programming automatically when the optimum charge state is reached.

Since the EEPROM stores the data inverted, a programmed "0" will have a high voltage level (V_{mar0}) and the margin voltage can be directly verified. The cells with a programmed "1" will have a low voltage level (V_{mar1}) and their margin voltage might be slightly negative. For these cells, only a maximum margin level can be checked.
Figure 17 shows the two ranges for a programmed "1" and "0" and **Table 17** gives the specification for the margin voltage levels.

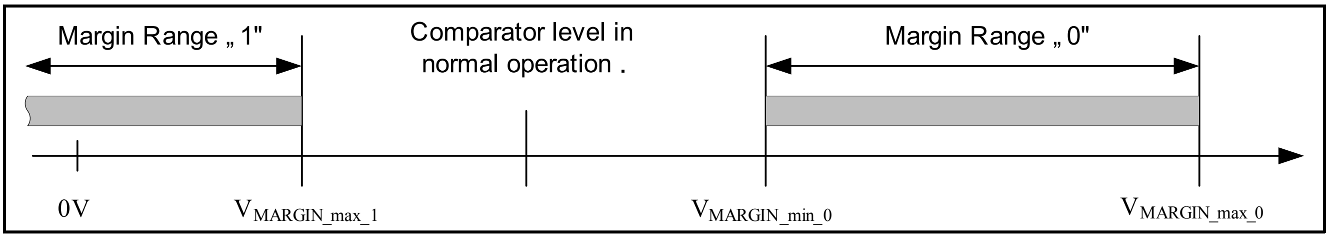

Figure 17 Margin Range

The TLE4999I3 offers an automatic margin check mechanism, which shall be implemented in the programming procedure to ensure the reliability of the EEPROM programming.

Table 17 Margin voltages

Parameter	Symbol	Values			Unit	Note or Test Condition
		Min.	Typ.	Max.		
Margin voltage "1"	V_{mar1}	–	0	0.25	V	
Margin voltage "0"	V_{mar0}	2	–	5	V	

The automatic margin check gives a fast confirmation whether the margin voltages of all EEPROM cells are within the target levels. This check is excecuted by issuing the "EEP Automatic Margin Check" command and applying the programming pulse for a time $t_{prog\ MT}$.
In order to support a more robust test procedure it is possible to specify a certain delay for the test to start (within the command). For this purpose the auto margin command is issued by the Test-Interface and the programming voltage can be applied within the specified delay. Therefore it is possible to accurately raise the voltage to programming level before the test starts. The auto margin command supports a 8 bit delay with 32µs steps (0ms to ~8ms delay). The same voltage level and start time window as used for an EEPROM programming operation are valid (V_{prog} and t_{Vprog}).
After the supply voltage has returned to normal, the EEPROM assembly buffer data registers (Address: $C8_H$ and $C9_H$) contain the following information:

- Address $C8_H$, bits[5:0]: value for the weakest programmed '0'
- Address $C8_H$, bits[11:6]: value for the strongest programmed '0'
- Address $C9_H$, bits[5:0]: value for the weakest programmed '1'
- Address $C9_H$, bits[11:6]: value for the strongest programmed '1'

All readout values can be interpreted as follow:

- All values are 6 bit and each LSB represents 100mV, giving a range of 0.0V – 6.3V.
- All values are rounded up (e.g. if the margin voltage is 4.23V, the returned value will be 4.3V)
- If the programmed '1's have negative margin voltage, the values will be clamped to 0.0V.

3 Calibration of TLE4999I3

3.1 Temperature Compensation

A temperature compensation mechanism is implemented in the Programmable Linear Hall Sensor with PSI5 Interface to account for thermal drift of the Hall probe sensitivity and thermal reduction of the remanent magnetization of a permanent magnet used in a position sensing application. Initially, the Programmable Linear Hall Sensor with PSI5 Interface is pre-configured by Infineon to have a constant magnetic sensitivity over temperature.

In case the Programmable Linear Hall Sensor with PSI5 Interface is used to measure an absolute magnetic field, for example in a current sensing application, then no additional adaption of the temperature compensation by the user is required.

