Improved SENSE Calibration and Benefits Guide

About this document

Scope and purpose

This application note illustrates the achievable current sense accuracy of Infineon's high-side power switch family Power PROFET. It provides details to the current sense "default" accuracy explaining relevant fundamentals and explains thee effects on quantitative examples. The application note illustrates possible measures to improve system accuracy by means of calibration including recommendations regarding software implementation.

Intended audience

This application note is targeted for all design engineers, which need to understand and possibly further improve the system accuracy performance of the Power PROFET current sense functionality.

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1 Abstract

Smart, high-side power switches from Infineon® are designed to control all types of resistive, inductive, and capacitive loads. These devices provide protection and diagnostic functions and are specially designed to drive loads in harsh automotive environments.

The diagnostic feature analog current sense is often used to diagnose, control and protect the load as well as to protect and diagnose the overall system including wire harness. Ideally the analog current sense diagnostic should reflect the load current without any additional error contribution. However in reality analog current sense diagnostics does always have an inherent inaccuracy associated.

Infineon offers multiple high-side power switches families with different accuracy performance. For specific high-side power switches additional calibration techniques are supported, which achieve increased levels of accuracy compared to the specified, “default” overall sense performance.

This application note explains the calibration techniques for the high-side power switch family Power PROFET. The application note first introduces some fundamental concepts. It explains the dominating sources of inaccuracy, their observed behavior and how to reduce these by means of calibration. Beside the fundamental explanation quantitive examples are given for the Power PROFET BTS50015-1TAD. The application note also details the sense performance constraints which remain after calibration.

Note: The following information is given as an implementation suggestion only, and shall not be regarded as a description or warranty of a certain functionality, condition, or quality of any device.

2 Introduction

Current sensing is implemented within high-side switches to diagnose systems and to protect them in the event of failures. High-side current sensing is used to protect both the load and the wiring harness, to diagnose the load so as to ensure proper operation, and to measure the output current for the purpose of controlling the output power.

Note: Further generic information on high-side switches with diagnostics and protection can be found in the Application Note: [What the designer should know: Short introduction to PROFET™ +12V].

There are two main dominating effects with conventional high-side current sensing solutions which have an impact on the overall accuracy performance. The first is the inaccuracy which is resulting from an internal amplifier offset voltage. This offset voltage deteriorates the current sense accuracy especially at lower load currents. In addition it suppresses the current sense functionality below certain load current thresholds. The second is the slope (steepness) inaccuracy, which becomes more significant at higher load currents.

The overall current sense performance specified in the Power PROFET datasheet has to cover all possible combinations of both, offset voltage and slope (steepness) inaccuracy including their variation over production, life time and specified operating conditions. Whenever the overall specified sense performance does not meet the accuracy specified, additional calibration techniques can be introduced. In case of Power PROFET the supported option to further improve sense accuracy is to perform either a 1-point or preferably a 2-point calibration utilizing end-of-line measurement and low application software overhead.

2.1 Pin Names and Functions

Single-channel, high-side power switches of the general type considered in this paper have five pins (GND, IN, OUT, IS, and VS) as illustrated in Figure 1.

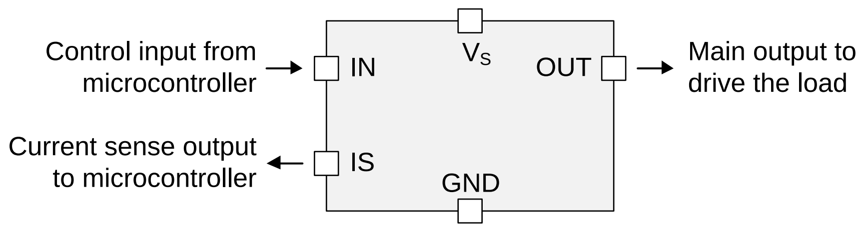

Figure 1 Pin names

The functions of these pins are detailed in Table 1.

Table 1 Pin functions

Pin Name	Pin Function
GND	**Ground:** Ground connection
IN	**Input:** Digital 3.3V and 5V compatible logic input; activates the power switch if set to HIGH level (definitions for HIGH and LOW can be found in the parameter tables of the

	respective device datasheet) Please Note that PowerPROFET 500xx-1TAD & TMD family offers a VS capable Input pin which supports in addition control with Voltages above 5V up to VS
OUT	**Output:** Protected high-side power output
I_S	**Sense:** Analog sense current signal
V_S	**Supply Voltage:** Positive supply voltage for both the logic and power stages

2.2 Voltages and Currents

Figure 2 illustrates the voltages and currents referenced in this application note. The load current I_L and the sense current I_{IS} will be the focus of the following discussions.

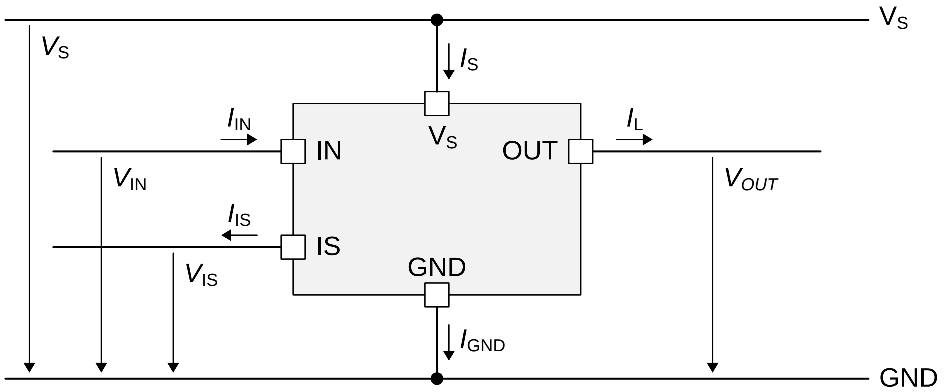

Figure 2 Definition of currents and voltages

These abbreviations are defined in Table 2.

Table 2 Voltage and current abbreviations

Abbreviation	Meaning
V_S	Supply voltage
GND	Ground
V_{IN}	Control input voltage
V_{OUT}	Output voltage driving the load

V_{IS}	Sense voltage
I_L	Load current
I_{IS}	Sense current
I_S	Supply current
I_{GND}	Ground current

2.3 Flowchart Nomenclature

With regard to flowcharts used in this application note, the representation of the five main symbols is illustrated in Figure 3.

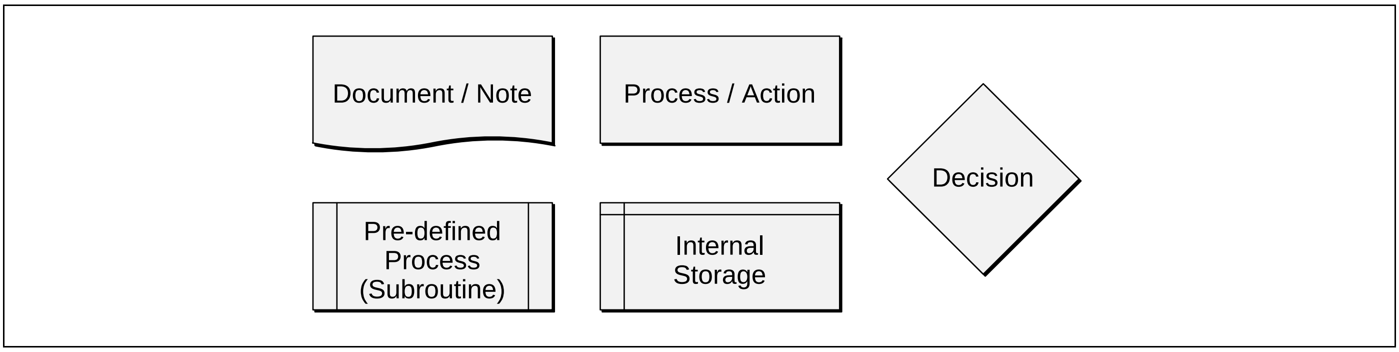

Figure 3 Flowchart nomenclature

2.4 Example Circuit Board Scenario

For the purposes of this application note, it is assumed that a circuit board containing a microcontroller and some number of single-channel, high-side power switches as illustrated in Figure 4.

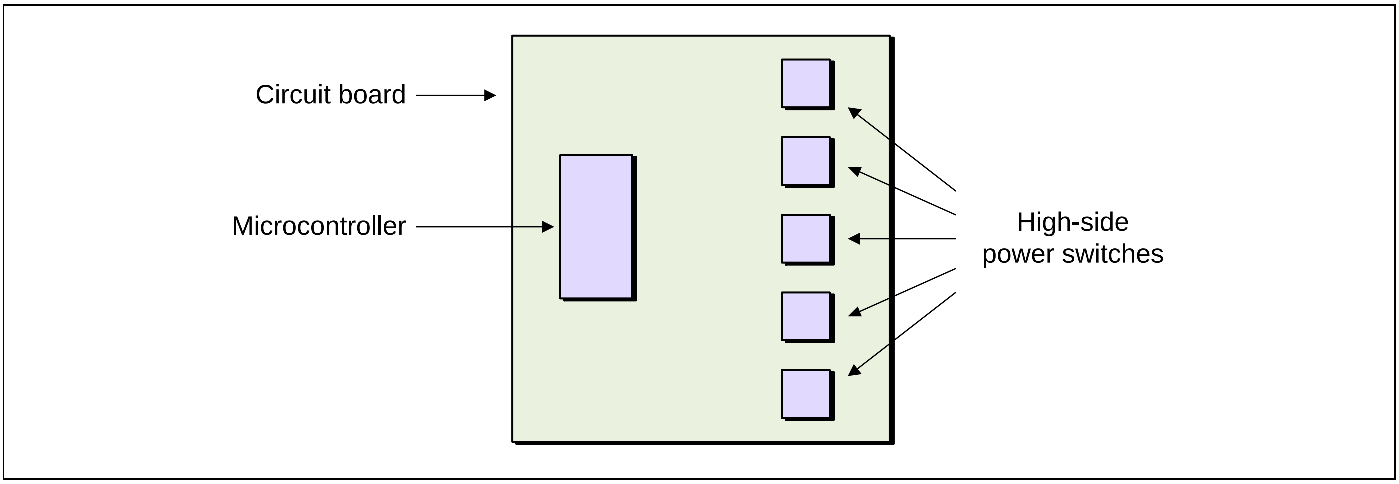

Figure 4 Example circuit board scenario

The microcontroller is used to turn the high-side power switches ON and OFF, and also to measure the value of the sense current (I_{IS}) outputs from the switches.

2.5 Fundamental Concepts

In order to understand the problems associated with conventional current sense functionality as also implemented in Power PROFET, it is first necessary to be familiar with some fundamentals.

The effects which dominate the resulting current sense performance as well as the measures to improve the overall current sense accuracy can be explained in the following simplified manner utilizing a straight line in "slope-intercept" form.

The general formula for a straight line in "slope-intercept" form, is presented in Equation (1).

Equation (1) $$y = m \times x + b$$

In this case, y is the value on the vertical axis (Y), x is the value on the horizontal axis (X), m is the slope of the line, and b – which is known as the y-intercept – is the point at which the line intersects the Y-axis. For the purposes of this application note, both, positive and negative y-intercept values need to be discussed as illustrated in Figure 5.

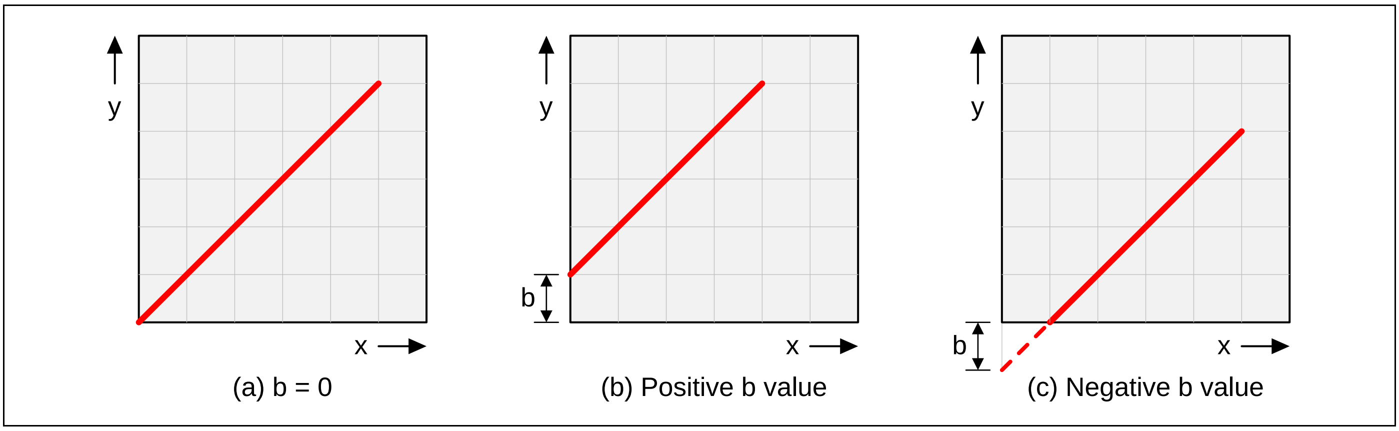

Figure 5 Generic lines with identical positive slopes

All three lines in Figure 5 have the same m (slope) value. The difference between the lines is the b (y-intercept) value. The line in Figure 5(a) has a b value of zero; the line in Figure 5(b) has a positive value for b; and the line in Figure 5(c) has a negative value for b.

