Application Note

PROFET^{TM} + CURRENT SENSE

What the designer should know

Application Note

Smart High Side Switches

Rev 1.1, 2014-03-14

Body Power

1 Abstract

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

The focus of this application note is to give a guide how to calculate the diagnosis capability of a PROFET™+ in connection with a micro controller. The cases for partial loss of load, open load detection in ON-state and OFF-state are discussed. Additionally, some possible sense circuit design examples are given.

2 Introduction

This application note intends to provide useful information to the designer in regards to the PROFET™+ current sense functionality. PROFET™+ is a familly of more than 20 members in the automotive field for 12 and 24V applications, offering identical features set. The familly is scaled in $R_{DS(ON)}$ to match the load requirements and uses current sense for load diagnosis. Current sense consists of providing a mirror current of the main load current flowing through the DMOS. A constant requirement is to achieve excellent accuracy at all load currents. PROFET™+ achieves state of the art accuracy at this point.
This application note also describes in detail the calibration methods the designer can use to furthermore improve the accuracy.

3 States to Diagnose

Usually the following load diagnostics are of relevance. “OFF” means the INput pin is in a LOW state.

- Open Load at OFF
- Short Circuit to Ground at OFF
- Nominal Load at OFF
- Short Circuit to Battery at OFF
- Short Circuit to Ground at ON
- Open Load at ON
- Partial Loss of Load at ON
- Overload at ON

The following chapters will explain how to diagnose these cases with PROFET™+.

3.1 Diagnosis at OFF

In case the PROFET™+ is in OFF state, the voltage at the output pin should be LOW as the load acts as a pull-down. If the load is disconnected, the output pin is floating and can be HIGH or LOW depending on the leakage current at the output. With the PROFET™+ it is possible to detect the Open Load at OFF and Short Circuit to Battery at OFF with the usage of external resistors. The dimensioning of these external resistors will be explained in the later chapters.

3.1.1 Open Load at OFF

When the PROFET™+ is switched OFF (IN=LOW), the diagnosis can still detect a disconnected load. To support this, an external resistor R_{OL} has to be placed between battery feed and the output, which will cause the output to go HIGH in case no load is connected. Often this connection is kept switchable via a transistor to limit the power losses and reduce the quiescent current. If the transistor T1 is used for more than one OUTput it is recommended to place a diode (D_{OL}) to avoid currents flowing from one OUTput to the other.

A typical value is: R_{OL} = 47k

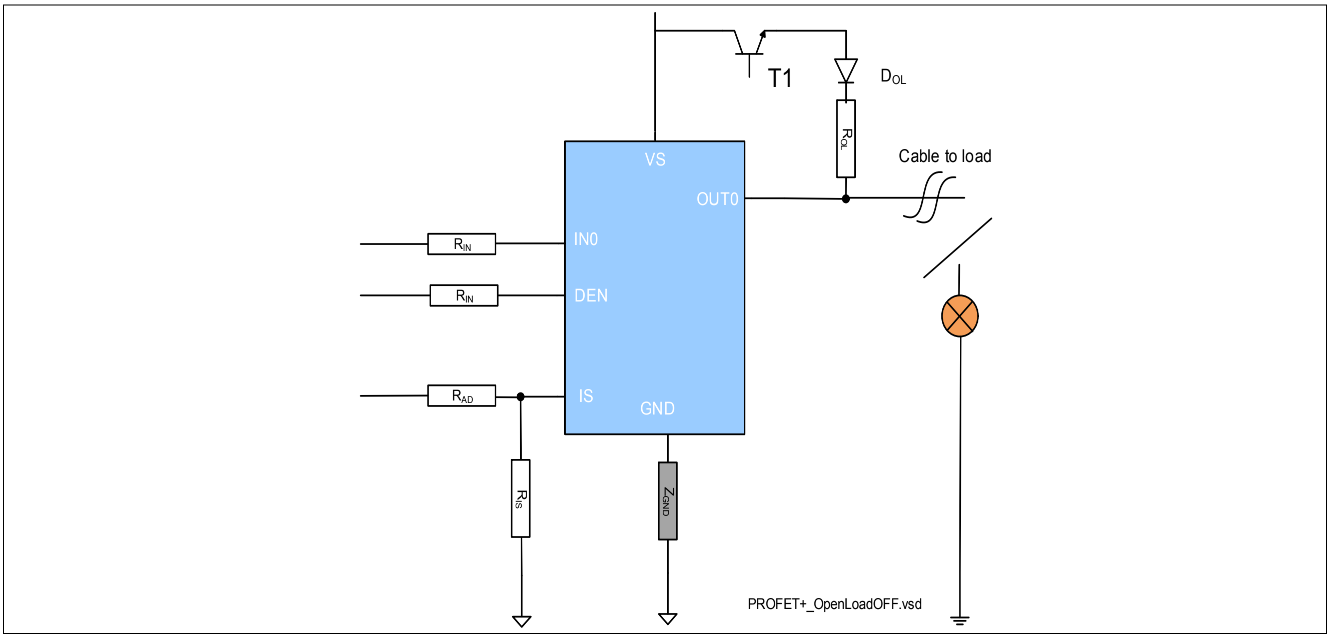

Figure 1 Open Load at OFF Detection

3.1.2 Short Circuit to Battery at OFF

To be able to distinguish between short circuit to battery and open load at OFF, an additional pull down resistor R_{PD} is recommended. Usually the load acts as a strong pull-down, but if this is lost, the voltage divider between R_{OL} and R_{PD} will cause the voltage at the output to be high enough to detect an open load. The open load at OFF comparator is battery related and therefore independent of the ground circuit and the ground shift. For more details on the detection of short circuit to battery and open load at OFF see **Table 1**.

Typical values are: R_{OL} = 1.5kΩ and R_{PD} = 47kΩ.

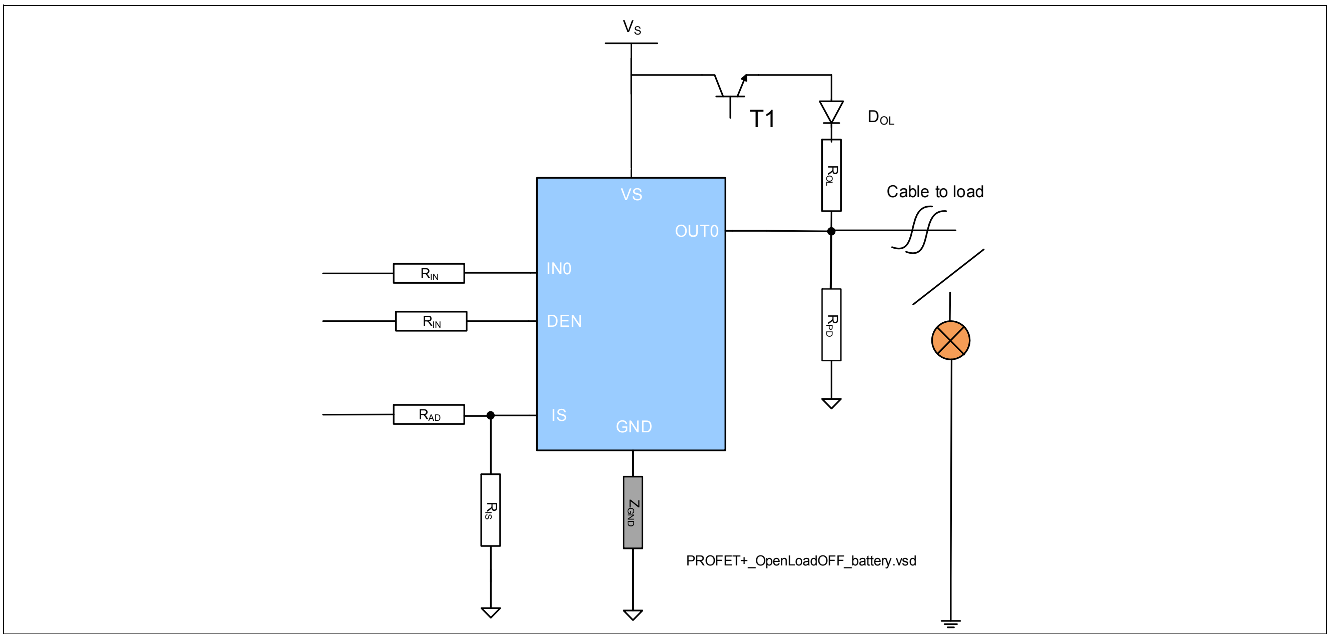

Figure 2 Short Circuit to Battery at OFF Detection with R_{OL}

To guarantee a working diagnosis the parameter P_7.5.1 (Open load detection at OFF state) must be considered. This parameter specifies that the difference between the voltage at the OUTput pin and the supply pin (VS) must be between 0...4V (worst case) to have an OL diagnosis. With **Equation (1)** and **Equation (2)** it is possible to calculate the minimum R_{PD} and maximum R_{OL}.

Equation (1) Known R_{OL}.

$$R_{PD} > \frac{R_{OL} \times V_{OL(OFF)}}{V_S - V_{OL(OFF)}} \tag{1}$$

Equation (2) Known R_{PD}.

$$R_{OL} < \frac{R_{PD} \times (V_S - V_{OL(OFF)})}{V_{OL(OFF)}} \tag{2}$$

It is also possible to use only a pull-down R_{PD} resistor without the pull-up resistor R_{OL} to do a short circuit to battery detection if no open load at OFF diagnosis is requested. (see **Figure 3**). Please note that the open load at OFF diagnosis is independent of the GND potential shift.

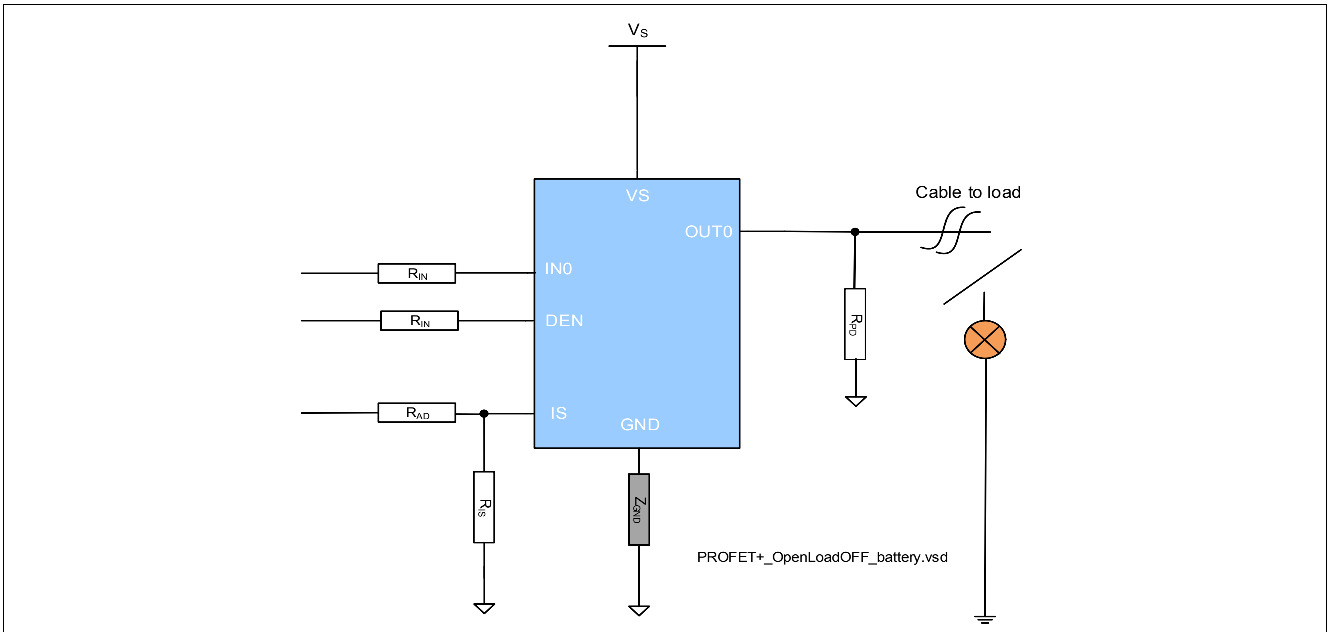

Figure 3 Short Circuit to Battery at OFF Detection without R_{OL}

In case a LED module is used as a load and a capacitor is connected in parallel, the timing of the diagnosis can be critical. The discharging speed of the capacitor after a switch OFF depends on the pull down (load and R_{PD}) and has to be considered. Having just a capacitor on the output of the PROFET™+ can lead to a permanent HIGH state as the DMOS leakage might be bigger than the leakage discharge of the capacitor.

