

A large, light blue, semi-transparent graphic element consisting of a thick, curved line that forms a partial circle. A small, solid light blue circle is positioned at the top of the curve, acting as a pivot point for the line.

Automotive Power

ADVANCED SENSE Calibration and Benefits Guide

Application Note

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ADVANCED SENSE

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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.

Analog current sense diagnostics signals in high-side switches have inherent inaccuracies associated with them. The two main sources of inaccuracy are the sense offset current, which dominates at lower load currents, and the slope (steepness) inaccuracy, which becomes more significant at higher load currents.

Infineon's ADVANCED SENSE technology allows for multiple calibration techniques offering increased levels of accuracy to be implemented depending on the application requirements.

Note: Devices that incorporate ADVANCED SENSE technology will have "Advanced analog load current sense signal" or similar wording in the Features section of their respective datasheets.

If a high-side power switch is enabled with Infineon's ADVANCED SENSE technology, its associated control system can perform a calibration to remove the sense offset current as a source of inaccuracy. Also, ADVANCED SENSE technology supports *Virtual 2-Point Calibration*, which means that it is possible for manufacturing test to obtain a true 2-point calibration by measuring at only one load current. This allows slope as a source of inaccuracy to be significantly improved.

This application note first introduces some fundamental concepts. This is followed by a discussion of the sources of inaccuracy experienced by conventional high-side power switches that do not support ADVANCED SENSE technology. Next, the way in which ADVANCED SENSE technology addresses these issues is discussed. The application note then details the multiple types of ADVANCED SENSE enabled calibration that may be employed during Manufacturing Test and/or by the Application Software.

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 problems with conventional high-side current sensing solutions. The first is the inaccuracy that is introduced by the internal amplifier offset voltage. This can deteriorate the current sense accuracy, especially at lower load currents, and can even disable 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 solution is high-side power switches that are enabled with Infineon's ADVANCED SENSE technology, which provides the ability to calibrate the current sense for high accuracy requirements utilizing simple end-of-line measurements 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.

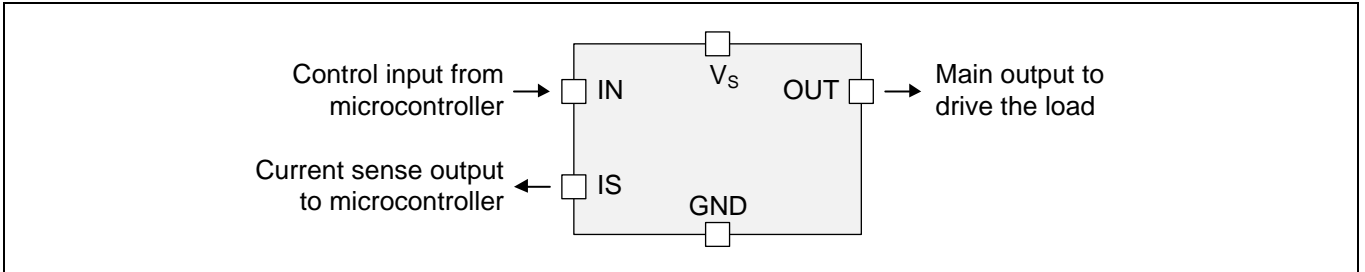


Figure 1 Pin names

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)
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_S will be the focus of the following discussions.

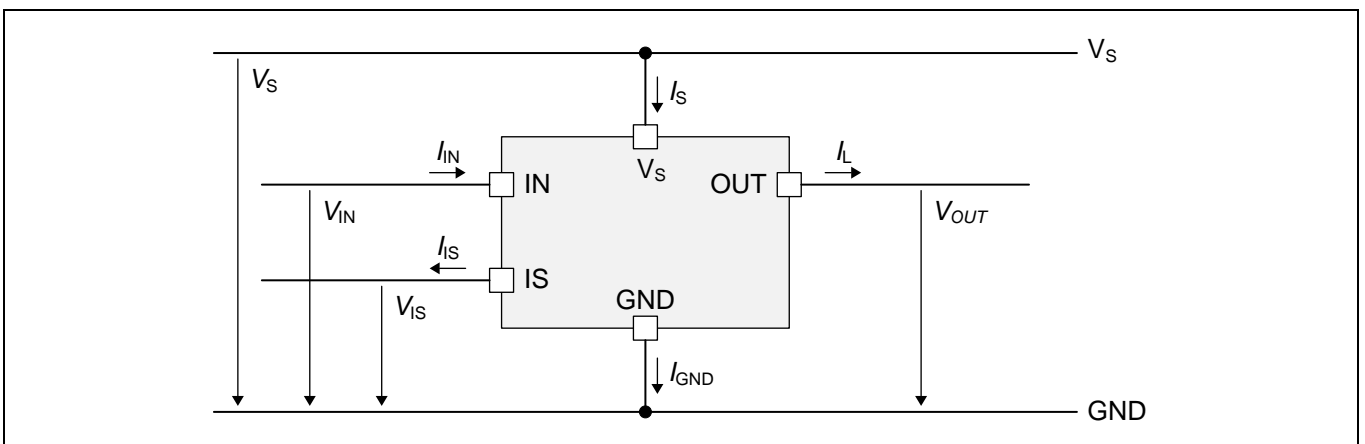


Figure 2 Definition of currents and voltages

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.