Let's take now a look to the high-level block diagram and the specified diagnosis performance for a conventional high-side power switch as illustrated in Figure 6.

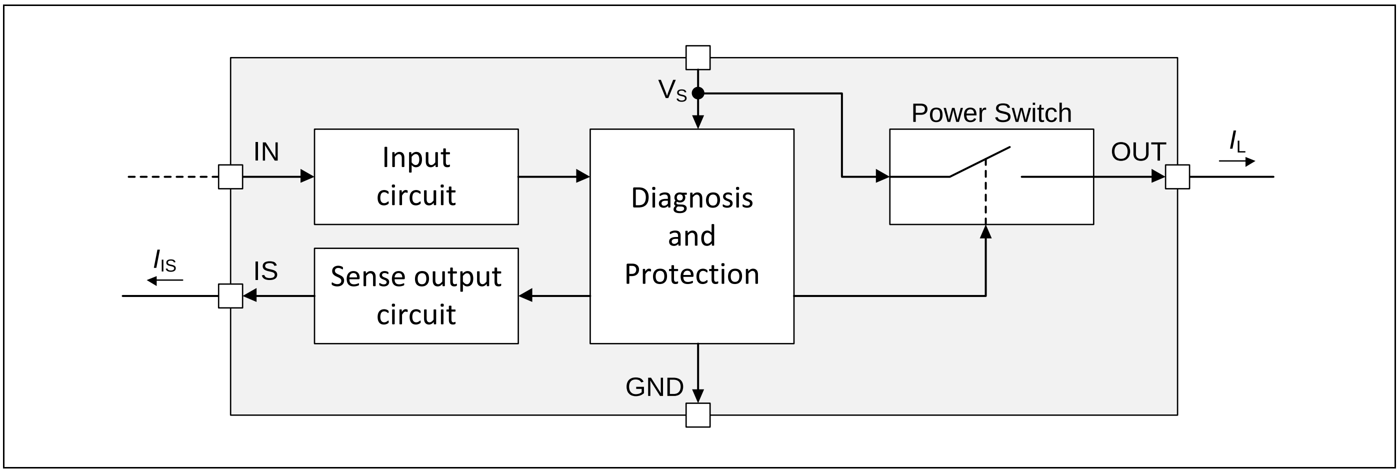

Figure 6 High-level block diagram for a conventional high-side power switch

The ideal relationship between the sense current I_{IS} and the load current I_L is shown in Figure 7(a). Ideally the sense current should show a replica of the load current across a load current range. Ideally the sense current should always be a fixed ratio (or portion) of the load current.

In reality, however, there may be errors involved. These errors will be a slope (steepness) error as illustrated in Figure 7(b). The slope error is mainly dependent on part-to-part production variation. The effects of slope error are more pronounced at higher load currents.

In addition there may also be a sense offset error. Resulting from an internal amplifier offset voltage. The sense offset error is strongly dependent on production variation and the operating temperature of the device. The effects of the offset are more pronounced at lower load currents.

The sense offset error for a Power PROFET may be both, positive and negative. Positive offset errors will result in a remaining current at the IS pin, even though no load current is flowing. Negative offset error will "disabled" the sense functionality below a certain load current threshold, which would cause a theoretical negative sense current. Load currents at this threshold or below will result in no sense current at the IS pin as illustrated by the horizontal portion of the solid green line in Figure 7(c).

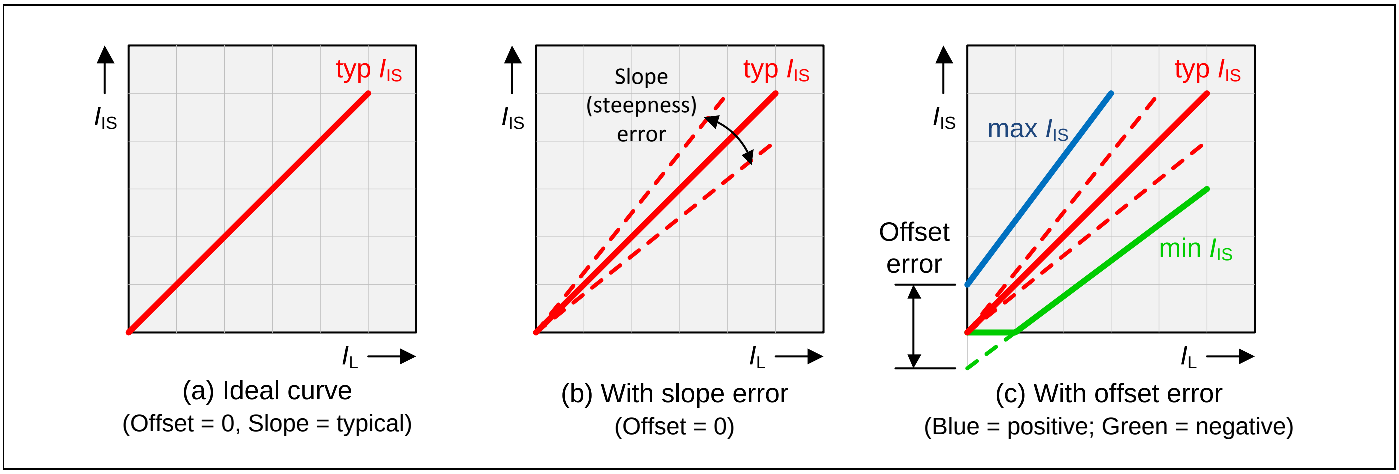

Figure 7 Relationship between I_{IS} and I_L in conventional devices

Figure 8 shows the enhanced illustration of Figure 5 considering both, offset error and slope error. The offset error varies between a negative and positive offset b_{MIN} and b_{MAX}. The slope error will decrease/increase the typical slope m towards a minimum slope m_{MIN} and a maximum slope m_{MAX}.

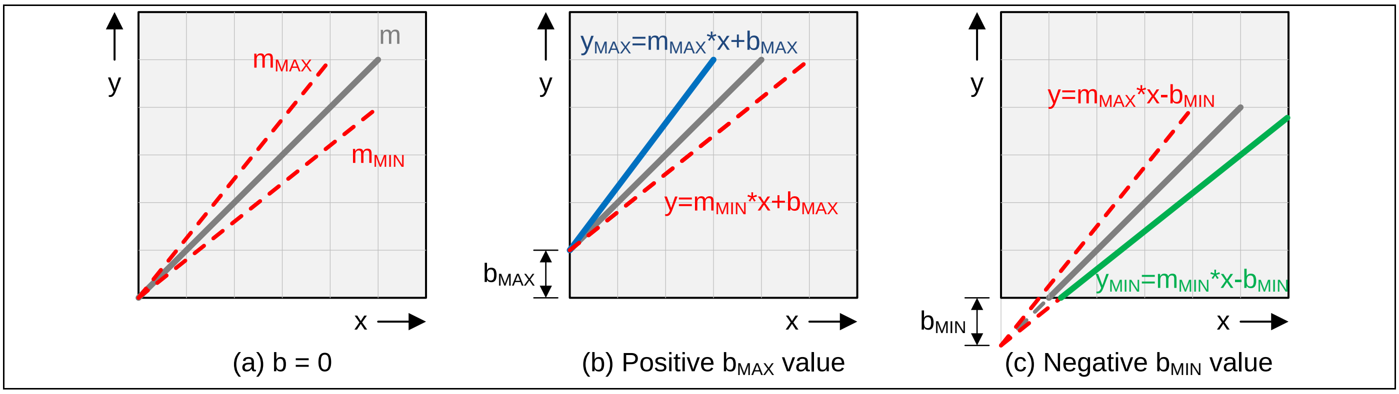

Figure 8 Generic lines with varying positive slopes

3 "Default" current sense performance

For a Power PROFET the relationship between the sense current I_{IS} and the load current I_L is expressed using Equation (2).

Equation (2) $$I_{IS} = \left(\frac{1}{dk_{ILIS}} \times I_L\right) + I_{IS0}$$

Comparing Equation (2) and Equation (1) it can be seen, that

- The sense current I_{IS} in Equation (2) corresponds to y in Equation (1)
- the load current I_L in Equation (2) corresponds to x in Equation (1)
- the slope defined by $1/dk_{ILIS}$ in Equation (2) corresponds to m in Equation (1). If dk_{ILIS} varies between a maximum limit and a minimum limit,
  - the maximum limit of $dk_{ILIS(MAX)}$ will result in a minimum slope steepness m_{MIN} and
  - the minimum limit of $dk_{ILIS(MIN)}$ will result in a maximum slope steepness m_{MAX}.
- the sense offset current I_{IS0} in Equation (2) corresponds to the y-intercept b in Equation (1).
  - A maximum limit of $I_{IS0(MAX)}$ represents a positive y-intercept b_{MAX}
  - A minimum limit of $I_{IS0(MIN)}$ represents a negative y-intercept b_{MIN}.

The "electrical characterstics" datasheet section "Diagnostic Function: Current Sense Ratio Signal in the Nominal Area, Stable Current Load Condition" outlines the "default" diagnosis performance of every Power PROFET device.

All shipped Power PROFET devices will show a sense performance within

- the specified MIN-MAX-range of the slope defined by $1/dk_{ILIS}$. The slope (steepness) error varies therefore from a minimum slope $m_{MIN}=1/dk_{ILIS(MAX)}$ to a maximum slope $m_{MAX}=1/dk_{ILIS(MIN)}$
- the specified MIN-MAX-range of the calculated sense offset current I_{IS0}. The calculated sense offset error at zero load current varies therefore between the limits of $I_{IS0(MIN)}$ and $I_{IS0(MAX)}$
- the specified minimum and maximum sense currents I_{IS1}, I_{IS2}, I_{IS3} and I_{IS4} for given load currents I_{IL1}, I_{IL2}, I_{IL3} and I_{IL4}.

Note: Due to the nature of the sense circuitry the calculated sense offset current I_{IS0} may vary for a given device over temperature ($I_{IS0}=f(T_J)$). All devices with a negative calculated sense offset current ($I_{IS0}<0$) will only provide a current at the IS pin, whenever the load current I_L exceeds a threshold I_{L0}, where the resulting sense current is larger than the sense offset ($I_L>I_{L0}=-(dk_{ILIS(MAX)}$ x $-I_{IS0}$).

Note: Since the calculated sense offset current I_{IS0} may vary for a given device over temperature ($I_{IS0}=f(T_J)$) the load current threshold I_{L0} may vary over temperature also ($I_{L0}=f(T_J)$).

Figure 9 shows the current sense transfer function of the Power PROFET BTS50015-1TAD.