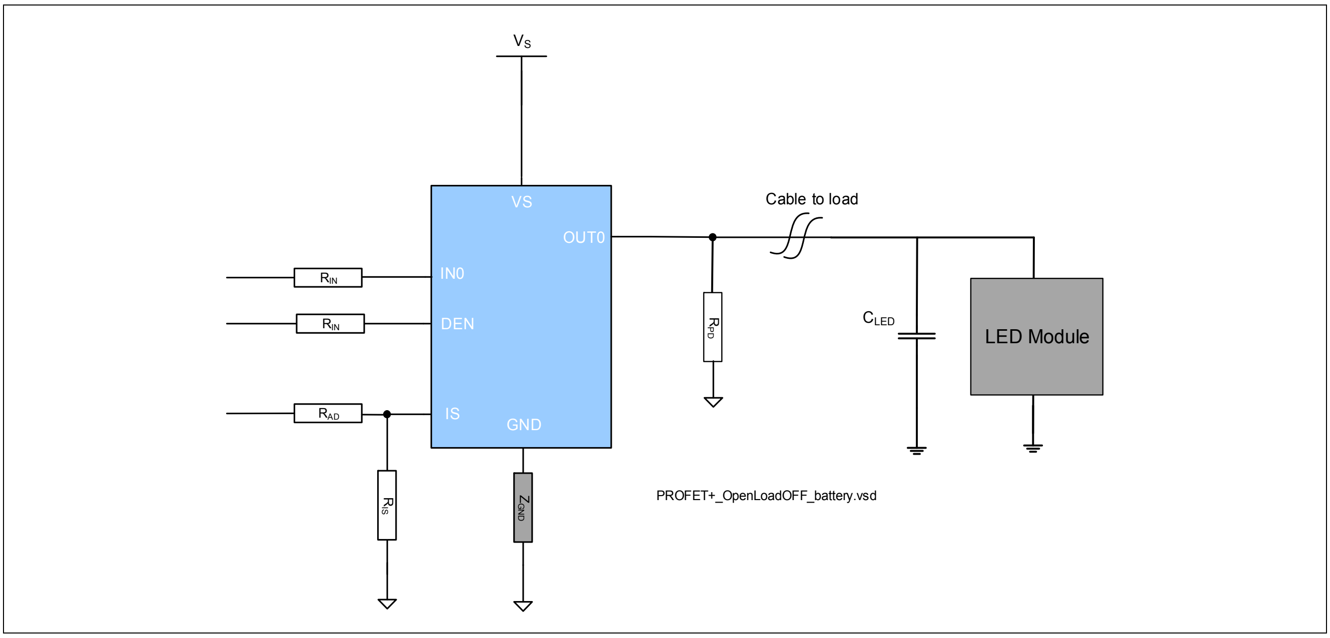

Figure 4 Short Circuit to Battery at OFF Detection with LED Module / without R_{OL}

3.1.3 Nominal Load / Short to Ground at OFF

A short to ground acts as a strong pull-down like the nominal load which means that it cannot be distinguished at OFF condition.

The **Table 1** sums up the different conditions of the load and the device output voltage. If the device ouput state is HIGH the fault current $I_{IS(FAULT)}$ is applied (referring to **Figure 2**).

Table 1 Output States in OFF

Condition Device in OFF state	Output State T1 conducting	Output State T1 open	detectable and distinguishable
Open Load	HIGH	LOW	YES
Short to Battery	HIGH	HIGH	YES
Nominal Load	LOW	LOW	NO
Short to Ground	LOW	LOW	NO

3.2 Load Detection in ON

For the load detection at ON state the load and sense current are considered to be settled.

3.2.1 Short to Ground at ON

In this application note, the short circuit is considered as a load current that is either triggering the current limitation or thermal limitation.. At the IS-pin the PROFET™+ device provides the $I_{IS(FAULT)}$ current.

3.2.2 Short to Battery at ON

Having a short to battery at ON condition would lead to a fully ON load while causing only a very small current across the PROFET™+. The resulting small current on the sense pin gives the indication that the load condition is not correct and can be misinterpreted as underload.

3.2.3 Open Load / Partial Loss / Overload at ON

Before selecting the appropriate external sense resistor, the application load thresholds have to be defined. The correct definition of these areas is a key point for further calculations and design in activities.

There are four areas that are of interest for the diagnosis at the micro controller:

- Open Load
- Short Circuit
- Nominal Load
- Overload
- Underload

As it is impossible for the diagnosis circuit to distinguish between current values that are too close to each other, there must be a grey area between **LOAD** and **OPEN LOAD / SHORT CIRCUIT**, otherwise a clear assignment is impossible.

Figure 5 shows the analog values of the load current mapped to digital values on the micro controller. The micro controller should decide, based on the internal threshold definition whether the load is operating in the nominal range (**LOAD**) or in a failure mode (**OPEN LOAD / SHORT CIRCUIT**).

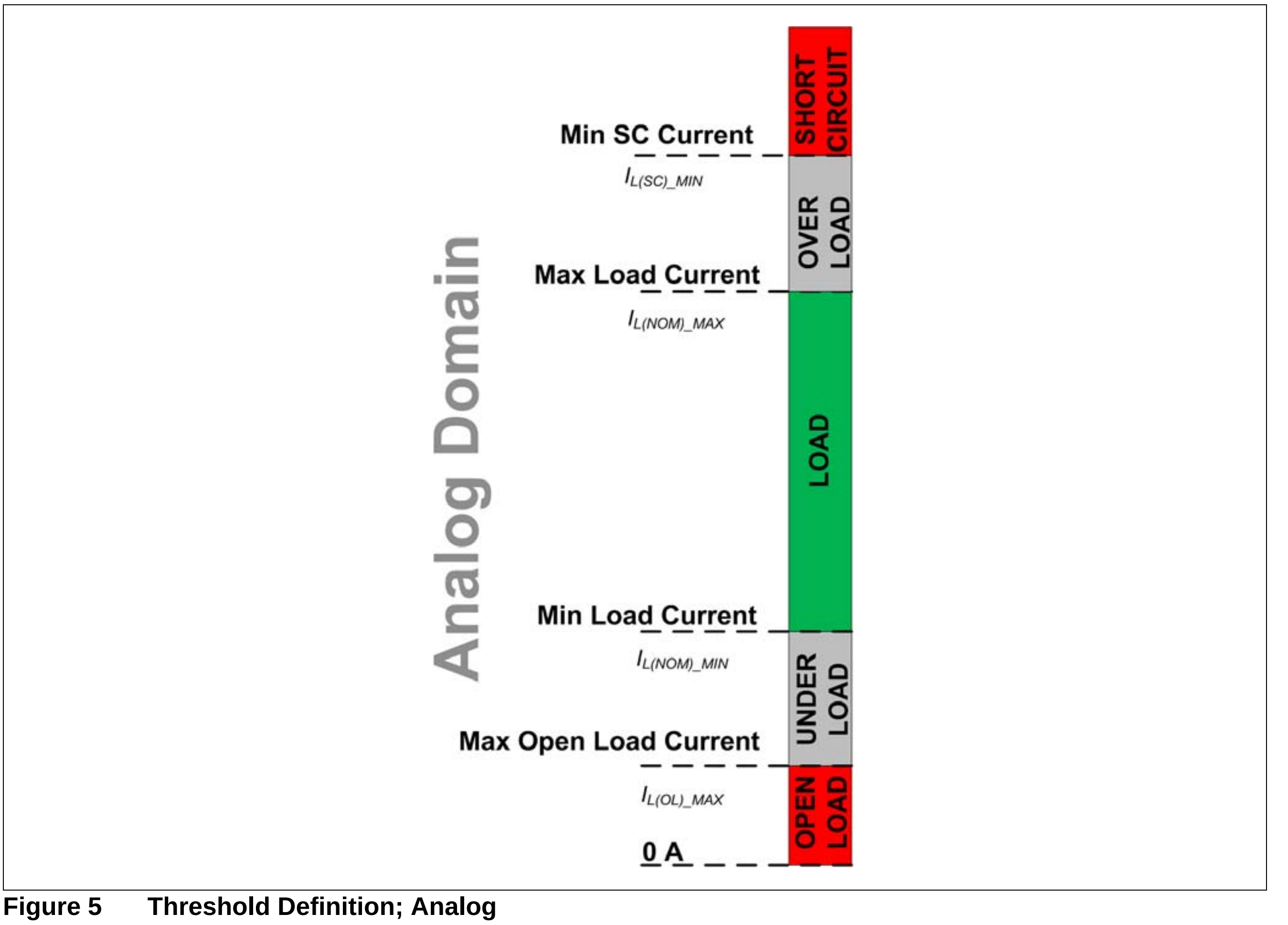

Figure 5 Threshold Definition; Analog

OPEN LOAD: In the case that no current is flowing (I_L = 0 A) the micro controller should detect an open load, which would mean that the load is disconnected or broken. However it is often the case that although the load is not connected anymore ($R_{LOAD} = \infty$), a current is still flowing. This current flow can be caused by a dirt resistance R_{DIRT} (high-ohmic connection between wires). As suggested in the PROFET™+ App Note (Chapter 6.3), R_{DIRT} can be considered with 4.7 to 30kΩ and maximum 5mA.

UNDERLOAD: The grey area represents a kind of guard band in which the current is not clearly assigned as LOAD or OPEN LOAD. Depending on the application, this area can be large or small.

LOAD: This is the nominal operation range for the load and the micro controller should diagnose this as OK. The upper value (Max Load Value) should be lower than the maximum value at the micro controller to leave room for the overload detection.

OVERLOAD: In this region the current is higher than the maximum nominal value but lower than the active protection treshold of the device. If this state persists, the micro controller should react on it as the increased power losses in the system can be harmful.

SHORT CIRCUIT: In this case the micro controller should switch OFF the device immediately to avoid degrading the device.

4 PROFET™+ Accuracy

In each PROFET™+ datasheet, the nominal load is specified and has to be respected for partitioning. Depending on the mOhm-range of each device, certain current points for the k_{ILIS} were chosen and the values specified in the datasheet.

4.1 Definition

Figure 6 provides the internal circuit principle of current sensing. The size ratio between T2 and T3 defines the mirror transformation ratio. This ratio is commonly called k_{ILIS}, meaning that the load current I_L is k_{ILIS} times higher than sense current I_S, $I_L = k_{ILIS} \times I_{IS}$. The transistor T1 supplies the $I_{IS(FAULT)}$ current to the IS pin in case the logic detects a FAULT condition.

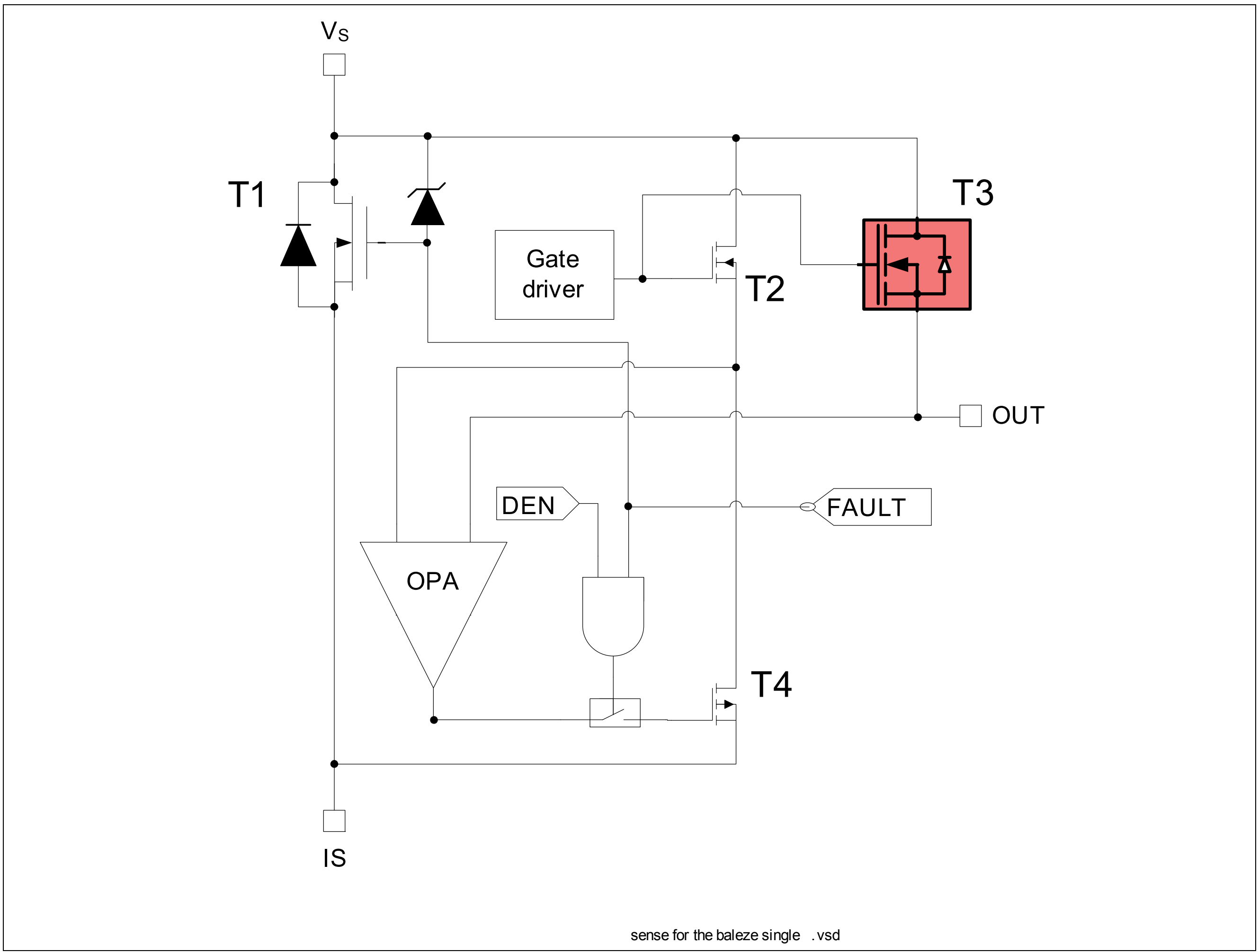

Figure 6 Current Sense Circuitry

4.2 k_{ILIS} and Current Sense representation

The current sense in specification is graphically represented in two possible ways. Either sketching the sense current I_{IS} on the Y axis and load current I_L on X axis as in **Figure 8**, or by by sketching the k_{ILIS} value on the Y axis, and load current on the X axis as in **Figure 7**; this curve is commonly called trumpet curve. A simple mathematical formula links the two curves. Usually the designer will prefer **Figure 8** as it gives a quick read out of the current sense value. Also for an interpolation operation, this curve proves to be appropriate as the progression is nearly linear. The benefit of **Figure 7** is that it shows that accuracy improves as load current increases. The motivation for **Figure 7** is the accuracy improves with load current current increase. But it doesn't appear as obvious as in the current I_L / I_{IS} graphic, since 8% error at 2A is higher than 50% error at 50mA in absolute value.