If the Programmable Linear Hall Sensor with PSI5 Interface is used in a position sensing application where it measures the magnetic field generated by a moving permanent magnet, then it is typically desired that the output signal of the Programmable Linear Hall Sensor with PSI5 Interface depends only on the magnet position. In this case, a user adaptation of the temperature compensation parameters TC1 and TC2 for main and sub channel is required to account for thermal reduction of the magnet's remanence. Therefore, the Programmable Linear Hall Sensor with PSI5 Interface has to be configured to increase its sensitivity accordingly with increasing temperature to compensate the thermal reduction of the remanence.

This temperature coefficient of the remanence depends on the chosen magnet material, so the temperature compensation of the Programmable Linear Hall Sensor with PSI5 Interface has to be adapted to the permanent magnet used in the application.

3.1.1 Magnet Temperature Compensation Polynomial

The user temperature compensation of the Programmable Linear Hall Sensor with PSI5 Interface uses a diverse second order polynomials for main and sub channel. **Equation (3.1)** shows the calculation for the main channel, which shall be used for the derivation of the user temperature coefficients TC1 and TC2. The same TC1 and TC2 values shall be used also for the sub channel.

$$S(\mathrm{TINT}) = 1 + (\mathrm{TINT} - 32 \cdot T_0) \cdot \left(\frac{\mathrm{TC1} - 315}{2^{22}} + \frac{\mathrm{TC2} - 256}{2^{20}} \cdot \frac{\mathrm{TINT} - 32 \cdot T_0}{2^{13}}\right) \tag{3.1}$$

with:

$$\mathrm{TINT} = 32 \cdot T_J[°\mathrm{C}] \tag{3.2}$$

T_J is the junction temperature in °C. The coefficients TC1, and TC2 are the linear and quadratic temperature compensation coefficients, respectively. They are stored in the EEPROM and pre-configured by Infineon for a constant magnetic sensitivity over temperature (see **Chapter 2.3.3.6**).

The reference temperature T_0 is the temperature where the polynomial has the value "1" and is thus the temperature where the absolute magnetic sensitivity matches the configured gain value. T_0 can be chosen freely in the application. It is recommended to leave it at default setting.

3.1.2 Determination of Compensation Parameters from Measurement

For the determination of the coefficients for the application sensitivity polynomial (**Equation (3.1)**) a measurement of the temperature behavior of the sensor output in the application is recommended. A basic

example for a position sensing application using the Programmable Linear Hall Sensor with PSI5 Interface and a moveable permanent magnet is shown in **Figure 18**.

In a setup that uses a permanent magnet, the magnetic field has a temperature dependency due to the thermal reduction of the remanence. In order to determine the optimum sensitivity compensation behavior of the sensor to cancel this temperature dependency, the sensor's output value shall be measured at different temperatures, with the permanent magnet in a fixed position.