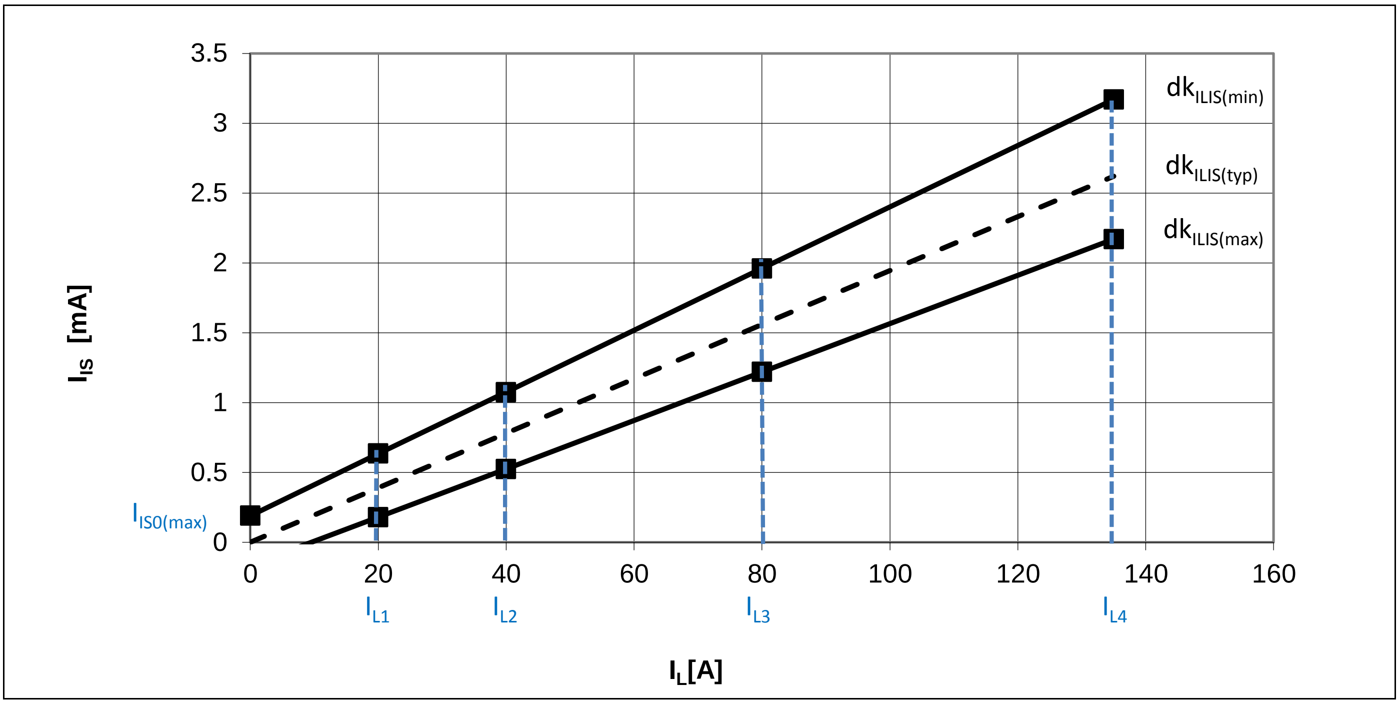

Figure 9 Power PROFET BTS50015-1TAD current sense

Comparing Figure 9 with Figure 8 it can be seen that the current sense performance of this specific Power PROFET varies in a range which is limited by

- an upper line resulting from a device which has a combination of maximum positive calculated sense offset current $I_{IS0(MAX)}$ and maximum $1/dk_{ILIS}$ slope (or vice versa a minimum $dk_{ILIS(MIN)}$). This line can be represented by the general formula $y_{MAX}=m_{MAX}*x+b_{MAX}$. Applying Power PROFET parameters the formula changes to $I_{IS(MAX)}=1/\ dk_{ILIS(MIN)}*\ I_L + I_{IS0(MAX)}$
- a lower line resulting from a device which has a combination of maximum negative calculated internal sense offset current $I_{IS0(MIN)}$ and minimum $1/dk_{ILIS}$ slope (or vice versa a maximum $dk_{ILIS(MAX)}$). This line can be represented by the general formula $y_{MIN}=m_{MIN}*x-b_{MIN.}$. Applying Power PROFET parameters the formula changes to $I_{IS(MIN)}=1/\ dk_{ILIS(MAX)}*\ I_L + I_{IS0(MIN)}$ (with $I_{IS0(MIN)}$ being negative).

Note: Connecting the points of the maximum sense current limits for given load currents ([I_{ISi};I_{ILi}] with i=1..4) will form the upper limiting line (blue line according Figure 7 and Figure 8). Connecting the points of the minimum sense current limits ([I_{ISi};I_{ILi}] with i=1..4) will form the lower limiting line (green line according Figure 7 and Figure 8).

Note: Any negative offset error I_{IS0} will not result in sense current that is sinked by the IS pin. The IS pin can only source a sense current. Any negative offset error will disable the load current sense function once the load current is less than a certain threshold.

The variation of this "default" current sense performance brings some limitations in terms of measurable load current range and accuracy.

3.1 Measureable load current range

In general the measurable load current range is limited towards a lower load current threshold and towards an upper load current threshold.

- The lower load current threshold results from the limiting lower line ($y_{MIN}=m_{MIN}*x-b_{MIN}$) where the line intercepts the x-Axis. In order to guarantee any variation in x will result in a variation of y, a lower threshold of $x>-(-b_{MIN}/m_{MIN})$ needs to be exceeded.
- Applying Power PROFET parameters the formula changes to the lower load current threshold $I_L > I_{L0}=-(I_{IS0(MIN)}*dk_{ILIS(MAX)})$ (with $I_{IS0(MIN)}$ being negative).

Note: Looking at Figure 9 bottom solid $d_{ILIS(MAX)}$ line it can also be seen, that for the example of a Power PROFET BTS50015-1TAD only load currents of I_{L0}>~9A will result in a sense current at the IS pin.

- The upper load current threshold results from the limiting upper line ($y_{MAX}=m_{MAX}*x+b_{MAX}$) which can be reliably provided to peripheral readout ciruit.
- For Power PROFET in general the upper load current threshold is the specified maximum load current I_{L4}. Load currents above I_{L4} may already trigger the activation of protection mechanisms or the resulting maximum sense current $I_{IS4(MAX)}$ may start to saturate.

Note: Looking at Figure 9 it can be seen that for the example of a Power PROFET BTS50015-1TAD only load currents up to I_{L4}=135A are specified. Checking BTS50015-1TAD datasheet limits of the "Current Trip Detection Level" (P_6.1.35) and and "Sense Signal Saturation Current" (P_6.1.75) will show, that at higher load currents the device may already switch off from over current or that the sense current may already saturate.

3.2 "Default" current sense accuracy

The "default" accuracy depends on the load current.

For the "default" accuracy is of general interest, in which error limits the x value may vary, assuming a certain y value is read and processed.

Figure 10 illustrates the x_i error for a given y_i value

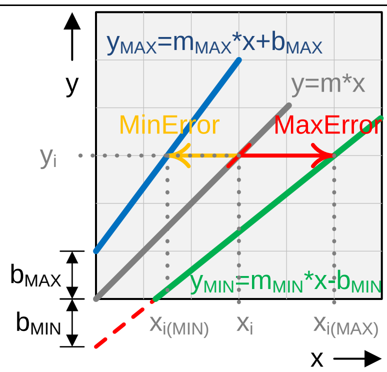

Figure 10 X-Axis error for generic lines with varying positive slopes

The general absolute error for any x_i value will range between a minimum value $x_{i(MIN)}$ and a maximum $x_{i(MAX)}$.

The minimum error results from the limiting upper line ($y_{MAX}=f(x)=m_{MAX}*x+b_{MAX}$) in relation to the typical line ($y=f(x)=m*x$).

The maxmum error results from the limiting lower line ($y_{MIN}=f(x)=m_{MIN}*x-b_{MIN}$) in relation to the typical line ($y=f(x)=m*x$).

"Default" current sense performance

In general the absolute minimum x- error-value can be calculated from solving the equation (x=f(y_{MAX}))-(x=f(y)).

The absolute minimum x- error-value (MinError=$x_{i(MIN)}$- x_i) can be calculated according Equation (3)

Equation (3) $$\text{MinAbsError} = \frac{x\times(m-m_{MAX})-b_{MAX}}{m_{MAX}}$$

The relative minimum x-error (MinRelError=($x_{i(MIN)}$- x_i)/x_i) can be calculated according Equation (4)

Equation (4) $$\text{MinRelError} = \frac{m\times x-b_{MAX}}{m_{MAX}\times x} - 1 = \frac{m}{m_{MAX}} - \frac{b_{MAX}}{m_{MAX}\times x} - 1$$

The absolute maximum x- error-value (MaxError=$x_{i(MAX)}$- x_i) can be calculated according Equation (5)

Equation (5) $$\text{MaxAbsError} = \frac{x\times(m-m_{MIN})+b_{MIN}}{m_{MIN}}$$ with b_{MIN} being an absolute number.

The relative maximum x-error (MaxRelError=($x_{i(MAX)}$- x_i)/x_i) can be calculated according Equation (6)

Equation (6) $$\text{MaxRelError} = \frac{m\times x+b_{MIN}}{m_{MIN}\times x} - 1 = \frac{m}{m_{MIN}} + \frac{b_{MIN}}{m_{MIN}\times x} - 1$$ with b_{MIN} being an absolute number

Applying Power PROFET parameters to Equation (3) to Equation (6) results in Equation (7) to Equation (10).

Equation (7) $$\text{MinAbsError} = \left(I_L \times \left(\frac{1}{dK_{ILIS(TYP)}} - \frac{1}{dK_{ILIS(MIN)}}\right) - \frac{I_{IS0(MAX)}}{10^6}\right) \times dK_{ILIS(MIN)}$$
with $I_{IS0(MAX)}$ as µA value

Equation (8) $$\text{MinRelError} = \frac{dK_{ILIS(MIN)}}{dK_{ILIS(TYP)}} - \frac{I_{IS0(MAX)}\times dK_{ILIS(MIN)}}{I_L\times 10^6} - 1$$

Equation (9) $$\text{MaxAbsError} = \left(I_L \times \left(\frac{1}{dK_{ILIS(TYP)}} - \frac{1}{dK_{ILIS(MAX)}}\right) - \frac{I_{IS0(MIN)}}{10^6}\right) \times dK_{ILIS(MAX)}$$
with $I_{IS0(MIN)}$ as µA value being negative

Equation (10) $$\text{MaxRelError} = \frac{dK_{ILIS(MAX)}}{dK_{ILIS(TYP)}} - \frac{I_{IS0(MIN)}\times dK_{ILIS(MAX)}}{I_L\times 10^6} - 1$$ with $I_{IS0(MIN)}$ as µA value being negative

Table 3 shows the calculated absolute and relative errors for certain load currents for the example of BTS50015-1TAD. These values can alternatively also be graphically derived from Figure 9, estimating the load current difference for any, fixed sense current between the typical, dashed line in comparison to the limiting upper and lower solid line.

"Default" current sense performance

Table 3

I_{Load}	minimum absolute I_{Load} error	minimum relative I_{Load} error	Maximum absolute I_{Load} error	maximum relative I_{Load} error
10A	-10A	-98%	+11A	+107%
20A	-11A	-55%	+12A	+60%
40A	-13A	-34%	+14A	+36%
60A	-16A	-26%	+17A	+28%
80A	-18A	-23%	+19A	+24%
100A	-21A	-21%	+22A	+22%

In terms of accuracy it can be seen, that the "default" accuracy reaches at nominal current just ~35..40%. This accuracy deteriorates further towards lower load current. At high load a "default" accuracy of about 22% can be achieved.

Note: The above example outlines approximated values to show the general accuracy trend. For full system performance additional contributors like board leakage currents, variation of sense resistor RIS, error contribution of uC for analog digital conversion etc. need to be considered.

4 Calibration Techniques

Whenever the “default” sense performance does not meet the system accuracy targets, additional calibration techniques can be introduced.