The k_{ILIS} values that are guaranteed and tested are written down in the datasheet. However, some applications may require a calculation with unspecified k_{ILIS} values. A linear interpolation for these values can be easily performed on the I_{IS} values (see **Figure 8**).

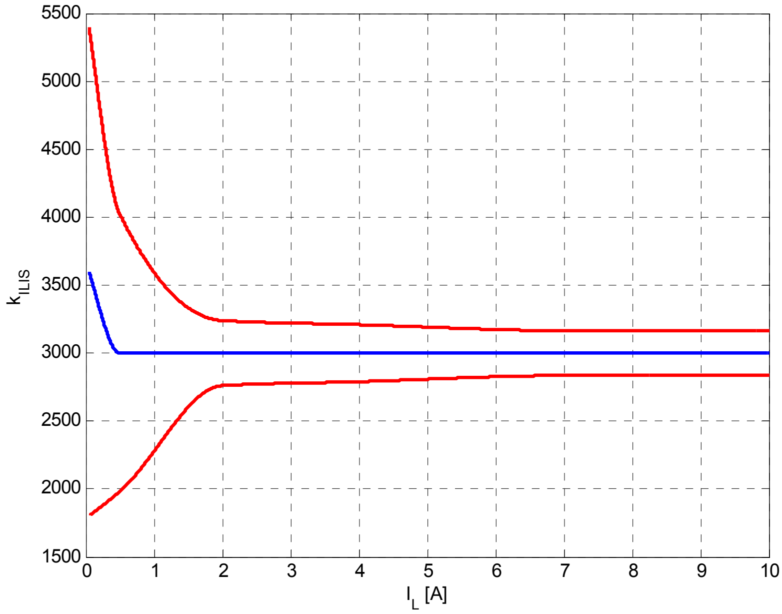

Figure 7 BTS5020-2EKA k_{ILIS} Trumpet

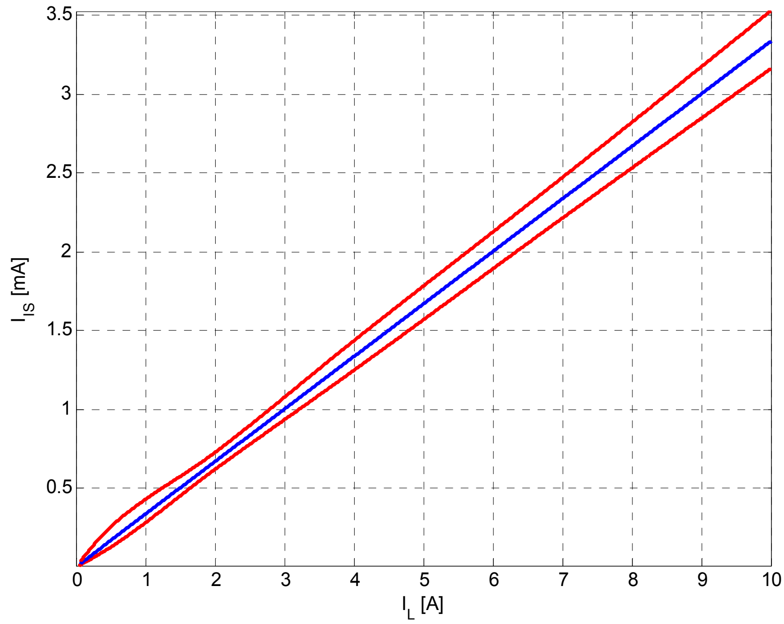

Figure 8 BTS5020-2EKA Sense Current vs. Load Current

Note that the the PROFET™+ have the accuracy of the kilis always specified symmetrically (e.g: k_{ILIS_typ} = 3000, k_{ILIS_max}= 3240 (+8%, p1= 1.08) , k_{ILIS_min}= 2760 (-8%, p2=0.92)). However if the I_{IS} representation is used this symmetry is lost (e.g: k_{ILIS_typ} = 3000 with +/- 8% spread, $I_{IS\_max} / I_{IS\_typ} = 1.087$; $I_{IS\_min} / I_{IS\_typ} = 0.926$)

A third graphic, often omitted is necessary to provide a full picture of the current sense, is sketched on **Figure 9**. It provides the current sense dynamic and the load current which will be confused with a short circuit. Three different cases are shown:

- **typical:** sense current in kilis mode and fault current have typical values
- **IS_max and ISfault_min:** sense current has maximum value and the fault current minimum value
- **IS_max and ISfault_max:** sense current in kilis mode and fault current have maximum values

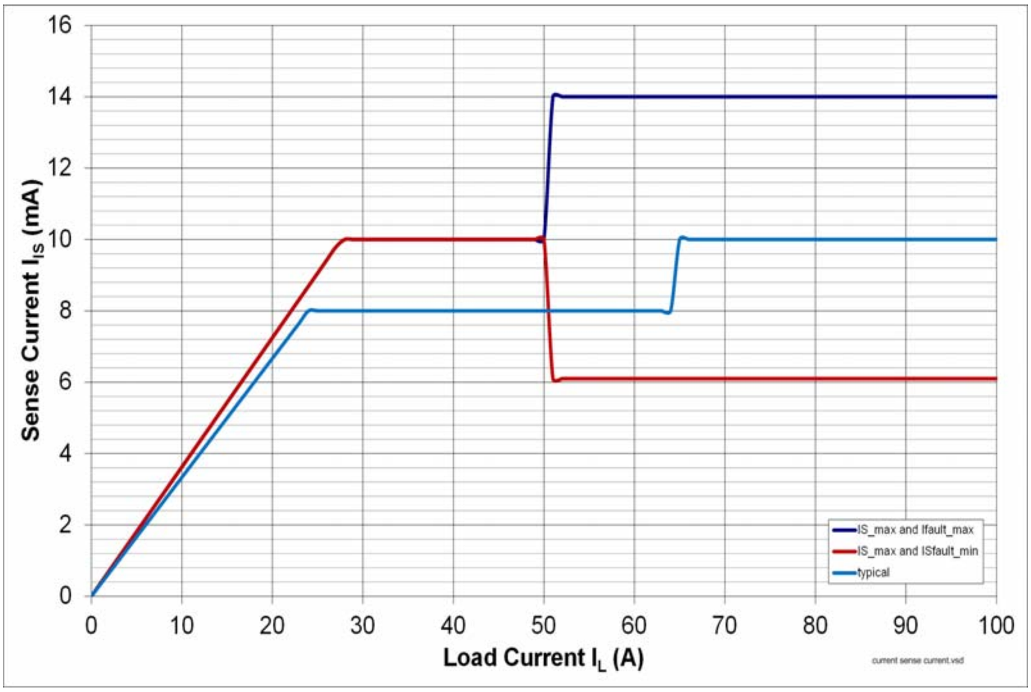

Figure 9 Current Sense Limitation Curve. BTS5020 Case

This shows that the sense current (k_{ILIS} current) can be higher than the fault current. The current through the sense pin (IS) is usually limited by the sense resistor R_{IS} and the supply voltage (V_S). Details are given in the next chapter.

4.3 Power Losses in the Sense Resistor R_{IS}

Looking at the specification of the PROFET™+, the current source of the $I_{IS(FAULT)}$ can provide up to 35mA. For most cases it is wrong to calculate the power losses of the resistor R_{IS} with this current $I_{IS(FAULT)\_max}$. As parameter P_7.5.6 (Sense signal saturation voltage) defines, the voltage at the IS pin cannot be higher than the voltage at V_S. Typically it is 2V below V_S. The correct calculation of the power losses is shown by **Equation (3)** and **Equation (4)**.

$$\mathrm{Ploss}_{\mathrm{typical}} = \frac{(V_S - 2)^2}{R_{IS}} \tag{3}$$

$$\mathrm{Ploss}_{\mathrm{worstCase}} = \frac{V_S^{\ 2}}{R_{IS}} \tag{4}$$

The internal sense circuit is battery related and will cause an internal voltage drop; therefore the Equation (3) draws a more realistic scenario. Figure 10 shows a PSPICE simulation of a device in fault condition (Open Load at OFF) where the fault current $I_{IS(FAULT)}$ is applied to the external resistor R_{IS} = 1.2k

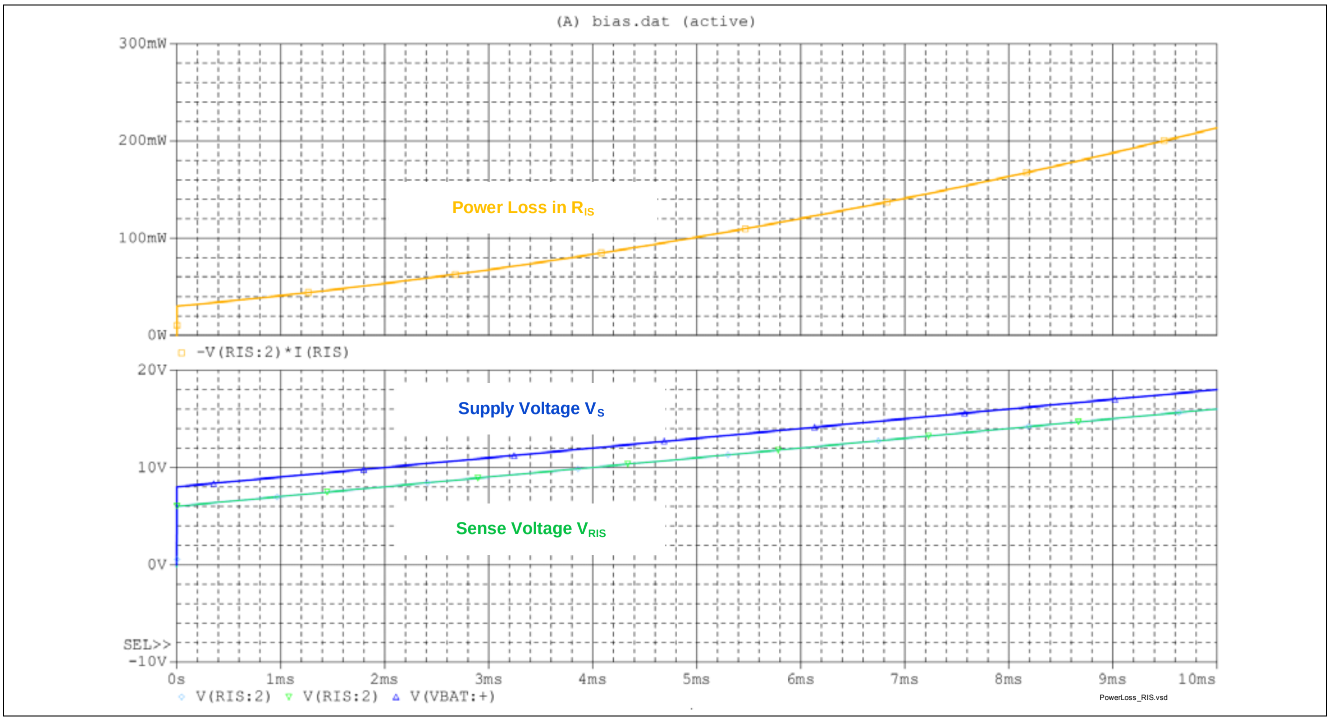

Figure 10 Power Losses in R_{IS} in Fault Condition. BTS5020 Case with Increasing Supply Voltage.