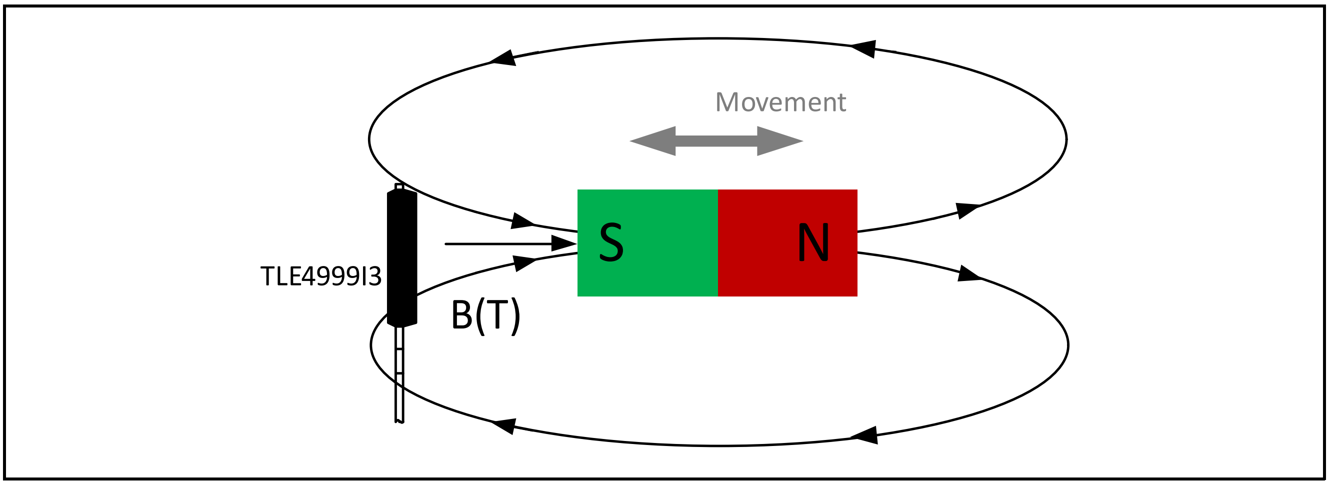

Figure 18 Example Position Sensing Application

The thermal reduction of the remanence depends mainly on the magnetic material used and has typically only minor variations from sample to sample.

Therefore a reference measurement on a (small) number of application samples is typically sufficient to determine a reference polynomial for the application in general and can be used for production.

It is typically not required to perform the described measurement over temperature for every individual sample.

With the described setup, the following procedure is used to obtain the coefficients of the application sensitivity polynomial:

- Measure the sensor output for at least three different temperatures at a defined, fixed magnet position. The magnetic flux densitiy at the sensor shall be non-zero at this given magnet position. It is recommended for best accuracy of the calibration procedure to use a magnet position that leads to the highest possible magnetic flux at the sensor, while still being inside the allowed magnetic flux operating range.
- For each data point, read the junction Temperature $T_J^{(i)}$, and the $OUT^{(i)}$ value via the programming interface.
- For each data point, calculate the compensation sensitivity value $S^{(i)}$ from the $OUT^{(i)}$ value and the output value at zero field OUT_0, using **Equation (3.3)**

$$S^{(i)} = \frac{OUT_0}{OUT^{(i)} - OUT_0} \tag{3.3}$$

- Plot $S^{(i)}$ as a function of $T_J^{(i)}$ and apply a quadratic fit ($cx^2 + bx + a$) which yields coefficients a, b and c (see **Figure 19**).

- Derive the coefficients of the application sensitivity polynomial from the parameters a, b, and c obtained from the quadratic fit using **Equation (3.4)** and **Equation (3.5)**.

$$TC_1 = \frac{b + 2 \cdot c \cdot T_0}{a + b \cdot T_0 + c \cdot T_0^2} \tag{3.4}$$