4.1 Variation effects

During the development of Power PROFET Infineon performed intense stress and characterization efforts to understand the overall sense performance after calibration. The investigations revealed the following findings:

- the $1/dk_{ILIS(i)}$ slope of any calibrated Power Profet varies after calibration for each individual Power PROFET (i) over temperature and stress within certain limits. These limits vary depending on the Power PROFET product type / respective family member. The maximum variation per calibrated Power PROFET product type will remain within the limits of the Parameter $\Delta(d_{KILIS(CAL)})$ (see datasheet parameter P_6.1.47).
- devices, which show after calibration an individual $dk_{ILIS(i)}$ value, which is close to the absolute limits of the Current Sense Differential Ratio d_{KILIS} (Parameter 6.4.41), will not violate these limits over temperature and stress
- The calculated sense offset current $I_{IS0(i)}$ of any calibrated Power Profet varies after calibration for each individual Power PROFET (i) over temperature and stress within certain limits. These limits vary depending on the Power PROFET product type / respective family member. The maximum variation per Power PROFET product type will remain within the specified temperature dependant calculated sense offset current limits (see datasheet limits of Parameter P_6.1.42).
- devices, which show after calibration an individual calculated sense offset current $I_{IS0(i)}$ which is close to the absolute limits of the calculated sense offset current I_{IS0} (Parameter 6.4.42), will not violate these limits over temperature and stress

Based on the example of Power PROFET BTS50015-1TAD this means:

- According to datasheet parameter P_6.1.47 the individual $1/dk_{ILIS(i)}$ slope of any calibrated BTS50015-1TAD varies after calibration for each individual BTS50015-1TAD (i) over temperature and stress a maximum of +/-5%.
  To give an example, assuming an individual $dk_{ILIS(i)}$=50000 (or vice versa $1/dk_{ILIS(i)}$=2E-5) has been derived by means of calibration at T_j=25°C, the device specific $dk_{ILIS(i)}$ will maximum vary over life time and temperature (-40°C<=T_j<=+150°C) between
  47500<=dk_{ILIS}<=52500 (or vice versa 2.105E-5>=$1/dk_{ILIS}$>=1.9E-5).
- BTS50015-1TAD (i), which have an individual $dk_{ILIS(i)}$ value close to the minimum limit of parameter 6.1.41 of 45300, will not violate this limit over temperature and stress. BTS50015-1TAD (i), which have an individual $dk_{ILIS(i)}$ value close to the maximum limit of parameter 6.1.41 of 57700, will not violate this limit over temperature and stress.
- In case a calibrated BTS50015-1TAD (i) shows a positive calculated current sense offset, $I_{IS0(cal)}$>0, then this individual sense offset will vary over temperature and stress towards the differences between the room temperature maximum limit and the respective maximum limits at “cold” (T_j=-40°C) and “hot” (T_j=+150°C).
  To give an example, assuming an individual positive calculated current sense offset, $I_{IS0(cal)}$=50µA, has been derived by means of calibration at T_j=25°C, the device specific $\Delta I_{IS0(cal)}$ will vary over life time and temperature (-40°C<=T_j<=+150°C) between the MAX datasheet limits of I_{IS0}.
  This results in a
  lower difference of $I_{IS0(MAX)}(@T_J=150°C)-I_{IS0(MAX)}(@T_J=25°C)$=60µA-125µA=-65µA and an

upper difference of $I_{IS0(MAX)}$ (@T_J=-40°C)−$I_{IS0(MAX)}$(@T_J=25°C)=190µA-125µA=+65µA.
So the individual calculated current sense offset will vary over life time and temperature from typically 50µA down towards -15µA (50µA-65µA) and up to +115µA (50µA+65µA).

- In case a calibrated BTS50015-1TAD (i) shows a negative calculated current sense offset, $I_{IS0(cal)}$<0, then this individual sense offset will vary over temperature and stress towards the differences between the room temperature minimum limit and the respective minimum limits at "cold" (T_j=-40°C) and "hot" (T_j=+150°C)..
  To give an example, assuming an individual negative calculated current sense offset, $I_{IS0(cal)}$=-100µA, has been derived by means of calibration at T_j=25°C, the device specific $\Delta I_{IS0(cal)}$ will vary over life time and temperature (-40°C<=T_j<=+150°C) between the MIN datasheet limits of I_{IS0}.
  This results in an
  upper difference of $I_{IS0(MIN)}$(@T_J=150°C)−$I_{IS0(MIN)}$(@T_J=25°C)=-65µA-(-115µA)=+50µA and a
  lower difference of $I_{IS0(MIN)}$(@T_J=-40°C)−$I_{IS0(MIN)}$(@T_J=25°C)=-165µA-(-115µA)=-50µA.
  So the individual calculated current sense offset will vary over life time and temperature from typically -100µA down towards -150µA (100µA-50µA) and up to -50µA (-100µA+50µA).

4.2 1-point calibration

One option to improve the current sense performance is to perform a 1-point calibration. The idea of 1-point calibration is to perform a manufacturing test that measures the sense current $I_{IS(x1)}$ at a defined load current $I_{L(x1)}$, where ideally $I_{L(x1)}$ is in the load current range where the highest accuracy needs to be achieved. Usually this manufacturing test is performed at an ambient temperature of 25°C. The measured values will be stored in the microcontroller's non-volatile memory to be used by the application software.

To state it upfront, although the 1-point calibration offers the lowest measurement effort during manufacturing of all possible calibration options, the accuracy improvements of a 1-point calibration remain in the special case of Power PROFET moderate. This results from the circumstance, that the device specific slope and offset remains unknown. Therefore certain assumptions have to be made which will under worst case conditions contribute to a remaining error. Nevertheless 1-point calibration achieves an improved current sense function compared to "default" sense accuracy. In case of Power PROFET, it specifically helps to reduce the offset error as it will be shown in the later BTS50015-1TAD example.

The fundamental aspects of the 1-point calibration will be explained in the remaining portion of this section. However, if a significant accuracy improvement is required, the 2-poin calibration should be applied (and the reader should directly jump to the next chapter).

In general mathematical terms 1-point calibration means, that first the point x1,y1 needs to be identified. As stated in chapter 3.1, x needs to be chosen in a way that x>-(-b_{MIN}/m_{MIN}) will be fulfilled. Since the slope m can not be derived from 1-point calibration and hence remains unknown, it has to be assumed that the slope m will be typical m_{TYP}. The resulting y-intercept can then be calculated by changing Equation (1) to Equation (11)

Equation (11) $\mathrm{b} = \mathrm{y} - \mathrm{m_{TYP}x}$

Although calculated, b remains in the end an estimated value only. With the assumed values of slope m=m_{TYP} and offset b (y-intercept) these values can be substituted into the generic equation for a line as defined in Equation (1), and then this equation can be used to determine the (x, y) values of any other point on the line.

To derive the achievable accuracy of 1-point calibtarion the following aspects have to be considered. Since the typical assumed slope m can vary between certain limits, m_{MIN1} and m_{MAX1}, two extreme y intercepts, b_1 and b_2, need to be derived for the accuracy investigation. Assuming, that the possible, individual slopes m_{MIN1} and m_{MAX1} will further vary over lifetime stress and temperaure, m_{MIN1} between a lower slope m_{MIN12} and an upper slope m_{MIN11}, and m_{MAX1} between a lower slope m_{MAX12} and an upper slope m_{MAX11}, certain error ranges already appear in case the extreme y-intercepts b_1 and b_2 would remain constant. Assuming that in addition the y-Intercepts b_1

and b_2 will additionally vary within certain limits over lifetimes stress and temperature , b_1 between a lower offset b_1-Δb_1 and upper offset $b_1+\Delta b_1$, and b_2 between a lower offset b_2-Δb_2 and upper offset $b_2+\Delta b_2$, these error ranges further increase defining the limiting conditions for the final achievable accuracy of 1-point calibration.

Figure 11 illustrates these effects.

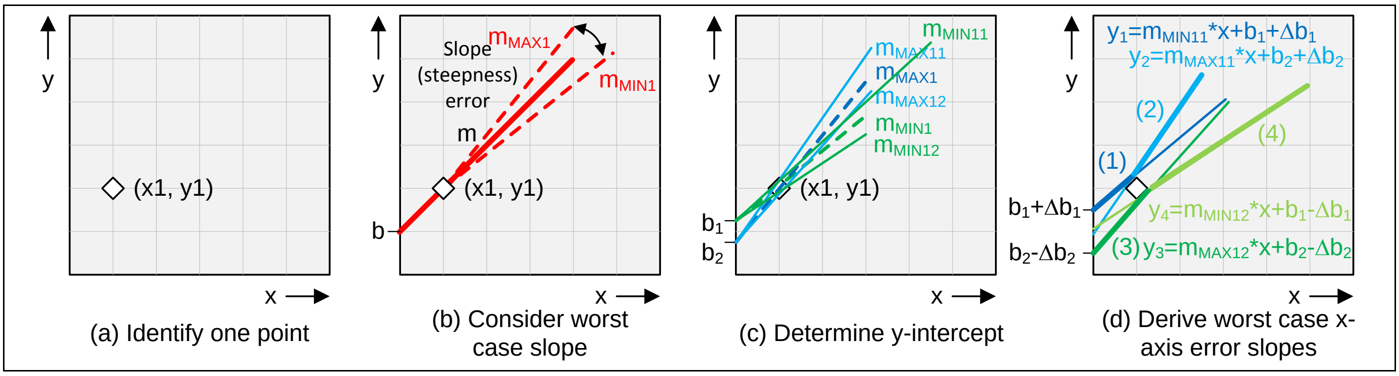

Figure 11 X-Axis error for generic lines with varying positive slopes and offsets

As it can be seen Figure 11 (d), the x_i error for a given y_i value will be determined by the four limiting functions

- $y_1=f(x)=m_{MIN11}*x+b_1+\Delta b_1$
- $y_2=f(x)=m_{MAX11}*x+b_2+\Delta b_2$
- $y_3=f(x)=m_{MAX12}*x+b_2-\Delta b_2$ and
- $y_4=f(x)=m_{MIN12}*x+b_1+\Delta b_1$.
- The typical function, assuming a typical slope m_{TYP} will follow the formula $y=m_{TYP}*x+b$.

For low x and low y values the error of the typical function $y=m_{TYP}*x+b$ will vary towards a lower error. This error can be calculated solving the equation MinAbsError=(x=f(y_1))-(x=f(y)). The error will also vary towards an upper error. This error can be calculated solving the equation MaxAbsError=(x=f(y_3))-(x=f(y)).

Whenever formula $y_4=f(x)$ results in a lower y value for a certain x value compared to $y_3=f(x)$, the maximum error will vary to an upper error, which can be calculated solving the equation MaxAbsError=(x=f(y_4))-(x=f(y)).

For high x value and high y values / whenever formula $y_2=f(x)$ results in a higher y value for a certain x value compared to $y_1=f(x)$, the lower error can be calculated solving the equation MinAbsError=(x=f(y_2))-(x=f(y)).

The absolute minimum x- error-value (MinAbsError=$x_{i(MIN)}$- x_i) can be calculated according Equation (12) and Equation (13).

Equation (12) $\mathrm{MinAbsError}_{CASE(1)} = \frac{m_{TYP}x \times + b - b_1 - \Delta b_1}{m_{MIN11}} - x$ with Δb_1 being an absolute number

Equation (13) $\mathrm{MinAbsError}_{CASE(2)} = \frac{m_{TYP}x \times + b - b_2 - \Delta b_2}{m_{MAX11}} - x$ with Δb_2 being an absolute number

The absolute maximum x- error-value (MaxAbsError=$x_{i(MAX)}$- x_i) can be calculated according Equation (14) and Equation (15).

Equation (14) $$\text{MaxAbsError}_{CASE(3)} = \frac{m_{TYP}x \times + b - b_2 + \Delta b_2}{m_{MAX12}} - x$$ with Δb_2 being an absolute number

Equation (15) $$\text{MaxAbsError}_{CASE(4)} = \frac{m_{TYP}x \times + b - b_1 + \Delta b_1}{m_{MIN12}} - x$$ with Δb_1 being an absolute number

In addition it has to be considered, that there are enveloping conditions which will never be exceeded. In reference to Figure 10 positive values resulting from y_1=f(x) and y_2=f(x) will never exceed y_{MAX}=f(x)=m_{MAX}*x+b_{MAX}. So whenever y_1=f(x) and y_2=f(x) would cause a higher y-value for a given-x value, y will be limited to y_{MAX}=m_{MAX}*x+b_{MAX}.

In reference to Figure 10 negative values resulting from y_3=f(x) or y_4=f(x) will never "exceed" y_{MIN}=f(x)=m_{MIN}*x+b_{MIN}. (with b_{MIN} being negative). So whenever y_3=f(x) or y_4=f(x) would cause a lower y-value for a given-x value, y will be limited to y_{MIN}=m_{MIN}*x+b_{MIN}.

These beneficial circumstances and high m_{MAX} and b_{MAX} as well as low m_{MIN} and b_{MIN} values will however have no effect on the maximum achievable accuracy since the overall accuracy will be defined by possible devices that will neither violate y_{MAX}=f(x)=m_{MAX}*x+b_{MAX} nor y_{MIN}=f(x)=m_{MIN}*x+b_{MIN}.

To show the possible accuracy improvement another BTS50015-1TAD example is outlined. Although the example is based on a very specific sense current measurement, the resulting load current errors are valid also for other sense current measurements as long as the load current $I_{L(cal)}$, the $\Delta I_{IS0(cal)}$ and $\Delta(dk_{KILIS(cal)})$ values remain.