4.4 Applications with Small Currents

- W3W, P5W, P10W, P21W (24V) incandescent bulbs
- LED
- Relay
- Stepper Motor Supply
- …

Suggested 12V Devices:

- BTS5120-2EKA
- BTS5180-2EKA
- BTS5200-4EKA

Suggested 24V Devices:

- BTT6100-2EKA
- BTT6200-1EJA
- BTT6200-4EMA

Table 2 k_{ILIS} Accuracy - Small Currents

Current [mA]	BTS5120-2EKA	BTS5180-2EKA	BTS5200-4EKA
10	-	-	+/- 50%
25	-	-	+/- 35%
50	+/- 35%	+/- 35%	+/- 22%
100	+/- 31% 1)	+/- 31% 1)	+/- 18%
200	+/- 24% 1)	+/- 24% 1)	+/- 14% 1)
250	+/- 21%	+/- 21%	+/- 13% 1)
400	+/- 13% 1)	+/- 13% 1)	+/- 11% 1)
500	+/- 9%	+/- 9%	+/- 10%
1000	+/- 7.5%	+/- 7.5%	+/- 10%
2000	+/- 6%	+/- 6%	+/- 10%

1) interpolation value

Current [A]	BTT6100-2EKA	BTT6200
10	-	+/- 50%
25	-	+/- 45% 1)
50	+/- 50%	+/- 40%
100	+/- 40%	+/- 28% 1)
200	+/- 27% 1)	+/- 15%
250	+/- 22% 1)	+/- 13% 1)
400	+/- 15%	+/- 12% 1)
500	+/- 21% 1)	+/- 11%
1000	+/- 9%	+/- 9%
2000	+/- 9%	+/- 9%

1) Interpolation Value

4.5 Applications with Medium Currents

- P21W, P27W incandescent bulbs
- H8 35W halogen bulb

Suggested 12V Devices:

- BTS5020-2EKA / BTS5020-1EKA
- BTS5030-2EKA / BTS5030-1EJA
- BTS5045-2EKA / BTS5045-1EJA
- BTS5090-2EKA / BTS5090-1EJA

Suggested 24V Devices:

- BTT6030-2EKA / BTT6030-1EKA
- BTT6050-2EKA / BTT6050-1EKA

Table 3 k_{ILIS} **Accuracy - Medium Currents**

Current [A]	BTS5020	BTS5030	BTS5045	BTS5090
0.05	+/-50%	+/-50%	+/-50%	+/-50%
0.25	+/-41% 1)	+/-26% 1)	+/-23% 1)	+/-23% 1)
0.5	+/-34%	+/-20%	+/-16%	+/-16%
1	+/-22% 1)	+/-17% 1)	+/-10%	+/-10%
2	+/-8%	+/-8%	+/-7%	+/-7%
4	+/-7%	+/-6.5%	+/-6.5%	+/-6.5%
7	+/-5.5%	+/-5.5%	+/-6.5%	+/-6.5%

1) interpolation value

Current [A]	BTT6030	BTT6050
0.05	+/-50%	+/-50%
0.25	+/-45% 1)	+/-41% 1)
0.5	+/-40%	+/-40%
1	+/-32% 1)	+/-22%
2	+/-22%	+/-18%
4	+/-18%	+/-17%
7	+/-17%	+/-17%

1) Interpolation Value

4.6 Applications with High Currents

- H1, H3, H4, H7, H8, H9, H10 halogen bulbs (35-65W 12V) (70-75W 24V)
- Bulb combinations up to 100W (12V) and 147W (24V)

Suggested 12V Devices:

- BTS5008-1EKB
- BTS5010-1EKB
- BTS5012-1EKB
- BTS5016-2EKA/ BTS5016-1EKB
- BTS5020-2EKA / BTS5020-1EKA

Suggested 24V Devices:

- BTT6020-1EKA
- BTT6010-1EKA

Table 4 k_{ILIS} **Accuracy - High Currents**

Current [A]	BTT6020-1EKA	BTT6010-1EKA
0.05	+/-50%	+/-50%
0.25	+/- 45%1)	+/-45% 1)
0.5	+/-40%	+/-40%

Table 4 k_{ILIS} Accuracy - High Currents

Current [A]	BTT6020-1EKA	BTT6010-1EKA
2	+/-22%	+/-18% [1)]
4	+/-18%	+/-10%
7	+/-17%	+/-9%
10	+/-17%	+/-9%

1) interpolation value

Current [A]	BTS5008-1EKB	BTS5010-1EKB	BTS5012-1EKB	BTS5016	BTS5020
0.05	+/-50%	+/-50%	+/-50%	+/-50%	+/-50%
0.25	+/-45% [1)]	+/-45% [1)]	+/-45% [1)]	+/-45% [1)]	+/-45% [1)]
0.5	+/-40%	+/-40%	+/-40%	+/-40%	+/-34%
2	+/-22%	+/-22%	+/-22%	+/-22%	+/-8%
4	+/-18%	+/-18%	+/-18%	+/-18%	+/-7%
7	+/-17.5% [1)]	+/-17.5% [1)]	+/-17.5% [1)]	+/-17.5% [1)]	+/-5.5%
10	+/-17%	+/-17%	+/-17%	+/-17%	+/-5.5%

1) Interpolation value

5 Diagnosis System

Figure 11 shows the typical connections between a two-channel PROFET™+ and a micro controller. The diagnosis chain consist of measuring the load current, mirrored in the current sense, converted to voltage in the R_{IS} resistor and read by the AD converter of the micro controller. External components mainly consist of three resistors: R_{IN}, R_{IS} and R_{ADC}. The external components between the device ground (GND) and the module ground is modelled as a general block and will be discussed in detail in the following chapters.

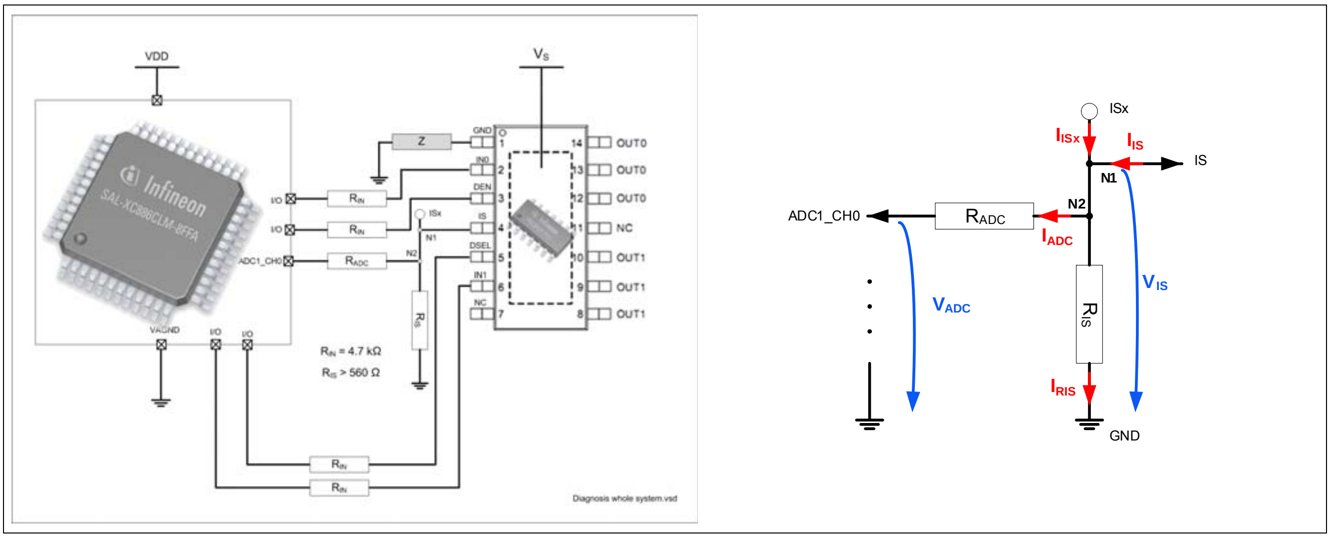

Figure 11 PROFET™+ with Microcontroller

The most relevant current-nodes for the diagnosis circuit are marked with N1 and N2. For a simplified calculation, the voltage drop caused on R_{ADC} can be neglected as the current I_{ADC} should be very small in normal operation.

5.1 Choosing the Sense Resistor

To make use of the Full Scale Range (FSR) of the microcontroller, it is recommended to take a sense resistor R_{IS} that converts the sense current of the nominal load current to a voltage near V_{DD} / 2. The k_{ILIS} of the PROFET™+ devices are scaled to achive the V_{DD} / 2 at nominal load with a 1.2k to 1.8k resistor. The power losses in the sense resistor should be also considered (see **Chapter 4.3**).

Adding the digital domain to the **Figure 5** gives the complete picture of the diagnosis mechanism.

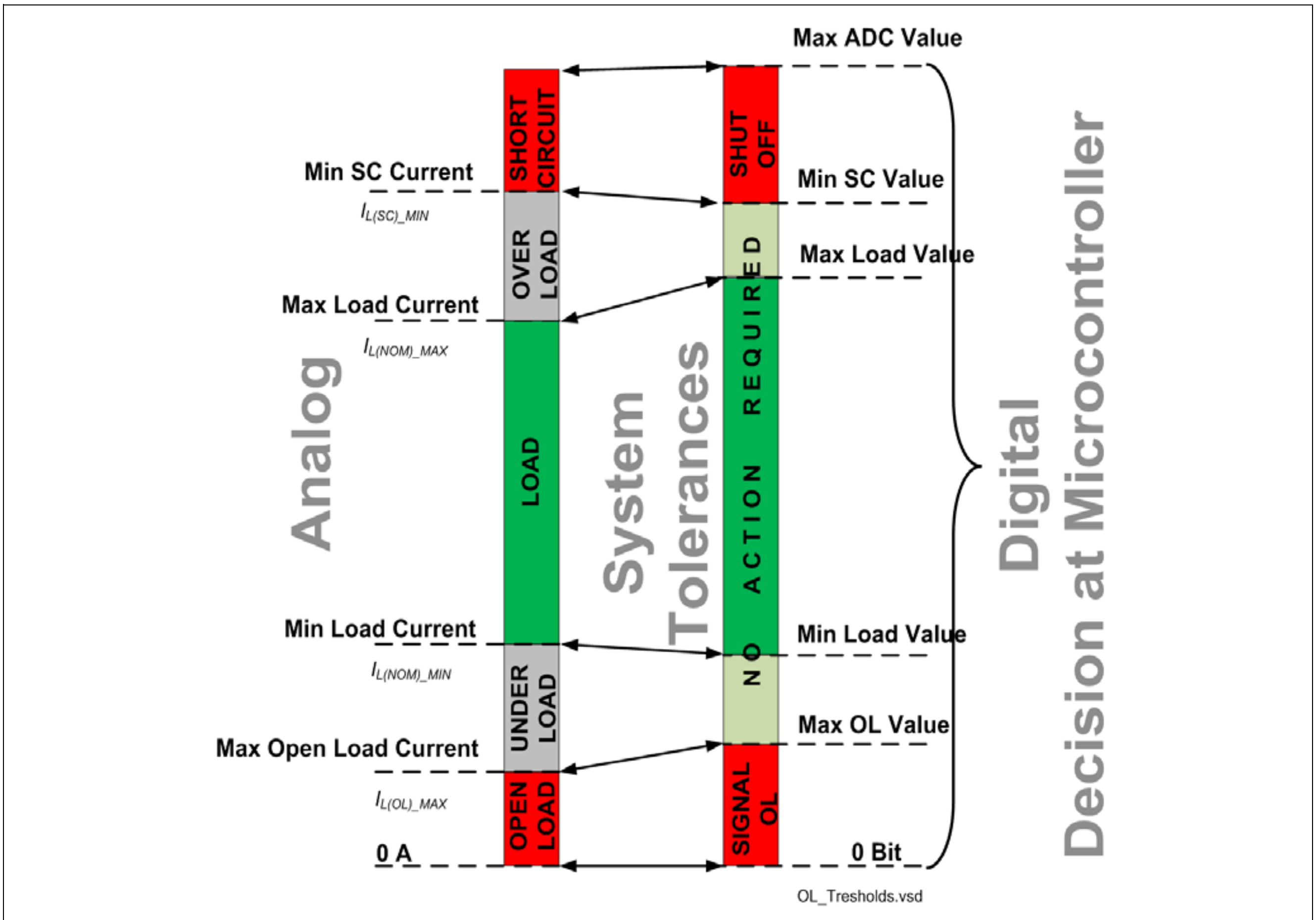

Figure 12 Threshold Definition; Analog to Digital

5.2 Digital Threshold Calculations

To calculate the digital values at the micro controller, the following parameters should be known:

Table 5 Considered Inaccuracies

Source of Influence	Load	PROFET™+	External Analog System	Micro Controller
Influence 1	maximum open load current	k_{ILIS} values	tolerance	# of bits AD-Converter
Influence 2	nominal current range	leakage currents ISx	temperature coefficient	Total Unadjusted Error E_{TUE}
Influence 3	minimum overload current			Supply Voltage Tolerance

Formulas for the sense resistor R_{IS}

$$R_{ISmax} = R_{IS} \times (1 + tol) \times \langle 1 + \frac{|T0 - T_{max}| \times \alpha_{T0}}{1 \times 10^6} \rangle \quad (5)$$

$$R_{ISmin} = R_{IS} \times (1 - tol) \times \langle 1 - \frac{|T0 - T_{min}| \times \alpha_{T0}}{1 \times 10^6} \rangle \quad (6)$$

Formulas for the *Min Load Value*

$$I_{ISmin} = \frac{I_{Lmin}}{k_{ILISmax}} \quad (7)$$

$$V_{ISmin} = I_{ISmin} \times R_{ISmin} \quad (8)$$

$$LSB_{max} = \frac{V_{REFmax}}{2^N} \quad (9)$$

$$Bits_{min} = round\left(\frac{V_{ISmin}}{LSB_{max}}\right) - E_{TUE} \quad (10)$$

Formulas for the *Max Load Value*:

$$I_{ISmax} = \frac{I_{Lmax}}{k_{ILISmin}} \quad (11)$$

$$V_{ISmax} = I_{ISmax} \times R_{ISmax} \quad (12)$$

$$LSB_{min} = \frac{V_{REFmin}}{2^N} \quad (13)$$

$$Bits_{max} = round\left(\frac{V_{ISmax}}{LSB_{min}}\right) + E_{TUE} \quad (14)$$

5.3 Calculation of Open Load Threshold

The following calculation steps for the open load diagnosis takes the main inaccuracies into account, therefore an additional safety margin should be considered.