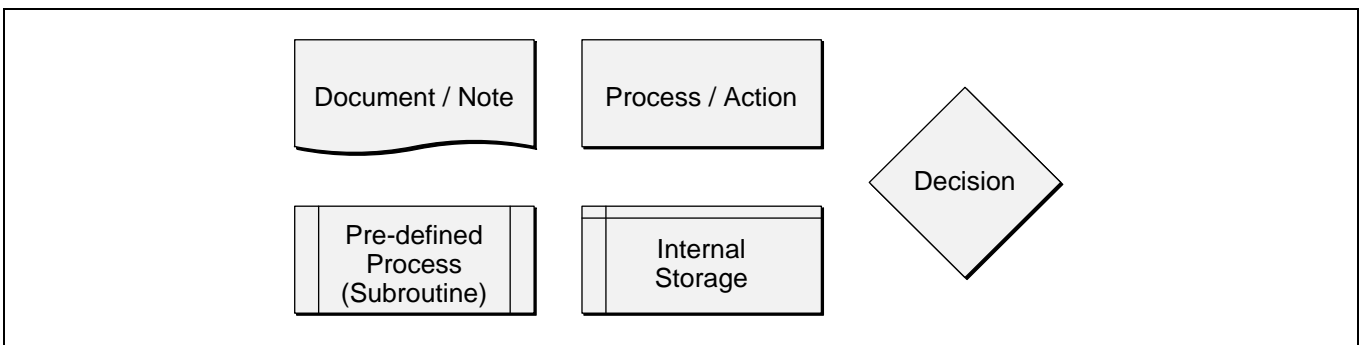


Figure 3 Flowchart nomenclature

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.

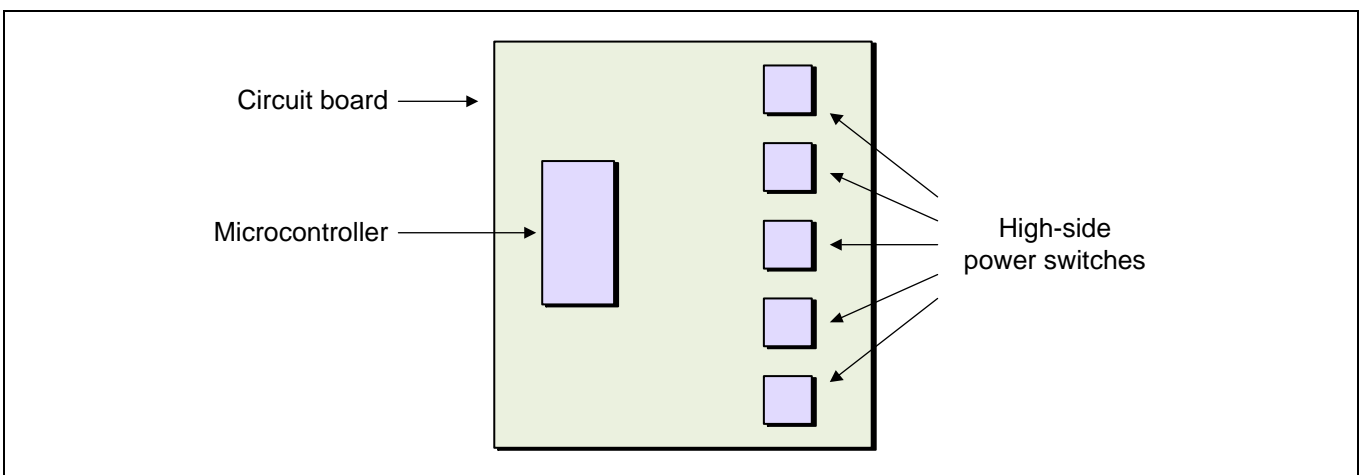


Figure 4 Example circuit board scenario

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_S) outputs from the switches.

2.5 Fundamental Concepts

In order to understand the problems associated with conventional current sense functions (and hence the advantages of solutions based on Infineon's ADVANCED SENSE technology), it is first necessary to be familiar with some fundamental concepts. Let's start with the general formula for a straight line in "slope-intercept" form, which is presented in Equation (1).