Assuming an individual sense current of a BTS50015-1TAD was measured at T_j=25°C and I_L=20A and showed a value of I_{IS}=0.5mA. Considering that according to the datasheet

- the current sense differential ratio dk_{ILIS} (Parameter P_6.1.41) varies in a range of MIN 45300, TYP51500 and MAX57700
- the current sense ratio spread of $\Delta(dk_{KILIS(CAL)})$ varies between MIN-5% and MAX+5% and that
- $\Delta I_{IS0(CAL)}$ for any positive calculated sense offset current varies according to the differences of the temperature dependent limits of Parameter P_6.1.42 between -65µA up to +65µA

The following values can be derived:

The assumed typical current sense function follows the formula:

I_{IS}=I_L/$dk_{ILIS(TYP)}$+$I_{IS(0)}$=I_L/51500+1.117E-4
with $I_{IS(0)}$= $I_{IS(x1)}$- $I_{L(x1)}$/$dk_{ILIS(TYP)}$=0.0005-20/51500=1.117E-4

To derive the achievable accuracy of 1-point calibration

- m_{MAX1}, m_{MAX11} and m_{MAX12} can be derived from $dk_{ILIS(MIN)}$ and $\Delta(dk_{KILIS(CAL)})$.
  m_{MAX11}=1/$dk_{ILIS(MIN)}$=1/45300=2.20751E-5,
  m_{MAX1}=(1-$\Delta(dk_{KILIS(cal)})$)/$dk_{ILIS(MIN)}$=0.95*m_{MAX11}=2.097E-5,
  m_{MAX12}=(1-$\Delta(dk_{KILIS(cal)})$)/$dk_{ILIS(MIN)}$/(1+$\Delta(dk_{KILIS(CAL)})$)=m_{MAX1}/1.05=1.9973E-5

- m_{MIN1}, m_{MIN11} and m_{MIN12} can be derived from $dk_{ILIS(MAX)}$ and $\Delta(dk_{KILIS(CAL)})$.
  $m_{MIN12}=1/dk_{ILIS(MAX)}=1/57700=1.7331E-5$
  $m_{MIN1}=(1+\Delta(dk_{KILIS(cal)}))/dk_{ILIS(MAX)}=1.05*m_{MIN12}=1.82E-5$
  $m_{MIN11}=(1+\Delta(dk_{KILIS(cal)}))/dk_{ILIS(MAX)}/(1-\Delta(dk_{KILIS(cal)})=m_{MIN1}/0.95=1.91553E-5$
- the offset calculation will result in b=1.117E-4, b_1=1.36E-4 and b_2=8.057E-5

Table 4 shows the calculated absolute and relative errors for certain load currents for the example of BTS50015-1TAD with a calibration at T_j=25°C and I_L=20A

Table 4

I_{Load}	minimum absolute I_{Load} error	minimum relative I_{Load} error	Maximum absolute I_{Load} error	maximum relative I_{Load} error
10A	-4.5A	-45%	+4.5A	+45%
20A	-4.4A	-22%	+4.8A	+24%
40A	-6.4A	-16%	+7.2A	+18%
60A	-8.8A	-15%	+9.6A	+16%
80A	-11.2A	-14%	+12A	+15%
100A	-13.6A	-14%	+14.1A	+14%

Table 5 shows the calculated absolute and relative errors for certain load currents for an additional example of BTS50015-1TAD with a calibration at T_j=25°C and I_L=40A.

Table 5

I_{Load}	minimum absolute I_{Load} error	minimum relative I_{Load} error	Maximum absolute I_{Load} error	maximum relative I_{Load} error
10A	-5.8A	-58%	+6.1A	+61%
20A	-5.7A	-28%	+5.8A	+29%
40A	-5.4A	-13%	+5.8A	+14%
60A	-7.4A	-12%	+8.2A	+14%
80A	-9.8A	-12%	+10.6A	+13%
100A	-12.2A	-12%	+13A	+13%

Table 6 shows the calculated absolute and relative errors for certain load currents for an additional example of BTS50015-1TAD with a calibration at T_j=25°C and I_L=10A.

Table 6

I_{Load}	minimum absolute I_{Load} error	minimum relative I_{Load} error	Maximum absolute I_{Load} error	maximum relative I_{Load} error
10A	-3.9A	-39%	+4.3A	+43%
20A	-4.6A	-23%	+5.5A	+27%
40A	-7.1A	-18%	+7.9A	+20%
60A	-9.5A	-16%	+10.3A	+17%
80A	-11.9A	-15%	+12.7A	+16%
100A	-14.3A	-14%	+15.1A	+15%

Comparing the content of 0 to Table 6 with Table 3 it can be seen that:

- 1-point calibration does improve the accuracy compared to “default” performance
- accuracy improves compared to “default” performance mostly near the load current, where the calibration was performed
- a calibration at a load current just above I_{L0} (see chapter 3.1) is recommended, since the accuracy improvements at medium and high currents (I_L>=40) will reach similar accuracy improvements compared to higher load current calibrations and the manufacturing test can be performed at more moderate load currents in relation to the test equipment capability.

4.3 2-point calibration

The recommended option to optimally improve the current sense performance is to perform a 2-point calibration. The idea of 2-point calibration is to perform a manufacturing test that measures two sense currents $I_{IS(x1)}$ and $I_{IS(x2)}$ at two different, defined load currents $I_{L(x1)}$ and $I_{L(x1)}$. Ideally $I_{L(x1)}$ is just above I_{L0} (see chapter 3.1). $I_{L(x2)}$ should be chosen in a way, that $I_{IS(x2)}$ will sufficiently differ from $I_{IS(x1)}$. Usually this manufacturing test is performed at an ambient temperature of 25°C. The measured values will be stored in the microcontroller’s non-volatile memory to be used by the application software.

The fundamental aspects of the 2-point calibration will be explained in the following. In general mathematical terms 2-point calibration means, that first the point x1,y1 needs to be identified followed by the second point x2, y2.

Note: As stated in chapter 3.1, x1 needs to be chosen in a way that x>-(-b_{MIN}/m_{MIN}) will be fullfilled.

With the values of x1, y1, x2 and y2 the individual slope m_2 can be derived as illustrated in Figure 12 and Equation (16).

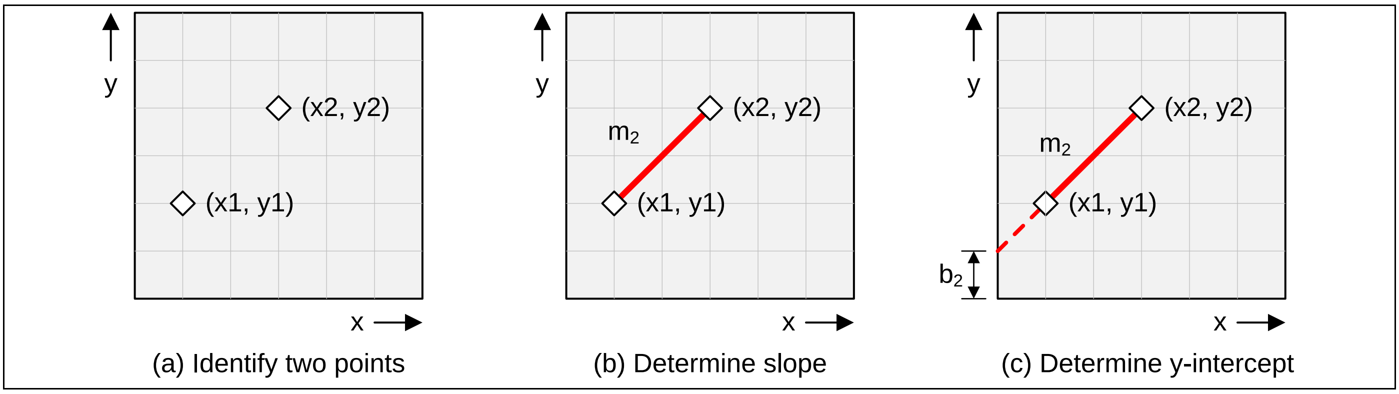

Figure 12 Determining the characteristics of a straight line

Equation (16) $m_2 = \frac{y_2 - y_1}{x_2 - x_1}$

Once the slope has been determined as illustrated in Figure 12(b), this value can be used to calculate the y-intercept (b_2) as illustrated in Figure 12(c). This can be accomplished by picking the (x,y) values for any point and solving for the y-intercept using Equation (17).

Equation (17) $b_2 = y - m_2 \times x$

After m_2 (slope) and b_2 (y-intercept) have been determined, these values can be substituted into the generic equation for a line as defined in Equation (1), and then this equation can be used to determine the (x, y) values of any other point on the line.

To derive the achievable accuracy of 2-point calibration the following aspects have to be considered. According to chapter 4.1 the derived slope m_2 may vary between certain limits m_{MIN2} and m_{MAX2}. Also the derived y-Intercepts b_2 may vary within certain limits towards a lower offset b_2-Δb and an upper offset b_2+Δb. Special attention has to be paid here that the variation of Δb may vary depending on the case, whether b_2 is positive or negative.

Figure 13 illustrates these effects for an example where b_2 is positive.

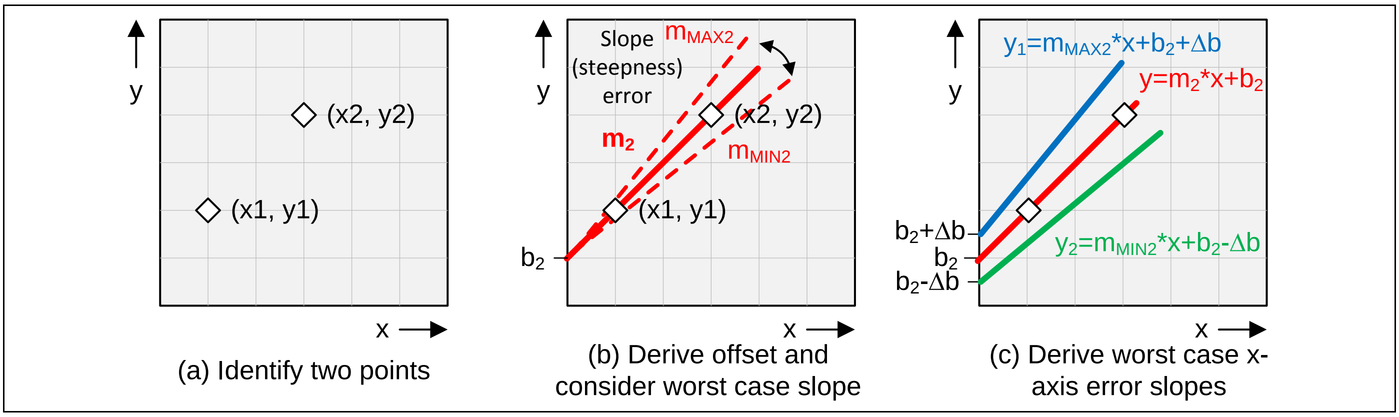

Figure 13 X-Axis error for generic lines with varying positive slopes and offsets

As it can be seen, the x_i error for a given y_i value will be determined by two limiting functions y_1=f(x) and y_2=f(x).

- $y_1=f(x)=m_{MAX2}*x+b_2+\Delta b$
- $y_2=f(x)=m_{MIN2}*x+b_2-\Delta b$
- The typical function, assuming a typical slope m_2 will follow the formula $y=m_2*x+b_2$.

Comparing Figure 13 with Figure 10 it can be seen, that the general absolute error for any x_i value will again range between a minimum value $x_{i(MIN)}$ and a maximum $x_{i(MAX)}$. Compared to "default" current sense performance however the error variation will reduce as following:

The absolute minimum x- error-value (MinError=$x_{i(MIN)}$- x_i) can be calculated according Equation (18)

Equation (18) $\mathrm{MinAbsError} = \frac{x \times (m_2 - m_{MAX2}) - \Delta b}{m_{MAX2}}$

The relative minimum x-error (MinRelError=($x_{i(MIN)}$- x_i)/x_i) can be calculated according Equation (19)

Equation (19) $\mathrm{MinRelError} = \frac{m_2 x \times -\Delta b}{m_{MAX2} \times x} - 1 = \frac{m_2}{m_{MAX2}} - \frac{\Delta b}{m_{MAX2} \times x} - 1$

The absolute maximum x- error-value (MaxError=$x_{i(MAX)}$- x_i) can be calculated according Equation (20)

Equation (20) $\mathrm{MaxAbsError} = \frac{x \times (m_2 - m_{MIN2}) + \Delta b}{m_{MIN2}}$ with Δb being an absolute number.

The relative maximum x-error (MaxRelError=($x_{i(MAX)}$- x_i)/x_i) can be calculated according Equation (21)

Equation (21) $\mathrm{MaxRelError} = \frac{m_2 x \times + \Delta b}{m_{MIN2} \times x} - 1 = \frac{m_2}{m_{MIN2}} + \frac{\Delta b}{m_{MIN2} \times x} - 1$ with Δb being an absolute number

Applying Power PROFET parameters to Equation (18) to Equation (21) results in Equation (22) to Equation (25).