The open load diagnosis can be considered as functional if the *Max Open Load Current* can be distinguished to the *Min Load Current*. In the PROFET™+ datasheets the parameter $I_{L(OL)}$ (Open Load detection threshold in ON state) defines the range above the open load current. Usually when the load is disconnected or broken still a leakage current can flow through the OUTput. This current can be caused by high ohmic connections of wires.

Infineon considers 5mA as leakage current in this condition. In the test condition of $I_{L(OL)}$ the sense current $I_{IS(OL)}$ is defined. With the former assumptions, the sense current in case of open load must be smaller or equal to $I_{IS(OL)}$.

Table 9 Electrical Characteristics: Diagnostics

V_S = 8 V to 18 V, T_J = -40 °C to +150 °C (unless otherwise specified).
Typical values are given at V_S = 13.5 V, T_J = 25 °C

Parameter	Symbol	Values			Unit	Note / Test Condition	Number
		Min.	Typ.	Max.			
Load Condition Threshold for Diagnostic							
Open load detection threshold in OFF state	$V_S - V_{OL(OFF)}$	4	–	6	V	[1] V_{IN} = 0 V V_{DEN} = 4.5 V See **Figure 26**	P_7.5.1
Open load detection threshold in ON state	$I_{L(OL)}$	5	–	30	mA	V_{IN} = V_{DEN} = 4.5 V $I_{IS(OL)}$ = 4 µA See **Figure 24** See **Figure 46**	P_7.5.2

IL(OL)_BTS5020.vsd

Figure 13 Parameter: Open Load Detection Threshold in ON State; BTS5020-2EKA

The graphical representation of the parameter definition of **Figure 13** is shown in **Figure 14**.

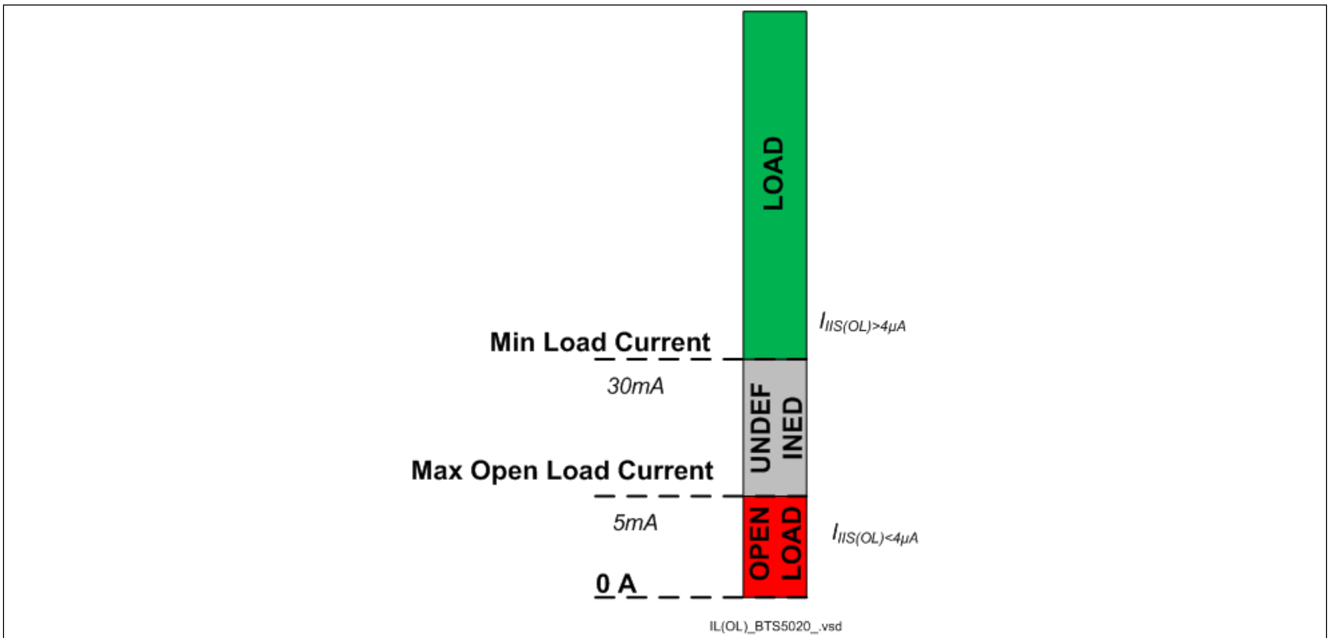

Figure 14 Illustration: Open Load Detection Threshold in ON State; BTS5020-2EKA

This means if only the device accuracy is considered, it is possible to distinguish between 5mA and 30mA load current. In reality the external system tolerances force the *Min Load Current* threshold to increase.

5.4 Calculation for Partial Load Loss

For many applications, especially with bulb and LED, multiple loads are connected to the output of the PROFET™+. It is beneficial to provide a diagnosis detecting the partial failure of the load, to meet the safety and legal requirements (i.e. flasher - 2x21W + 5W). This introduced the requirement to distinguish between the current range where all the loads are working as expected and the range where a partial load loss occurs. **Figure 15** visualizes these areas as **LOAD** and **PARTIAL LOAD**.

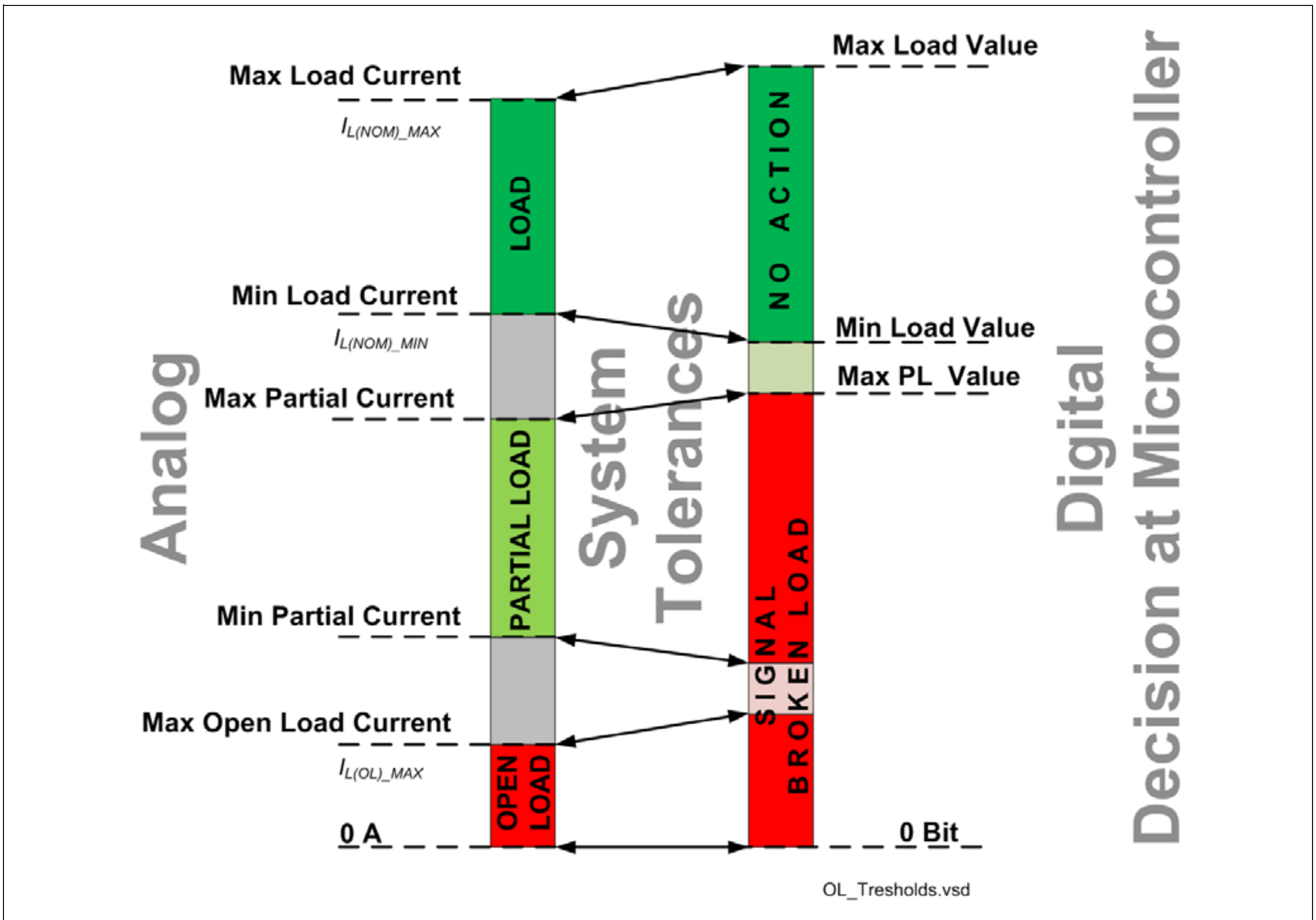

Figure 15 Threshold Definition for Partial Loss of Load

This figure is simplified to show only the digital thresholds that separate the critical red area from the uncritical green one. It is also possible to have different software strategies for the **OPEN LOAD** and **PARTIAL LOAD** case, which introduces new digital thresholds at the microcontroller.

To distinguish between a **LOAD** and **PARTIAL LOAD** the following equation, based on **Equation (10)** and **Equation (14)**, must be fulfiled.

$$\mathrm{Bits}_{\mathrm{MaxPartialLoadValue}} < \mathrm{Bits}_{\mathrm{MinLoadValue}} \tag{15}$$

$$\mathrm{round}\left(\frac{V_{\mathrm{ISmax}}}{\mathrm{LSB}_{\mathrm{min}}}\right) + E_{\mathrm{TUE}} < \mathrm{round}\left(\frac{V_{\mathrm{ISmin}}}{\mathrm{LSB}_{\mathrm{max}}}\right) - E_{\mathrm{TUE}} \tag{16}$$

To account for additional system inaccuracies and external factors it is recommended to have a safety margin of some LSBs between the *Max Load Value* and the *Max PL Value*.

The k_{ILIS} values specified in the PROFET™+ datasheets already considers production spread, temperature spread (-40...+150°C) and lifetime drifts. No k_{ILIS} deviation over different supply voltages (8...18V) has to be taken into account.

5.5 Sharing IS-Pins

When the design of a module with a high number of discrete components is done, there is often a shortage of available micro controller pins. With PROFET™+ it is possible to share input and/or output pins at the micro controller interface.

Figure 16 shows on the example of two dual channel devices how the connection can be done. The same concept can be applied to more than two devices. It is important that both devices share the same battery supply because otherwise a coupling through the PROFET™+ exists that can lead to device destruction.