$$TC_2 = \frac{c}{a + b \cdot T_0 + c \cdot T_0^2} \tag{3.5}$$

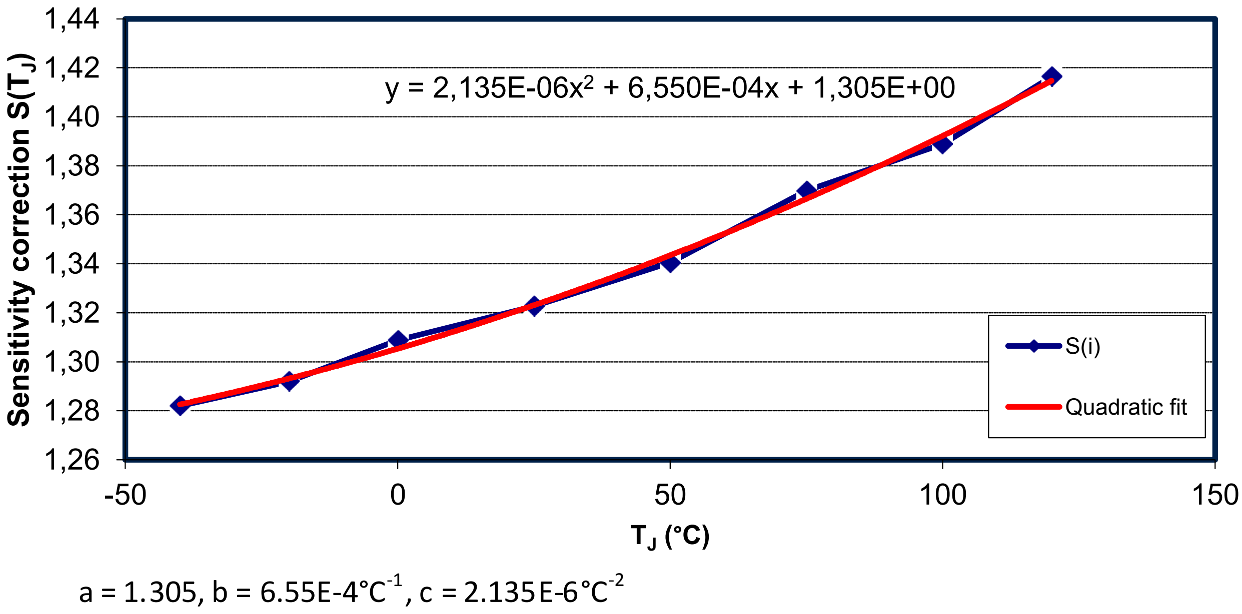

Figure 19 Example Polynomial Fit Procedure.

3.2 Output Calibration

In a position sensing application, the maximum and minimum magnetic field sensed by the Programmable Linear Hall Sensor with PSI5 Interface depends on the used permanent magnet and the movement range covered by the application. To achieve the maximum possible accuracy in such applications, it is recommended to adapt the output characteristic of the Programmable Linear Hall Sensor with PSI5 Interface to the application so the possible digital output range is matched to the magnetic input range that is available in the application.

3.2.1 Two-Point Calibration Procedure

Position sensor modules are typically subject to production variations in terms of magnet strength and magnet position, therefore it is recommended to do a two-point calibration of the Programmable Linear Hall Sensor with PSI5 Interface after assembly of each module to achieve the desired output characteristics independent of such production variations.

In order to configure an application specific output-characteristic, a two-point calibration procedure is used, where the IC-internal representations HCAL main, HCAL sub (compare **Figure 1**) of the Hall measurement values of main and sub channel is evaluated at two defined positions and the output zero point and gain are adjusted accordingly. This procedure is illustrated in **Figure 20**.