Equation (22) $\mathrm{MinAbsError} = \left(I_L \times \left(\frac{1}{dK_{ILIS(cal)}} - \frac{1}{dK_{ILIS(cal)} \times \left(1 + \frac{Min.\Delta\left(dK_{ILIS(cal)}\right)}{100\%}\right)} \right) - \frac{\Delta I_{IS0(cal)}}{10^6} \right) \times dK_{ILIS(cal)} \times \left(1 + \frac{Min.\Delta\left(dK_{ILIS(cal)}\right)}{100\%}\right)$

with Min.Δ($dK_{IILIS(cal)}$) being a negative % value and with $\Delta I_{IS0(cal)}$ as µA value.

Equation (23) $\mathrm{MinRelError} = \frac{dK_{ILIS(cal)} \times \left(1 + \frac{Min.\Delta\left(dK_{ILIS(cal)}\right)}{100\%}\right)}{dK_{ILIS(cal)}} - \frac{\Delta I_{IS0(cal)} \times dK_{ILIS(cal)} \times \left(1 + \frac{Min.\Delta\left(dK_{ILIS(cal)}\right)}{100\%}\right)}{I_L \times 10^6} - 1$

with Min.Δ($dK_{IILIS(cal)}$) being a negative % value and with $\Delta I_{IS0(cal)}$ as µA value.

Equation (24) $\mathrm{MaxAbsError} = \left(I_L \times \left(\frac{1}{dK_{ILIS(cal)}} - \frac{1}{dK_{ILIS(cal)} \times \left(1 + \frac{Max.\Delta\left(dK_{ILIS(cal)}\right)}{100\%}\right)} \right) - \frac{\Delta I_{IS0(cal)}}{10^6} \right) \times dK_{ILIS(cal)} \times \left(1 + \frac{Max.\Delta\left(dK_{ILIS(cal)}\right)}{100\%}\right)$

with Max.Δ($dK_{IILIS(cal)}$) being a positive % value and with $\Delta I_{IS0(cal)}$ as µA value being negative.

Equation (25) $\mathrm{MaxRelError} = \frac{dK_{ILIS(cal)} \times \left(1 + \frac{Max.\Delta\left(dK_{ILIS(cal)}\right)}{100\%}\right)}{dK_{ILIS(cal)}} - \frac{\Delta I_{IS0(cal)} \times dK_{ILIS(cal)} \times \left(1 + \frac{Max.\Delta\left(dK_{ILIS(cal)}\right)}{100\%}\right)}{I_L \times 10^6} - 1$

with Max.Δ($dK_{IILIS(cal)}$) being a positive % value and with $\Delta I_{IS0(cal)}$ as µA value being negative.

To show the possible accuracy improvement another BTS50015-1TAD example is outlined. Although the example is based on a very specific sense current measurement, the resulting load current errors are valid also for other sense current measurements as long as the $\Delta I_{IS0(cal)}$ and $\Delta(dk_{KILIS(cal)})$ values remain.

Assuming an individual sense current of a BTS50015-1TAD was measured at T_j=25°C and I_{L1}=10A and I_{L2}=20A showed a values of I_{IS1}=0.3mA and I_{IS2}=0.51mA. Considering that according the datasheet

- the current sense ratio spread of $\Delta(dk_{KILIS(cal)})$ varies between MIN-5% and MAX+5% and that
- $\Delta I_{IS0(cal)}$ for any positive calculated sense offset current varies according to the differences of the temperature dependant limits of Parameter P_6.1.42 between -65µA<=$\Delta I_{IS0(cal)}$<=+65µA (see also chapter 4.1)

The following values can be drived:

The assumed typical current sense function follows the formula:

$I_{IS}=I_L/dk_{ILIS(cal)}+I_{IS(0)}=I_L/47620+9E\text{-}5$
with $m=(y_2-y_1)/(x_2-x_1)= =(I_{IS(2)}- I_{IS(1)})/(I_{L(2)}- I_{L(1)})=(5.1E\text{-}4-3E\text{-}4)/(20-10)=2.1E\text{-}5$ or $dk_{ILIS(cal)}=1/m=47620$

And with $I_{IS(0)}= I_{IS(x1)}- I_{L(x1)}/dk_{ILIS}=0.0003-10/47620=9E\text{-}5$

To derive the achievable accuracy of 1-point calibtarion

- m_{MAX2} can be derived from m_2 and $\Delta(dk_{KILIS(cal)})$.
  $m_{MAX2}=m_2/(1-\Delta(dk_{KILIS(cal)}))=2.1E\text{-}5/0.95=2.211E\text{-}5$ or $dk_{ILIS(MIN)}=1/m_{MAX2}=45238$
- m_{MIN2} can be derived from m_2 and $\Delta(dk_{KILIS(CAL)})$.
  m_{MIN2} $m_2/(1+\Delta(dk_{KILIS(cal)}))= 2.1E\text{-}5/1.05=2E\text{-}5$ or $dk_{ILIS(MIN)}=1/m_{MAX2}=50000$
- the offset calculation will result in $b_2+\Delta b=9E\text{-}5+6.5E\text{-}5=1.55E\text{-}4$ and $b_2-\Delta b=9E\text{-}5-6.5E\text{-}5=-2.5E\text{-}5$

Table 7shows the calculated absolute and relative errors for certain load currents for the example of BTS50015-1TAD with a calibration at T_j=25°C and at I_{L1}=10A and I_{L2}=20A.

Table 7

I_{Load}	minimum absolute I_{Load} error	minimum relative I_{Load} error	Maximum absolute I_{Load} error	maximum relative I_{Load} error
10A	-3.4A	-34%	+3.8A	+38%
20A	-3.9A	-20%	+4.3A	+21%
40A	-4.9A	-12%	+5.3A	+13%
60A	-5.9A	-10%	+6.3A	+10%
80A	-6.9A	-9%	+7.3A	+9%
100A	-7.9A	-8%	+8.3A	+8%

Comparing the content of Table 7 with 0 to Table 6 and Table 3 it can be seen that:

- 2-point calibration does achieve the best accuracy
- Also at 2-point calibration the accuracy does depend on the load current. The higher the load current is, the smaller the relative error and the better the overall accuracy will be. At very high load currents an accuracy of ~8% can be achieved.

5 Important considerations

In order to utilize the sense performance of Power PROFET, independent whether calibration is applied or not, the following conditions have to be maintained:

- voltage conditions: in order to ensure that the sense circuitry works in the specified range a voltage drop between the VS pin and the IS pin of minimum 5V is required (V_S-V_{IS}>=5V). This condition can have an impact on the selection of the external Sense Resistor R_{IS} especially if the Power PROFET has to operate at low supply voltages (V_S<=10V provided the IS signal is read and processed by a 5V micro controller).
- measurement range: the load current range, in which the current sense function can be used – independent whether or not calibration is applied - is limited towards a lower load current I_{L0} and towards an upper load current I_{L4} (see chapter 3.1).
- timings:
  - whenever the Power Profet is commanded on by applying a positive IN signal, a certain time has to be considered to allow the device to switch on and to allow the sense current to provide a stable sense signal. According to the datasheet parameter P_6.1.48 the sense pin will provide a 90% value of the final steady state value within the time $t_{\mathrm{pIS(ON)\_90}}$. According to the datasheet parameter P_6.1.49 the sense pin will provide the steady state value latest after $t_{\mathrm{pIS(ON)}}$.
  - whenever the Power Profet is already in on-state and the load current changes, a certain time has to be considered to allow the sense circuit to adjust the sense current to the new, steady state sense signal. According to the datasheet parameter P_6.1.51 the sense pin will provide the new, steady state value within the time $t_{\mathrm{pIS(LC)}}$.

6 Calibrating Power PROFET

6.1 Calibration Nomenclature and Equations

The nomenclature used in the high-side power switch datasheets and the information presented earlier in this application note references calibration information in terms of current. However, the analog-to-digital converter (ADC) in the microcontroller that is used to monitor the IS (sense current) output from the high-side switch reads voltages, not currents. Thus, the calibration techniques discussed below are presented in terms of voltages because these are what the manufacturing test and application software read.

Consider the reference circuit illustrated in Figure 14 (the resistors R_{INPUT} and R_{SENSE} are for protection and have no or minimal effect on the calibration calculations).

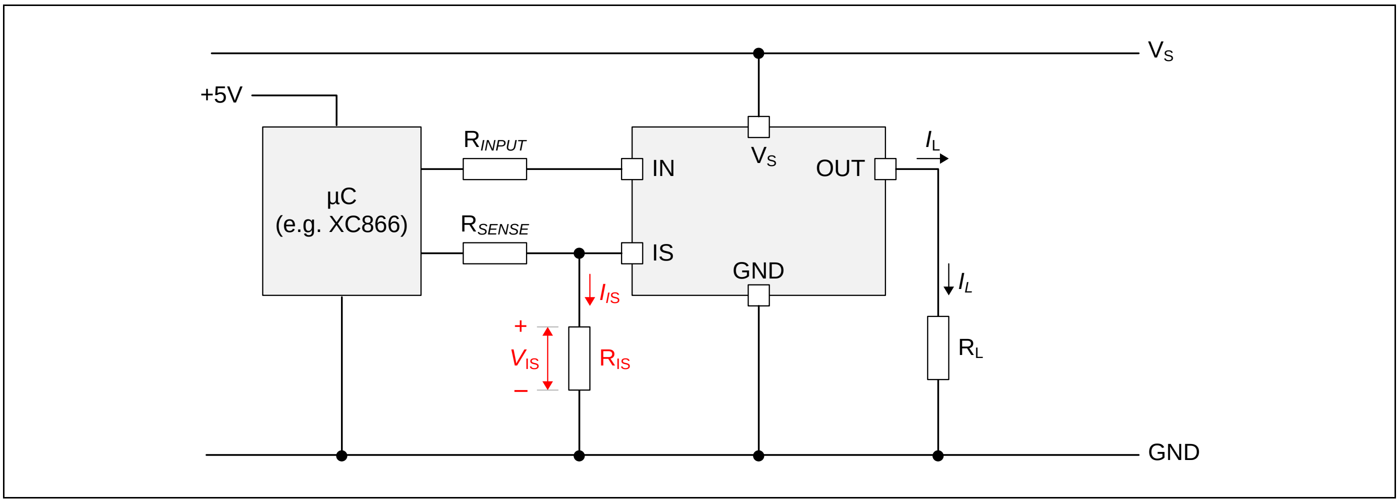

Figure 14 Reference circuit for calibration nomenclature

The analog sense current signal I_{IS} flows through resistor R_{IS}. The corresponding voltage potential V_{IS}, which is developed across this resistor, and which is seen by the microcontroller's ADC input, is determined by Ohm's law as shown in Equation (26).

Equation (26) $V_{IS} = I_{IS} \text{ x } R_{IS}$

With the exception of the *No Calibration* scenario discussed later in this application note, the initial values for $dk_{ILIS(cal)}$ and $V_{IS0(cal)}$ will be determined by manufacturing test and stored in the microcontroller's non-volatile memory for use by the application software.

Note: This application note assumes that manufacturing test will store $V_{IS0(cal)}$ (the voltage value in ADC counts) in the microcontroller's non-volatile memory; that is, it is assumed that manufacturing test will NOT store $I_{IS0(cal)}$ (the current value).

In case of a 1-point calibration $dk_{ILIS(cal)}$ is assumed to be $dk_{ILIS(TYP)}$, i.e. the typical value of datasheet parameter P_6.1.41.

Equation (27) $dk_{ILIS(cal)} = dk_{ILIS(TYP)}$

The individual offset is calculated

Equation (28) $V_{IS0(cal)} = I_{IS0(cal)} * R_{IS} = \left(I_{IS(x1)} - \frac{I_{L(x1)}}{dk_{ILIS(TYP)}}\right) * R_{IS}$
with $V_{IS0(cal)}$ being positive or negative

In case of a 2-point calibration $dk_{ILIS(cal)}$ is calculated as shown in Equation (29).

Equation (29) $dk_{ILIS} = \frac{I_{L1} - I_{L2}}{\left(V_{IS}(I_{L1})/R_{IS}\right) - \left(V_{IS}(I_{L2})/R_{IS}\right)}$

The load current I_L can be calculated changing Equation (2) as following

Equation (30) $I_L = dk_{ILIS(cal)} \text{ x } (I_{IS} - I_{IS0(cal)})$

Considering and Equation (26) and Equation (28) the load current can be calculated by

Equation (31) $I_L = dk_{ILIS(cal)} \text{ x } \left(\frac{V_{IS}}{R_{IS}} - \frac{V_{IS0(cal)}}{R_{IS}}\right)$

Factoring Equation (31) allows the application software to calculate the load current I_L as shown in Equation (32).