For the diagnosis of all channels, the micro controller has to use the DEN and DSEL pins eg. deactivate PROFET+_2 diagnosis, activate PROFET+_1 diagnosis, select channel 0 diagnosis (DSEL=0) on PROFET+_1 and read out the IS feedback. Sharing the ADC conncection is only possible because the leakage current of the PROFET™+ on the IS pins is very small (e.g.: BTS5020-2EKA, datasheet v2.1, P_7.5.2: leakage at IS pin is maximum 1µA)

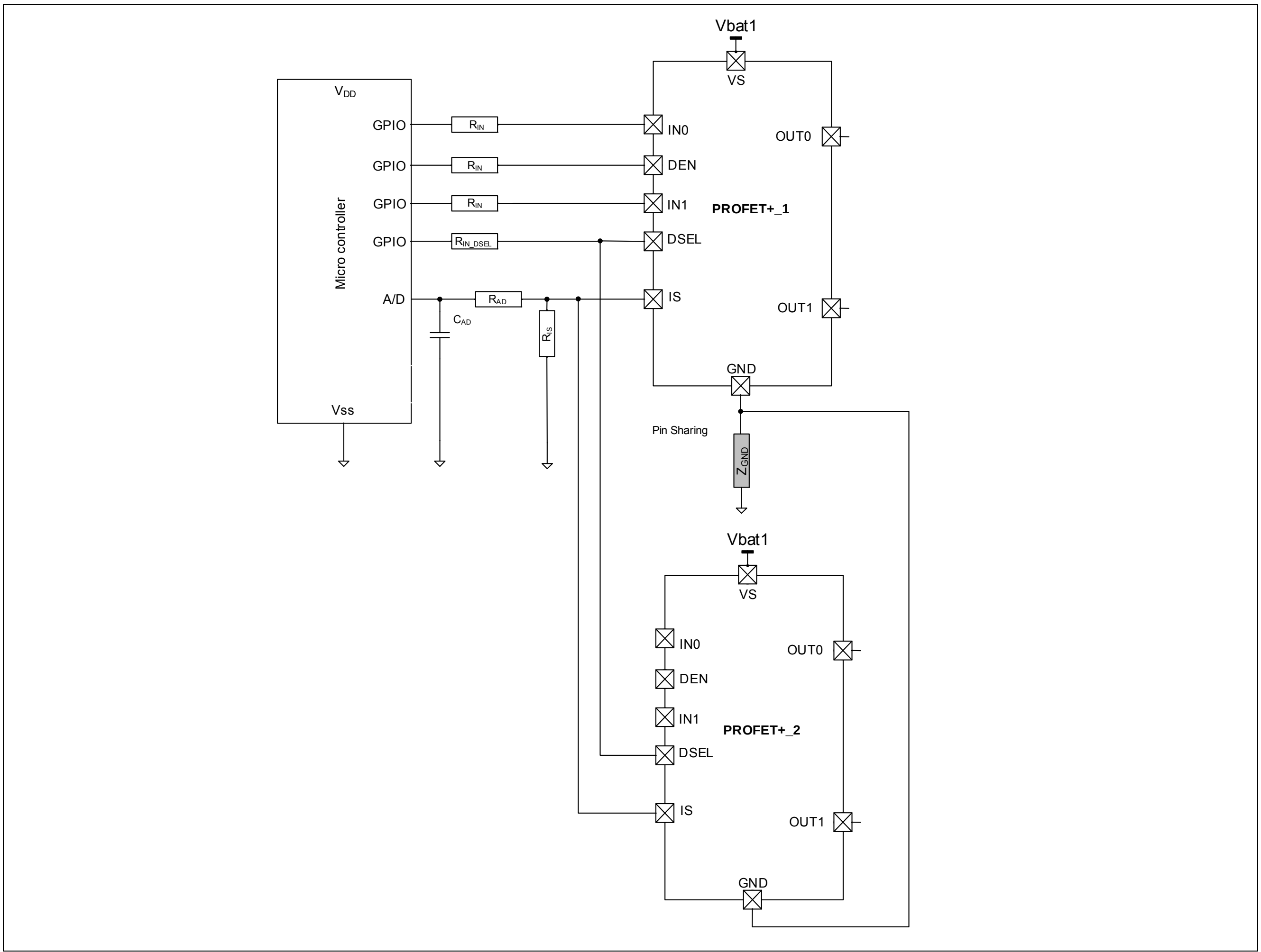

Figure 16 Sharing of Micro Controller Pins

6 Required Application Accuracy for Diagnosis

6.1 How to Define the Required Accuracy

Figure 17 describes graphically the way to define the requested accuracy. The designer should define, prior to anything else, several currents necessary to estimate the need for diagnostic. What is the maximum load current considered as open load or underload, $I_{L(OL)\_MAX}$, the minimum load current considered as nominal operation $I_{L(NOM)\_MIN}$, the maximum current considered as nominal operation $I_{L(NOM)\_MAX}$, and the minimum current considered as overload $I_{L(SC)\_MIN}$. The gap between $I_{L(OL)\_MAX}$; $I_{L(NOM)\_MIN}$ and between $I_{L(NOM)\_MAX}$; $I_{L(SC)\_MIN}$, appearing in grey in the graphic, has to be considered as the margin the system can use during the diagnosis process. These currents will be translated to current sense I_{IS} with the k_{ILIS} factor error. Then, this IIS current will be translated to voltage with the R_{IS} resistor and finally converted to digital information with the A/D converter.

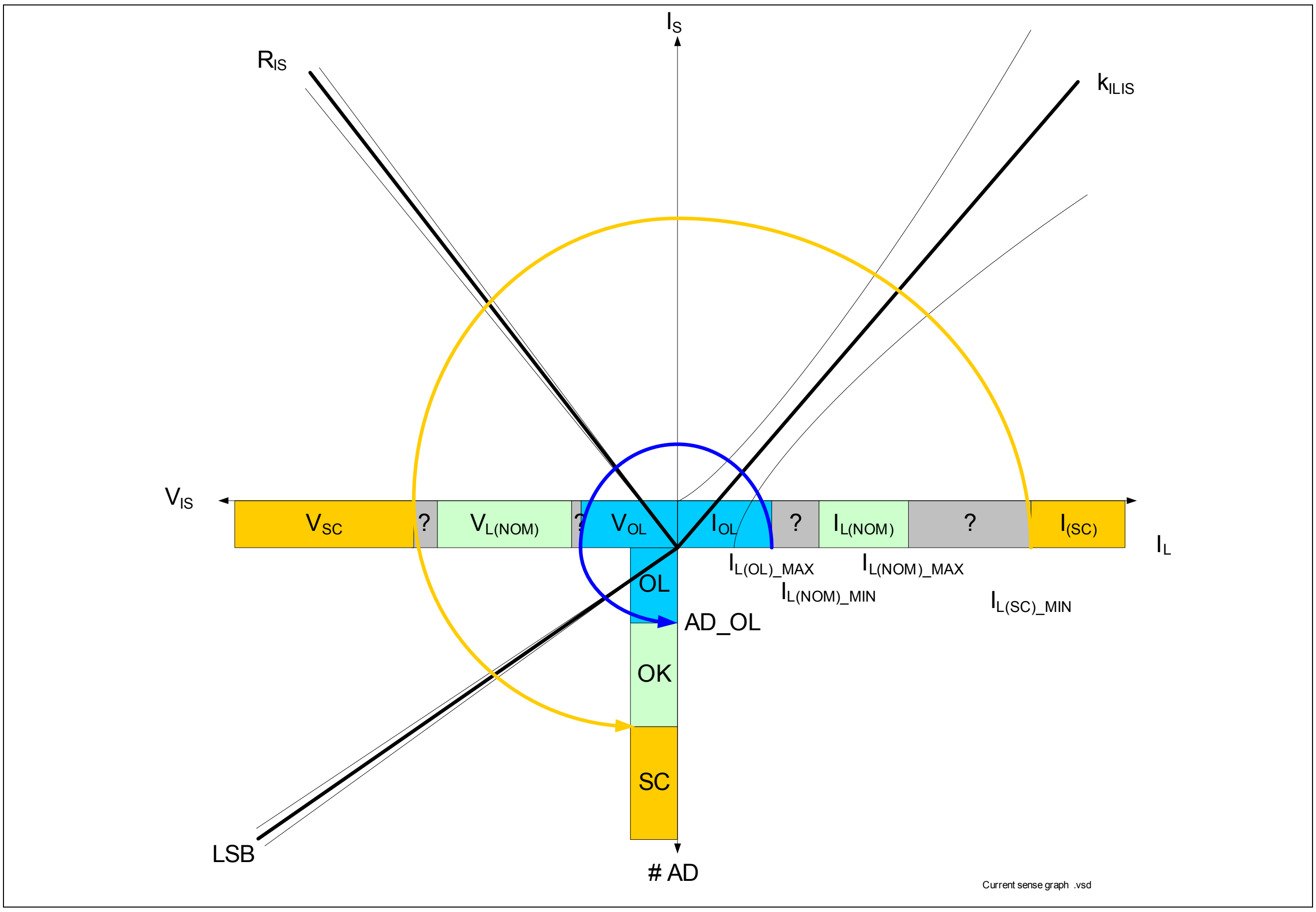

Figure 17 Graphical Description of the Required Current Measurement

6.2 System Influence

The largest influence on diagnosis performance of the system is not necessarily the current sense inaccuracy of PROFET™+. The following factors will also influence the diagnostic performance of the system:

- **A/D conversion** :inaccuracy of the A/D converter, expressed in LSB (i.e. 1,3,5, etc...)
- **A/D reference**: affecting the A/D reference voltage (i.e. 0.5%, 1%, 2%, etc...)
- **Sense resistor** : inaccuracy of the sense resistor value (i.e. 0.1%, 1%, etc...)
- **Number of devices connected to the A/D converter** : if multiple current sense outputs are connected to a single A/D converter on the microcontroller, leakage currents from other devices.

Addtionally, if an absolute threshold is not possible, due to inadequate margin between two currents steps (refer to the grey zone in the **Figure 17**), a voltage dependant threshold has to be implemented. This is shown in the example of bulb loads (see **Figure 19**). Therefore, additional sources of error should be considered:

- **Battery voltage measurement accuracy**: accuracy of the battery voltage measurements due to the voltage divider, A/D converter accuracy, and the possible variation of the battery voltage between two battery measurements
- **Ground shift voltage**: The ground shift between the module's ground and load ground can be a big source of inaccuracy. (shifts of up to ±1.5V should be considered).
- **PWM inaccuracy** : timing inaccuracies (i.e. differences between the turn-ON and turn-OFF time of the smart power switch) can cause a difference between the desired PWM duty cycle and actual duty cycle, affecting the equivalent lamp resistance and load current during PWM operation.

In the rest of the document, the set up considered is summed up in **Table 6**.

Table 6 System Set up Assumption

Parameter	Value
A/D converter	10 bit
A/D reference voltage	5V
A/D conversion accuracy; E_{TUE}	+/- 3 LSB
A/D reference voltage accuracy	+/- 2%
Sense resistor accuracy	+/- 1%
Leakage current on sense	1µA
Battery voltage measurement accuracy	2%
Ground shift voltage	+/- 1.5V
PWM inaccuracy	50µs * 100Hz = 0.5%
Timing error of PWM	3%

6.3 Diagnosis of a P21W Lamp

In this chapter the diagnosis of a very common bulb, the P21W is described in detail. **Figure 18** shows the load current of a 21W bulb, with dependance to the supply voltage and the tolerance of the bulb itself. Two points are of interest, the minimum current of the smallest lamp at the lowest voltage, here 1.12A and the maximum current of the biggest lamps at the highest voltage, here 2.39A.

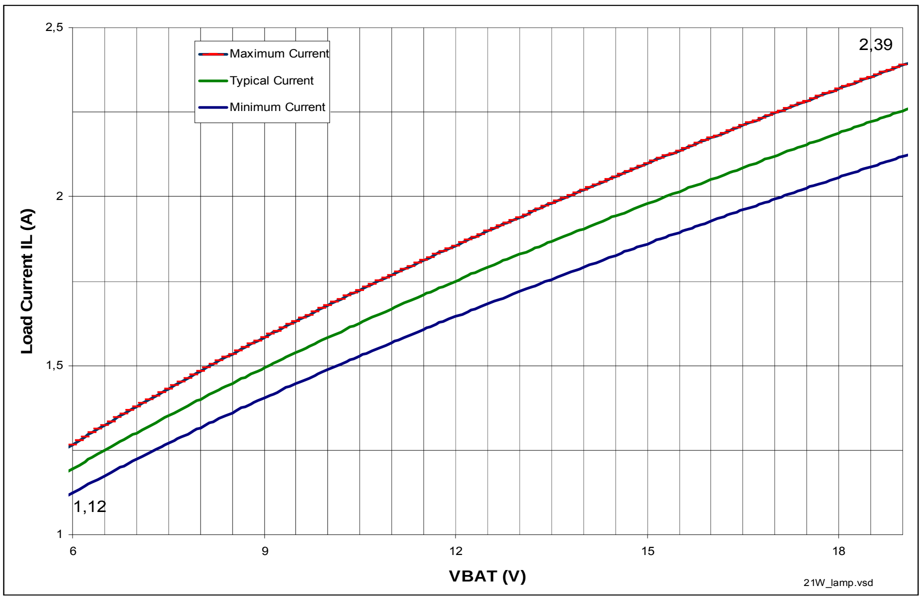

Figure 18 P21W Lamp Current as a Function of the Supply Voltage

Of course, different usage can be considered for the P21W, summed in **Figure 19** which shows that the load current $I_{L(NOM)}$ can be higher, either during power regulation in PWM, or during dimming with a low duty cycle.