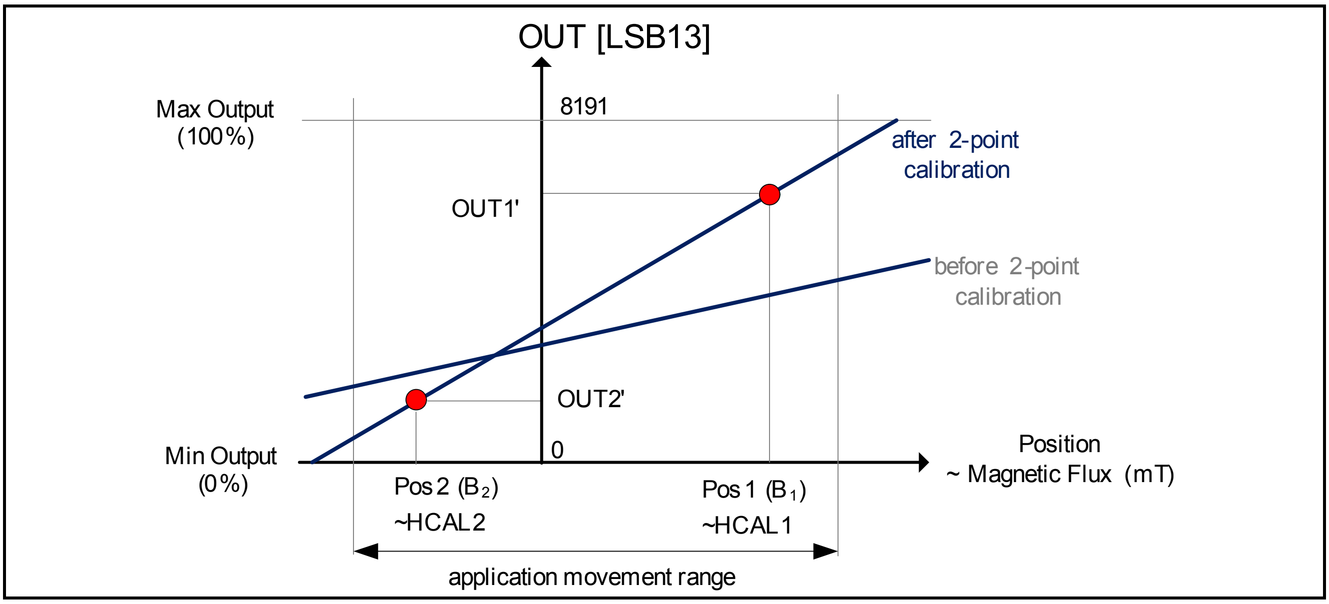

Figure 20 Schematic of Two-Point Calibration

The 13bit value OUT, which is transferred on the output protocol is calculated in the Programmable Linear Hall Sensor with PSI5 Interface with the configured zero point (Z) and gain (G) value according to **Equation (3.6)**.

$$OUT_{13bit} = \frac{G \cdot HCAL_{16bit}}{4096} + Z \tag{3.6}$$

Attention: Zero point (Z) is a 13 bit unsigned integer value ranging from 0 to 8191 and gain (G) is a 14 bit signed integer value ranging from -8192 to 8191. Both values are stored in the EEPROM.

For the two-point calibration, the following procedure is used for main and sub channel, separately:

1. Select two reference positions Pos1 and Pos2 for the moveable magnet in the application module. For maximum accuracy of the calibration routine it is recommended that the desired signal difference between these positions is at least half the full signal range.
2. Chose the desired output signals OUT1' and OUT2' which should correspond to positions Pos1 and Pos2 in the final configuration.
3. Fix the application module in position Pos1 and read the HCAL register via the programming interface. This values is HCAL1.
4. Fix the application module in position Pos2 and read the HCAL register via the programming interface. This value is HCAL2.
5. Calculate the according gain and offset parameters from the recorded HCAL1 and HCAL2 values and the desired OUT1' and OUT2' values using **Equation (3.7)** and **Equation (3.8)**.

$$G = 4096 \cdot \frac{OUT2' - OUT1'}{HCAL2 - HCAL1} \tag{3.7}$$

$$Z = OUT1' - \frac{G \cdot HCAL1}{4096} \tag{3.8}$$

6. Programm the gain (G) and zero point (Z) values into the sensor's EEPROM.

Attention: HCAL is a 16bit signed integer value ranging from -32768 to 32767. OUT is a 13bit unsigned integer value ranging from 0 to 8191.

Terminology

D	
DSP	Digital Signal Processing unit
E	
ECC	Error correction code to protect EEPROM content
EEPROM (abbrev. EEP)	Electrically erasable and programmable read only memory - programmable memory for sensor calibration and configuration data
G	
GND	Ground - ground line of sensor
L	
LSB	Least significant bit
M	
MSB	Most significant bis
MVS	Margin voltage selector
O	
OUT	Current modulator output pin of the sensor
P	
PSI5	Peripheral Sensor Interface 5
PDL	Peripheral Data Line - combined supply and data input/output line of a PSI5 sensor
PWM	Pulse-Width-Modulation
S	
SICI	Serial Inspection and Configuration Interface - Programming interface of the TLE4999I3

4 Revision History

Revision	Date	Changes
1.0	2018-07-24	Updated to new Infineon template.
Page 6		Added unit to **High time "1" bit to sensor**
Page 6		Added unit to **Low time "1" bit to sensor**
Page 6		Correct conditions at **Low time during sensor transmission**
Page 6		Corrected unit of **Capture time for response pulse from sensor**
Page 8		Corrected **Frame order for write commands**
Page 14		Corrected Gain **Quantization step**

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