Equation (32) $I_L = \frac{dk_{KLIS(cal)}}{R_{IS}} \text{ x } (V_{IS} - V_{IS0(cal)})$ with $V_{IS0(cal)}$ being positive or negative

6.2 Application Software Implementation

6.2.1 No Calibration (No Cal)

With this calibration option, no calibration is performed by manufacturing test; thus, no individual varying device values for $V_{IS0(cal)}$ and $dk_{ILIS(cal)}$ are stored in the microcontroller's non-volatile memory. Instead, the application developer simply sets $V_{IS0(cal)}$ to zero, $dk_{ILIS(TYP)}$ as specified in the datasheet and R_{IS} according the used value. This scheme is the least expensive in terms of time and manufacturing cost, but it also yields the least accuracy.

The term DUT (Device Under Test) refers to the high-side power switch that is being calibrated by manufacturing test or measured by the application software. The flowchart in Figure 15 summarizes the process used by the application software when the *No Calibration* option is being used.

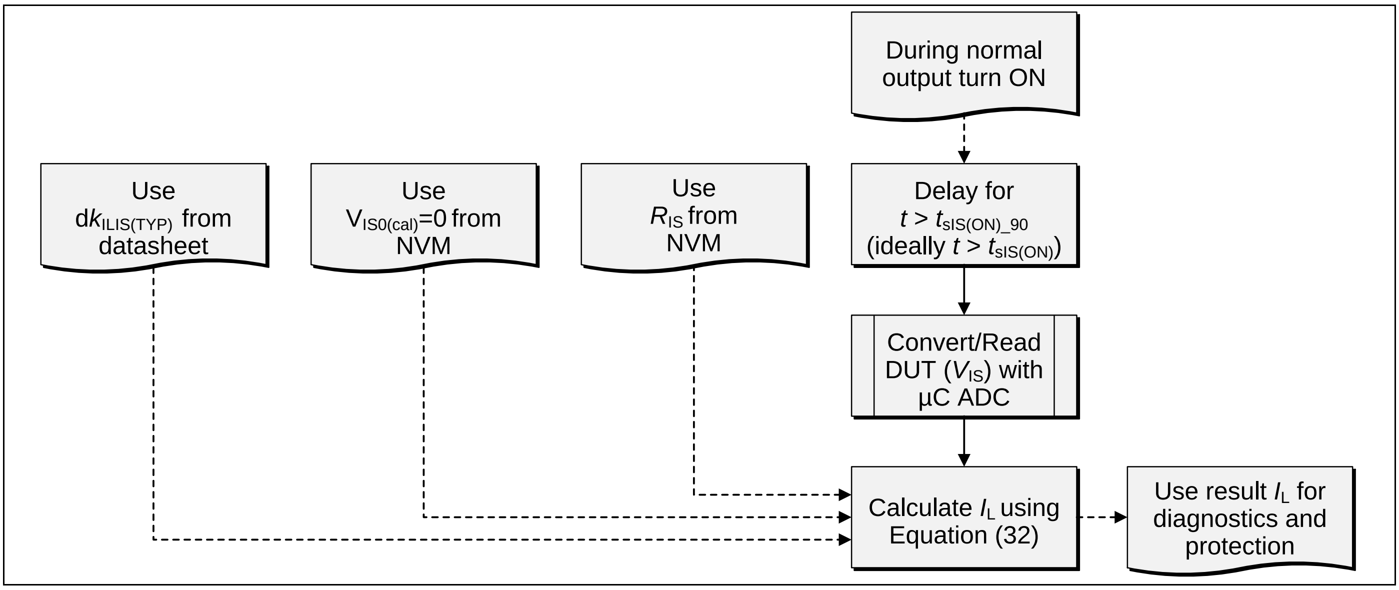

Figure 15 Application software procedure for No Calibration option

During normal device/load turn-on cycles, the software reads the IS pin from the ADC after delaying for the current sense settling time. It then uses the datasheet values for $dk_{ILIS(TYP)}$ to calculate the load current I_L using Equation (32).

The application software would then compare the calculated load current value to diagnostic threshold limits stored in the microcontroller's non-volatile memory to determine the load condition (normal, short-to-battery, short-to-ground, etc.)

6.2.2 1-point Calibration

With this calibration option, manufacturing test measures the value of $V_{IS(x1)}$ at load current $I_{L(x1)}$ at an ambient temperature of 25°C. This measured value will be further processed into "calculated", calibrated sense offset $V_{IS0(cal)}$ which will be stored in the microcontroller's non-volatile memory along with the typical datasheet value of $dk_{ILIS(cal)}=dk_{ILIS(TYP)}$ and R_{IS}. These are the values that will be used by the application software.

Single-point calibration involves switching a known load at a known temperature (typically 25°C) and then measuring the analog sense current. With conventional high-side switches, the polarity of the offset must be determined and tracked such that the software can add or subtract the offset value from the measured values.

Figure 16 summarizes the process used by manufacturing test when the *1-point* calibration option is being used.

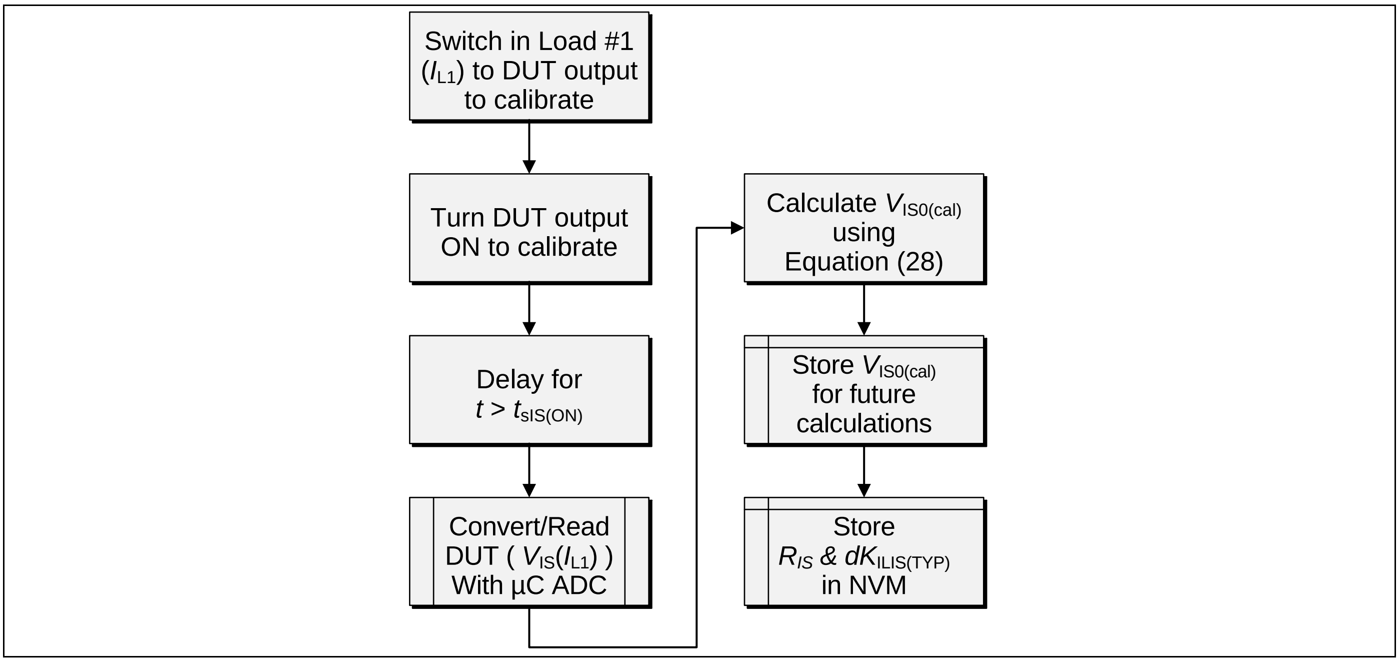

Figure 16 Manufacturing test procedure for the 1-point calibration option

The manufacturing test turns the device input ON with a known load connected to the device, delays for the current sense settling time and then reads and stores the corresponding $V_{IS}(I_{L1})$ value. Next the manufacturing test software calculates the offset using Equation (28) and stores this value plus the datasheet values of $dk_{IILIS(typ)}$ and the R_{IS} value in the microcontroller's non-volatile memory (NVM).

Figure 17 summarizes the process used by the application software when the *1-point* calibration option is being used.

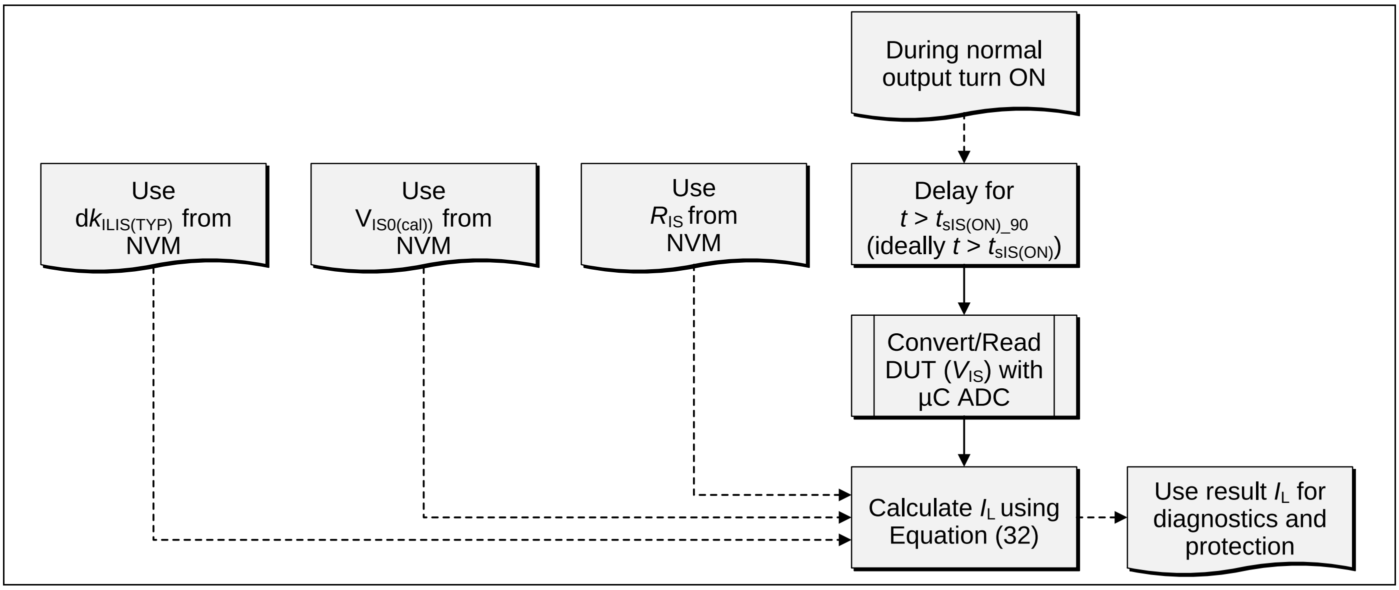

Figure 17 Application software procedure for the 1-point calibration option

During normal device/load turn-on cycles, the software reads the IS pin from the ADC after delaying for the current sense settling time. It then uses the values for d$k_{ILIS(TYP)}$, $V_{IS0(cal)}$ and R_{IS} stored in the microcontroller's non-volatile memory to calculate the load current I_L using Equation (32). This load current is then compared to normal or faulted threshold limits to determine the condition of the load.

6.2.3 2-Point Calibration

With this calibration option, manufacturing test measures two values of $V_{IS(x)}$ at two different load currents $I_{L(x)}$ at an ambient temperature of 25°C. Both of these measured values, $V_{IS(x1)}$ at low load current $I_{L(x1)}$ and $V_{IS(x2)}$ at higher load current $I_{L(x2)}$ will be stored in the microcontroller's non-volatile memory to be used by the application software.

Figure 18 summarizes the process used by manufacturing test when the *2-Point* calibration option is being used.