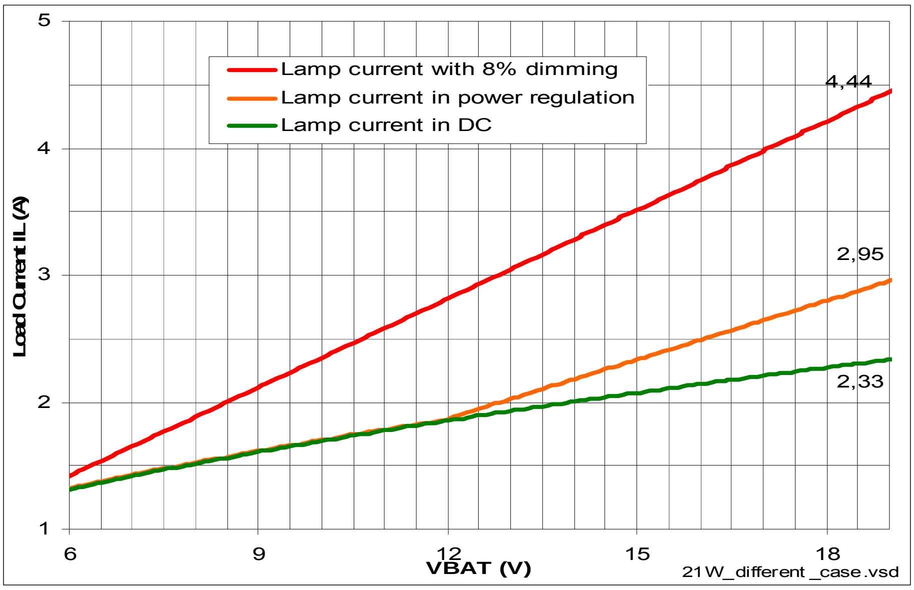

Figure 19 Maximum P21W Load Current Depending on the Usage[1)]

If the application is considered to be used in DC, the nominal current I_L is bordered by the values [1.12A ; 2.39A.]. The open load current is considered as $I_{L(OL)\_MAX}$ = 5mA. An open load recognition consists of distinguishing between 5mA to 1.12A. For the following calculations the specification of the appropriate PROFET™+ for a P21W bulb is used (BTS5090-2EKA).

Using **Equation (7)** to **Equation (10)** for the minimum number of LSBs for the load (1.12A) and **Equation (12)** (using $I_{IS(OL)}$ = 8µA from P_7.5.2) to **Equation (14)** for the maximum number of bits of the open load current (5mA)

1) The slight difference of current between **Figure 18** and **Figure 19** comes from the difference of calculation method. **Figure 18** uses a rigorous formula while **Figure 19** uses only an approximation

the following is obtained. Open Load Range = 0...5 LSBs; Load > 179 LSBs. This demonstrates that the P21W bulb can be easily diagnosed using PROFET™+.

Often it is necessary to support both a bulb and LED on the same BCM and provide a load diagnosis. A equivalent replacement of the P21W bulb would be a 4W LED with approximately 200mA load current. Keeping the above assumptions and changing to the 4W LED results in: Open Load Range = 0...5 LSBs; Load > 40 LSBs. This means also for an LED the diagnosis is feasible.

7 Current Sense Calibration

Specified k_{ILIS} values in the datasheet are guaranteed values and must be valid under all conditions. The minimum and maximum values have to account for lifetime drifts, production spread, voltage and temperature dependencies. Effects of the lifetime drift is not predictable and must be considered through approximations. As a result of this, one individual device shows much better accuracies if some of these factors are eliminated. **Figure 20** shows the accuracy of a singular BTS5020-2EKA device over different currents and at three termperatures. The accuracy is related to the k_{ILIS} value at 4A at 25°C which is 3000. Identifying this k_{ILIS} value is equal to a one point calibration at room temperature.

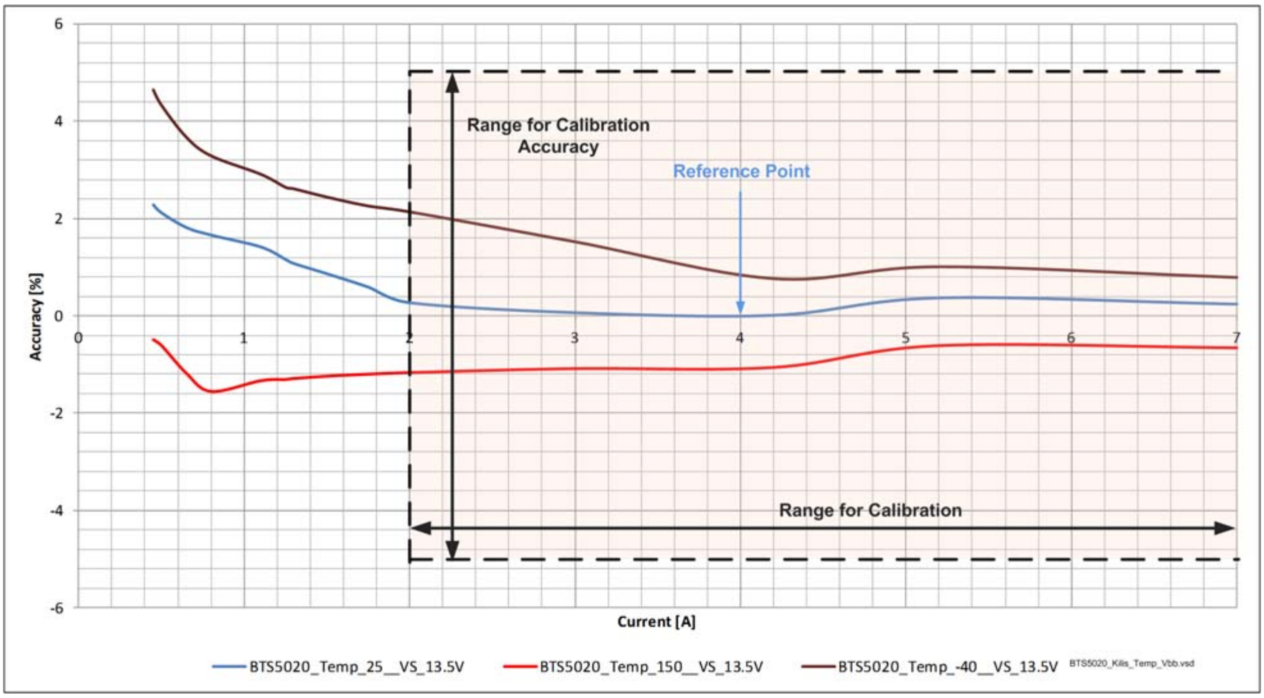

Figure 20 BTS5020-2EKA Zero Hour k_{ILIS} Performance

Smaller currents are more prone to the influences of the operational amplifier in the sense circuit. As a consequence it does not make sense to do a calibration at smaller load currents. For the BTS5020-2EKA the datasheet specifies that a calibration for currents bigger or equal to 2A is valid.

In case the current sense accuracy is not precise enough, calibration can be considered. The calibration point(s) choice is of primary importance to reach the best possible accuracy. This chapter describes the results applied to the BTS5020-2EKA. By analogy, all PROFET™+ can be described with this method.

7.1 Single Point Calibration

Single point calibration compensates the k_{ILIS} ratio error (mismatch between the current sense DMOS cells and the main DMOS). It is not compensating systematic error linked to the operational amplifier offset and will not compensate the aging. **Figure 21** shows as example, the results of a calibration realized at 1A and k_{ILIS} ratio measured at 7A, and the opposite. The blue color indicates the cold (-40°C) test, green indicates ambient and red hot (150°C) temperature. The different lines for a given color, indicates the drift observed due to aging.

The X-axis express the drift in percent, while the Y-axis provides the probability to find a device with such derating. Three lots, 30 samples each are tested.

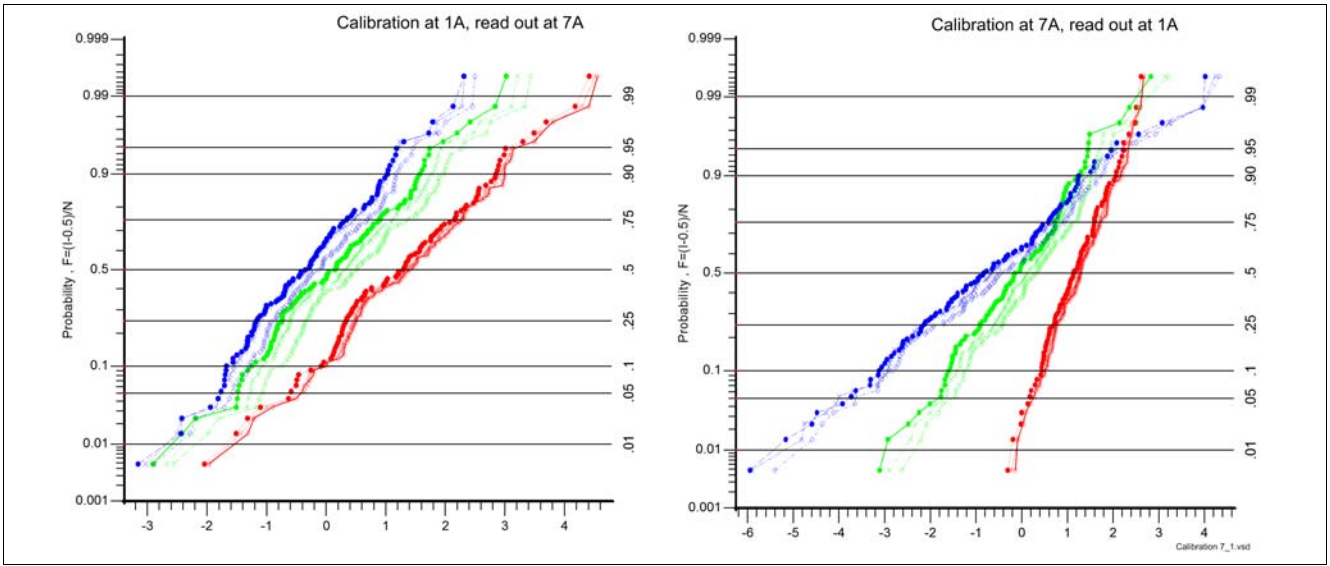

Figure 21 BTS5020-2EKA Calibrated at 1A (resp 7A) and Measured at 7A (resp 1A) with Aging

Out of these graphs, we can extract the **Table 7**, indicating both temperature, calibration point and load current influence.

Table 7 Calibration results of the BTS5020-2EKA in Percent of Error

Calibrated at	Measured at	1A	2A	4A	7A
1A	-40°C	-3 ; +2,5	-2 ; +2	-2,5 ; 2	-3,5 ; +3
	+25°C	-1 ; +1,5	-1,5 ; +2,5	-2,5 ; 3	-3,5 ; +3,5
	150°C	-1 ; +3	-1,5 ; +4,5	-2 ; +5	-2,5 ; +4,5
2A	-40°C	-5 ; +3,5	-2 ; +1	-1 ; +1	-2 ; +1
	25°C	-2 ; +2	-0,5 ; +1	-1 ; +1,5	-2 ; +1,5
	150°C	0 ; +2	-0,5 ; +2,5	-1 ; +3	-1 ; +3
4A	-40°C	-6 ; +5	-3 ; +2	-1,5 ; +1	-1 ; +0
	+25°C	-4 ; +3	-1,5 ; +1,5	0 ; +1	-1 ; +1
	150°C	-0,5 ; +2	0 ; +2	0 ; +2	-0,5 ; +2
7A	-40°C	-6 ; +5	-3 ; +2,5	-1,5 ; +1	-1 ; +0,5
	+25°C	-4 ; +4	-1,5 ; +2,5	-0,5 ; +1	0 ; +1
	150°C	-1 ; +2	0 ; +2	0 ; +2	0 ; +2

As temperature is quite difficult to take into account during software programming, **Table 7** can be reduced to **Table 8**.

Table 8 Calibration results of the BTS5020-2EKA in Percent of Error

Calibrated at	Measured at	1A	2A	4A	7A	Datasheet
1A	All temp	+/- 3	+/- 4,5	+/- 5	+/- 5	+/- 21%[1)]
2A	All temp	+/- 5	+/- 2,5	+/- 3	+/- 3	+/- 8%
4A	All temp	+/- 6	+/- 3	+/- 2	+/- 2	+/-7%
7A	All temp	+/- 6	+/- 3	+/- 2	+/- 2	+/-5.5%

1) Estimated by linearization

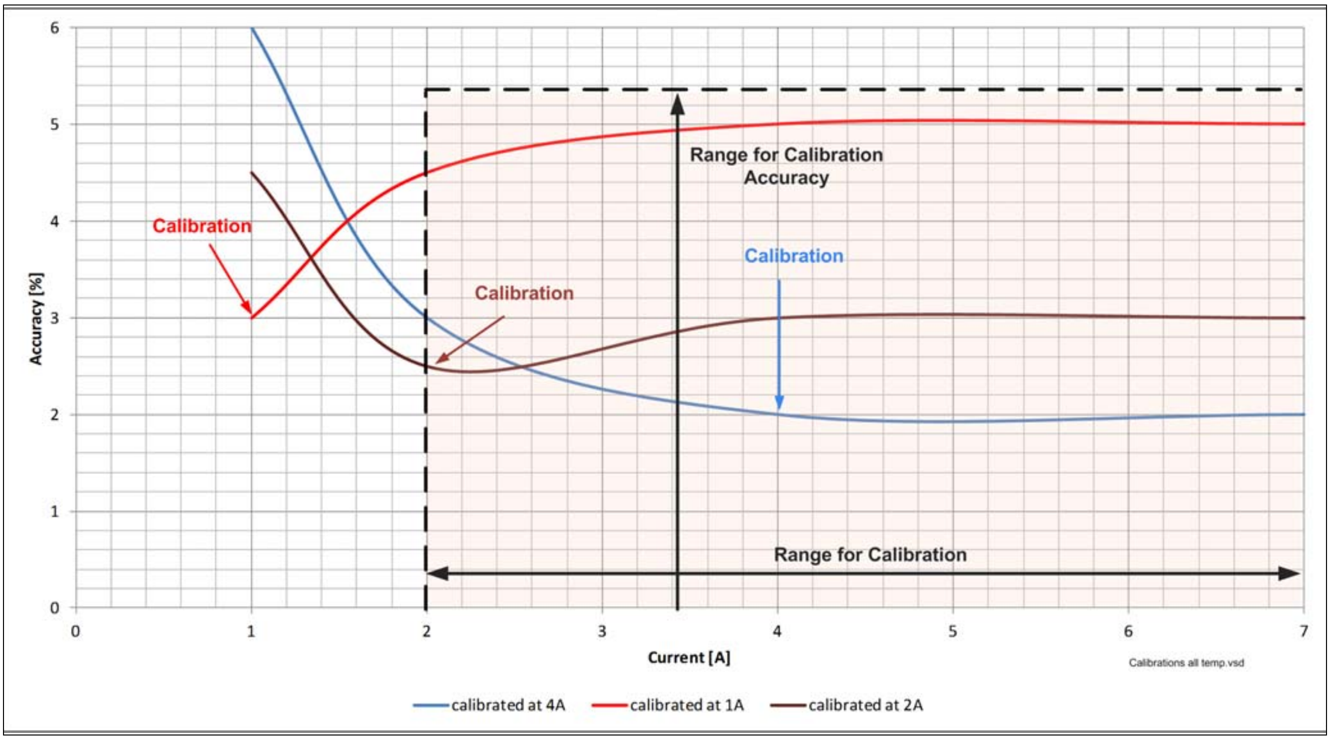

Figure 22 BTS5020. Calibration at 1A and expected Accuracy along the Load Current

Table 9 is the prolongation of the BTS5020-2EKA analysis.

Table 9 Calibration results of the PROFET™+ BTS5020-2EKA in Percent of Error

Calibrated at	Measured at	Half $I_{L(2)}$	$I_{L(2)}$	$I_{L(3)}$	$I_{L(4)}$	Datasheet
Half $I_{L(2)}$	All temp	-3 ; +3	-2 ; +4,5	-2,5 ; +5	-3,5 ; +4,5	+/- 21%[1)]
$I_{L(2)}$	All temp	-5 ; +3,5	-2 ; +2,5	-1 ; +3	-2 ; +3	+/- 8%
$I_{L(3)}$	All temp	-6 ; +5	-3 ; +2	-1,5 ; +2	-1 ; +2	+/- 7%
$I_{L(4)}$	All temp	-6 ; +5	-3 ; +2,5	-1,5 ; +2	-1 ; +2	+/- 5.5%

1) Estimated by linearization

6.4 Calibration at 20mA with 90 Devices of 3 Lots

To evaluate the calibration performance of the PROFET™+ a limited number of devices of the 45mOhm and 30mOhm dual channels were tested at three temperatures. This data shows the reachable accuracy at zero hour (no lifetime influence) with a single point calibration at a current of 20mA and 25°C ambient temperature and the deviation in percent at -40 and +150°C. At this low current the device is working in gate back regulation.

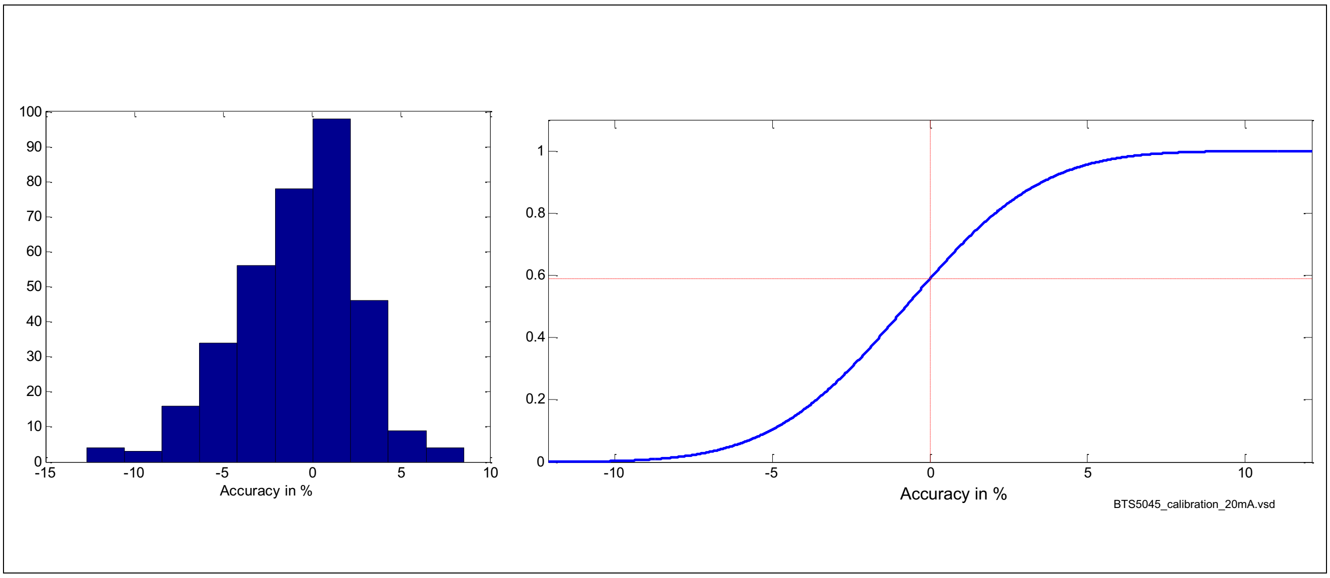

Figure 23 BTS5045-2EKA. Calibration at 20mA and Expected Accuracy.

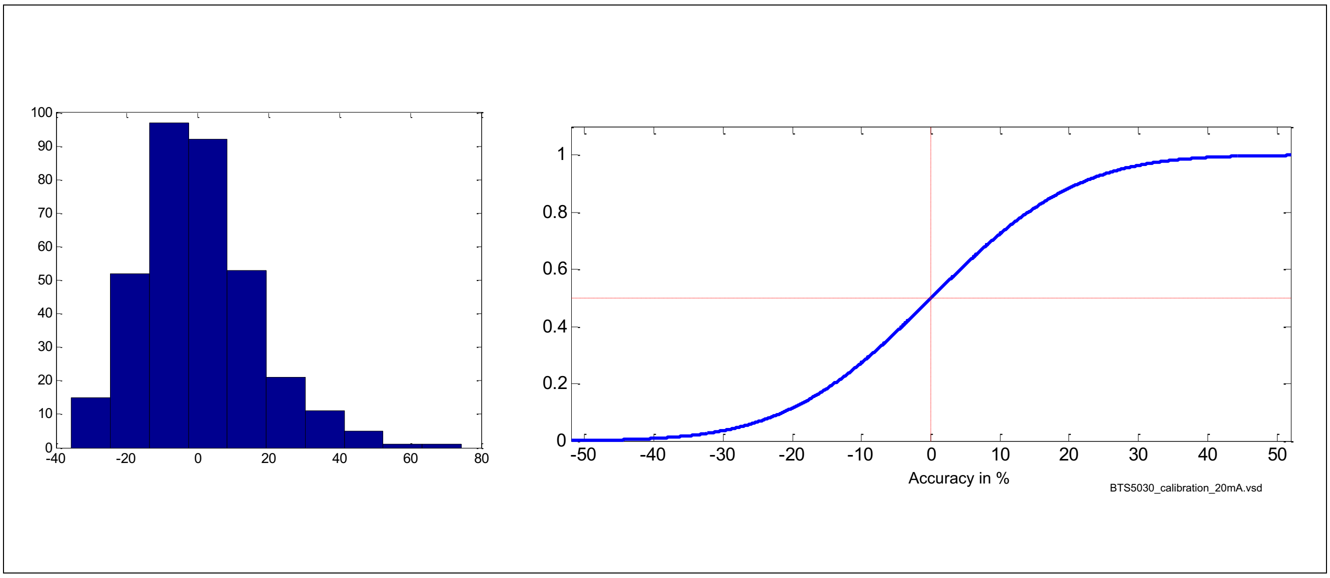

Figure 24 BTS5030-2EKA. Calibration at 20mA and Expected Accuracy.

The left side of the **Figure 23** and **Figure 24** shows the number of devices that have a certain in-accuracy at -40 and +150°C. A total number of 90 devices (30 pcs of 3 lots) was tested. On the right side, the cumulative distribution function is shown.

8 Conclusion

The PROFET™+ Family offers very accurate sense feedback to the microcontroller. With the right choice of the device and the external components, the diagnosis is easily implementable in the microcontroller.

The SMART6 technology that is used for PROFET™+ proves to be very accurate for k_{ILIS} relevant circuits like the op-amp and DMOS matching of the Sense- and Power-DMOS. Aging effects caused by electrical stress do not show a drastic effect on the accuracy of the sense circuit as is was shown in **Chapter 7.1**.

9 Glossary

Table 10 Symbol and Abbreviation

Symbol	Unit	Meaning
AEC	-	Automotive Electronic Council
α_{T0}		temperaturcoefficient 1st order at temperature T0
E_{AS}	J	Maximum inductive energy switchable once by the device over life time
E_{AR}	J	Maximum inductive energy switchable by the device repetitively
E_{TUE}	LSB	Total Unadjusted Error; This is the deviation between the Ideal Transfer Function and the actual one
FSR		Full Scale Range
GBR	-	Gate Back Regulation
GND	-	GrouND
I_{ADC}	A	Current that flows from or into into the ADC of the µC
I_{IS}	A	Current of the sense; IS Pin
I_{NOM}	A	Nominal current of a device
I_{L}	A	Load Current; Current through OUTput pin
$I_{L(RMS)}$	A	Root Mean Square of the Load Current, also called true current
I_{INRUSH}	A	Inrush current due to the load
I_{TRIP}	A	Short Circuit Tripping current, threshold where device switches OFF
$I_{L(SC)}$	A	Short Circuit Limiting current (limited by device or by short circuit impedance)
$I_{L(SC)\_TYP}$	A	Typical short circuit current
$I_{L(SC)\_MIN}$	A	Minimum short circuit current
$I_{L(SC)\_MAX}$	A	Maximum short circuit current
I_{RIS}	A	Current through the sense resistor R_{IS}
k_{ILIS}		ratio between I_{L} and I_{IS}
LSB		Least Significant Bit
L_{Supply}	H	Parasitic supply inductivity due to wire harness, also called primary inductance
L_{Short}	H	Parasitic load inductivity due to wire harness, also called secondary inductance
n_{RSC1}	cycle	Number of short circuit cycle the device can withstand before destruction
Op. Amp	-	Operational Amplifier
OEM	-	Original Equipment Manufacturer
PWM	-	Pulse Width Modulation
R_{Supply}	Ω	Parasitic supply resistance due to wire harness, also called primary resistance
R_{Short}	Ω	Parasitic load resistance due to wire harness, also called secondary resistance
R_{tc}		
SC1	-	Short Circuit type 1. Device switches into short circuit
SC2	-	Short Circuit type 2: The switch is ON while a short circuit occurs
tol	%	Tolerance
T_{J}	°C	Junction temperature of the DMOS
$T_{J(SC)}$	°C	Overtemperature threshold
$T_{J(MAX)}$	°C	Maximum acceptable temperature of silicon
ΔT	K	Temperature difference between T_{J} and T_{REF}

Table 10 Symbol and Abbreviation

Symbol	Unit	Meaning
ΔT_{IND}	K	Temperature overshoot due to inductive switch OFF
ΔT_{RST}	K	Restart hysteresis after ΔT switch OFF.
$\Delta T_{J(SC)}$	K	Restart hysteresis after $T_{J(SC)}$ switch OFF
T_{REF}	°C	Temperature reference of the device
T_{C}	°C	Leadframe or case temperature of the device
T	s	Period of a frequency signal
t_{ON}	s	Time while the input pin is set to logical level "1" or HIGH
t_{OFF}	s	Time while the input pin is set to logical level "0" or LOW
t_{LIM}	s	Time while the device actively limits the short circuit current
t_{COOL}	s	Time while the device is OFF to cool down after over thermal event
t_{RETRY}	s	Time while the application is still discriminating between inrush and short circuit
t_{LATCH_WAIT}	s	Time while the device waits before restarting.
V_{GS}	V	Gate source voltage of DMOS
V_{BB}	V	Battery Voltage
V_{REF}	V	Voltage supply of the micro controller
V_{S}	V	Supply Voltage
V_{DS}	V	Drain source voltage of DMOS

10 Revision History

Version	Date	Changes
1.1	2014-03-14	Upated kilis accuracy in chapter 4.4 / 4.5 and 4.6 Added 24V PROFET™+ Removed -2LAA devices because of product discontinuation Changed in Formula (13) LSB_max to LSB_min Added Chapter 5.5
1.0	2012-10-25	Creation of the document

Edition 2014-03-14

Published by
Infineon Technologies AG
81726 Munich, Germany