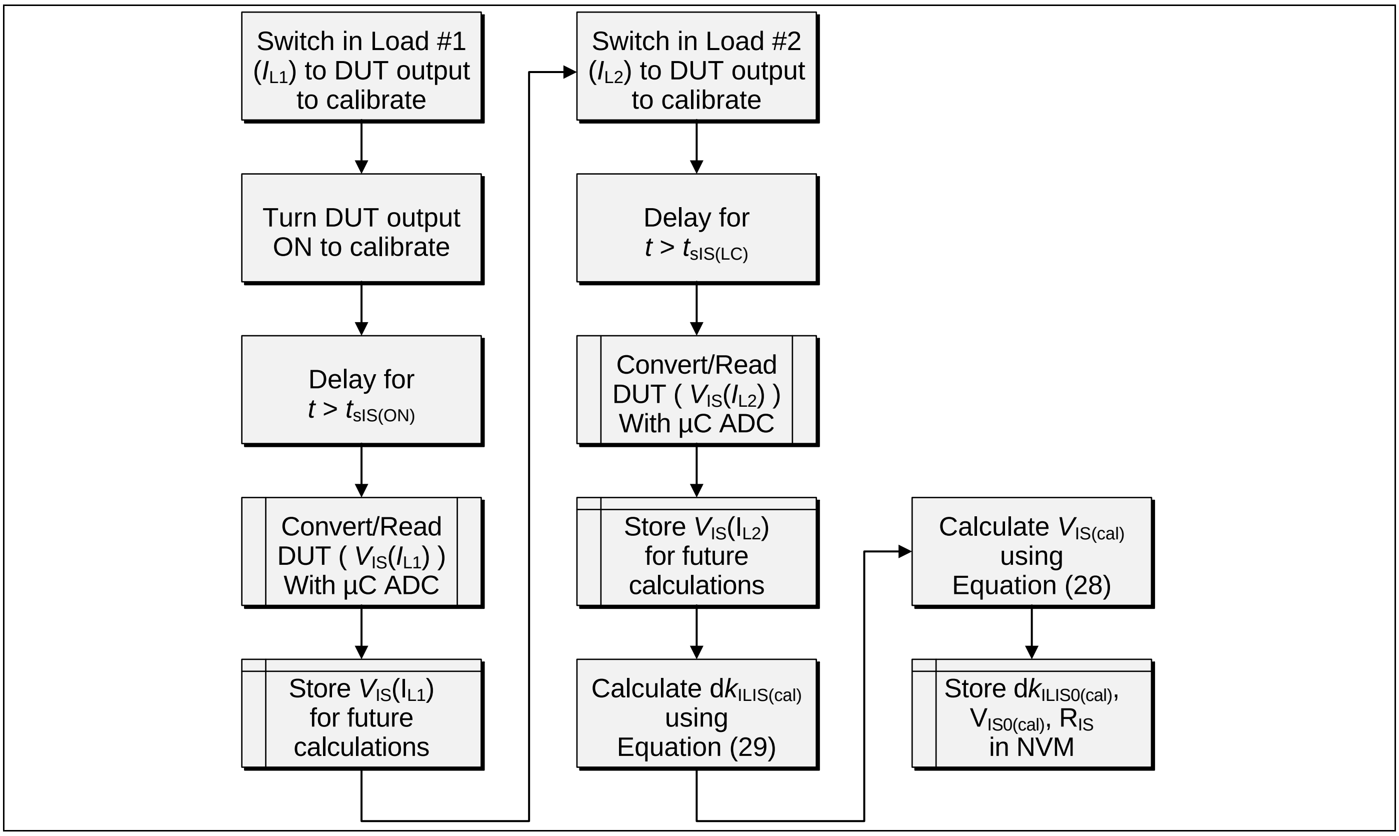

Figure 18 Manufacturing test procedure for the 2-Point calibration option

The manufacturing test turns the device input ON with a known load connected to the device, delays for the current sense settling time, and then reads and stores the corresponding $V_{IS}(I_{L1})$ value. Then manufacturing test changes to a higher current rated load, delays for the current sense settling time, and then reads and stores the corresponding $V_{IS}(I_{L2})$ value again. Next the manufacturing test software calculates the slope using Equation (29) and the offset using Equation (28) and stores these value plus the R_{IS} value in the microcontroller's non-volatile memory (NVM).

Figure 19 summarizes the process used by the application software when the *2-Point* calibration option is being used.

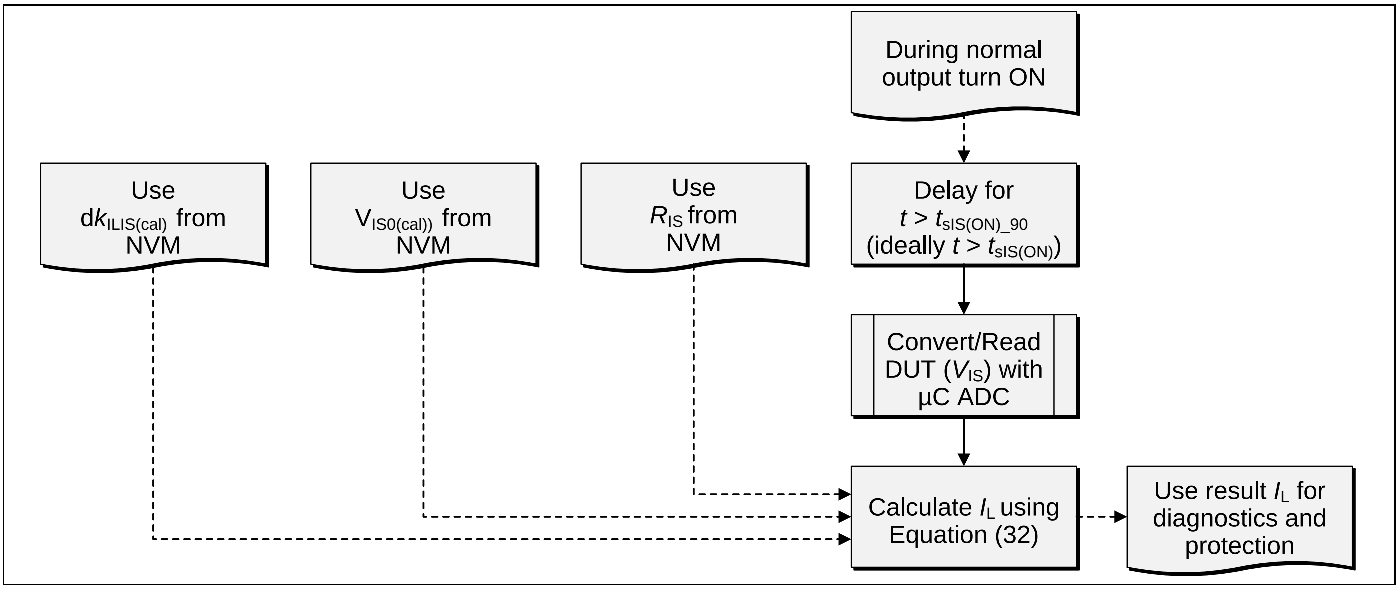

Figure 19 Application software procedure for the 2-Point calibration option

During normal device/load turn-on cycles, the software reads the IS pin from the ADC after delaying for the current sense settling time. It then uses the values for $dk_{ILIS(cal)}$, $V_{IS0(cal)}$ and R_{IS} stored in the microcontroller's non-volatile memory to calculate the load current I_L using Equation (32). This load current is then compared to normal or faulted threshold limits to determine the condition of the load.

6.3 Accuracy of Different Calibration Options

Figure 20 illustrates the accuracy provided by the various calibration options discussed above. In the case of the sense current graphs, the red lines represent the typical slopes, the blue lines represent the maximum deviation from typical, and the green lines represent the minimum deviation from typical.

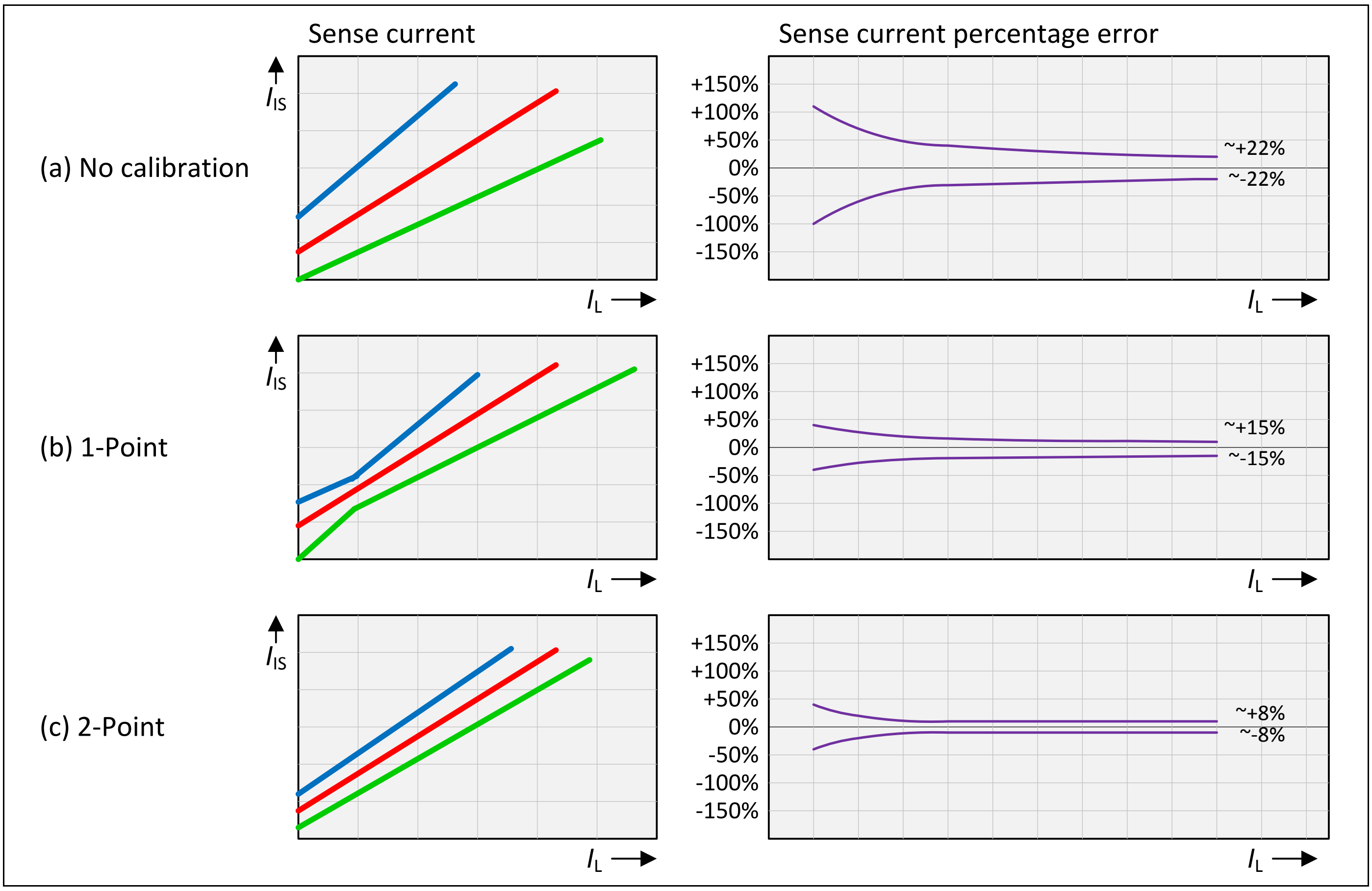

Figure 20 Accuracy of different calibration options

The sense current percentage error graphs clearly shows that 2-point calibration, although it requires the highest effort during manufacturing test, offers the best accuracy performance.

7 Conclusion

Current sensing is a well-accepted feature in high-side power switches. Devices with a traditional concept, to which also Power PROFET belongs, have an offset current that deteriorates the current sense accuracy, especially at lower load currents, and that may disable the current sense functionality below certain load current thresholds $I_{L(0)}$.

In case of Power PROFET the "default" current sense performance offers a moderate accuracy. Whenever this accuracy needs to be improved, 1-point or 2-point calibration can bring a significant accuracy improvement especially at higher load currents thanks to the nature of Power PROFET sense variations. Nevertheless, even with calibration the measureable load current range remains in the exact same range of $I_L = I_{L(0)}$ to $I_{L(4)}$ as in the case of the "default" sense performance.

Revision History

V1.0, 2016-04-07 (Major changes since the last revision)

Page or Reference	Description of change

Edition 2016-04-07

Published by

Infineon Technologies AG

81726 Munich, Germany

Do you have a question about this document?

Email: erratum@infineon.com

Document reference