Equation (1) $y = mx + b$

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, only positive slope values are discussed (and are applicable) as illustrated in Figure 5.

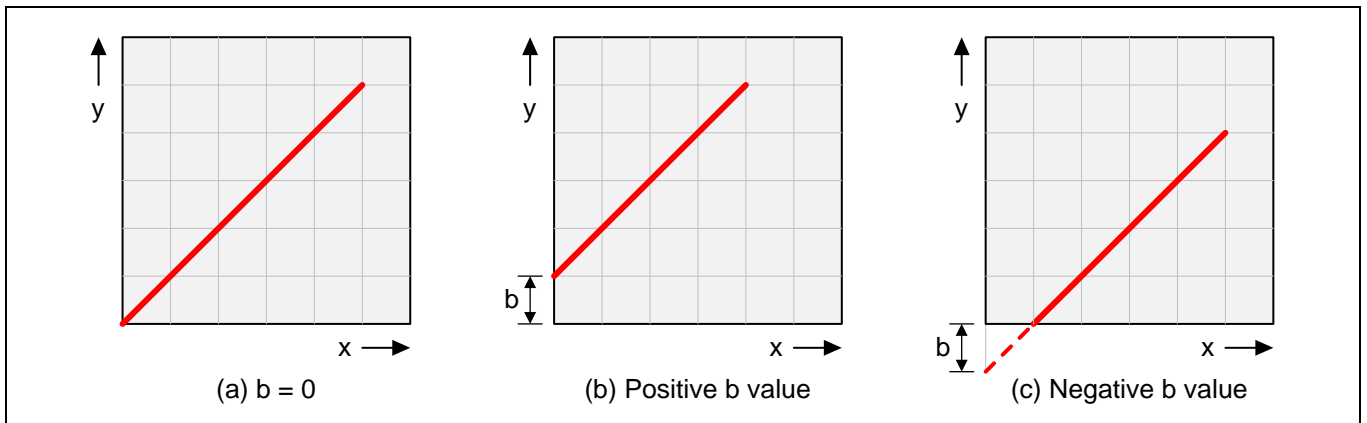


Figure 5 Generic lines with identical positive slopes

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 .

One way in which the characteristics of such a line can be determined is to first identify two points as illustrated in Figure 6(a).

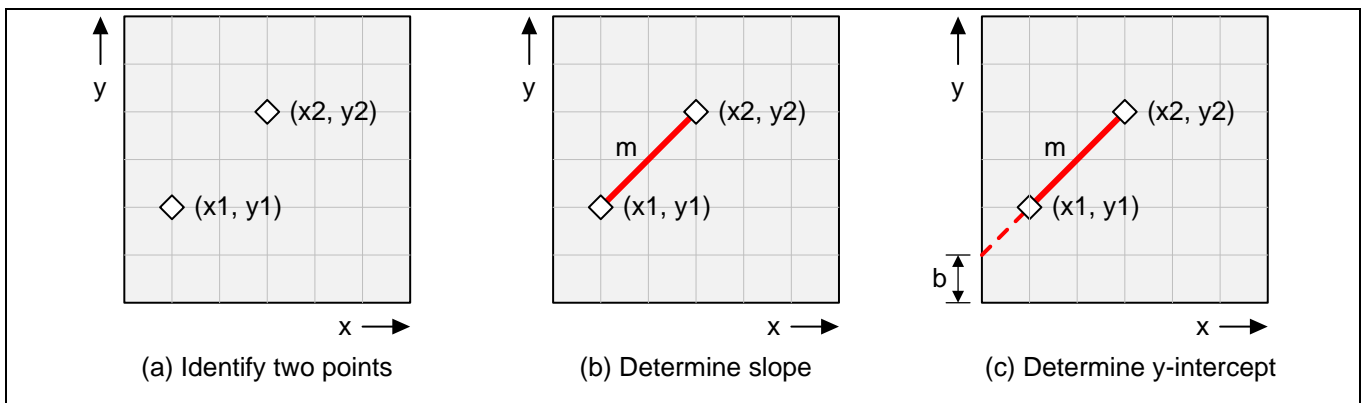


Figure 6 Determining the characteristics of a straight line

Given a straight line, the slope (m) of the line can be calculated using Equation (2).

Equation (2)
$$m = \frac{y_2 - y_1}{x_2 - x_1}$$

Once the slope has been determined as illustrated in Figure 6(b), this value can be used to calculate the y-intercept (b) as illustrated in Figure 6(c). This can be accomplished by picking the (x,y) values for any point and solving for the y-intercept using Equation (3).

Equation (3)
$$b = y - mx$$

After m (slope) and b (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.

2.6 Problems with Conventional Sense Functions

A high-level block diagram for a conventional high-side power switch is illustrated in Figure 7.

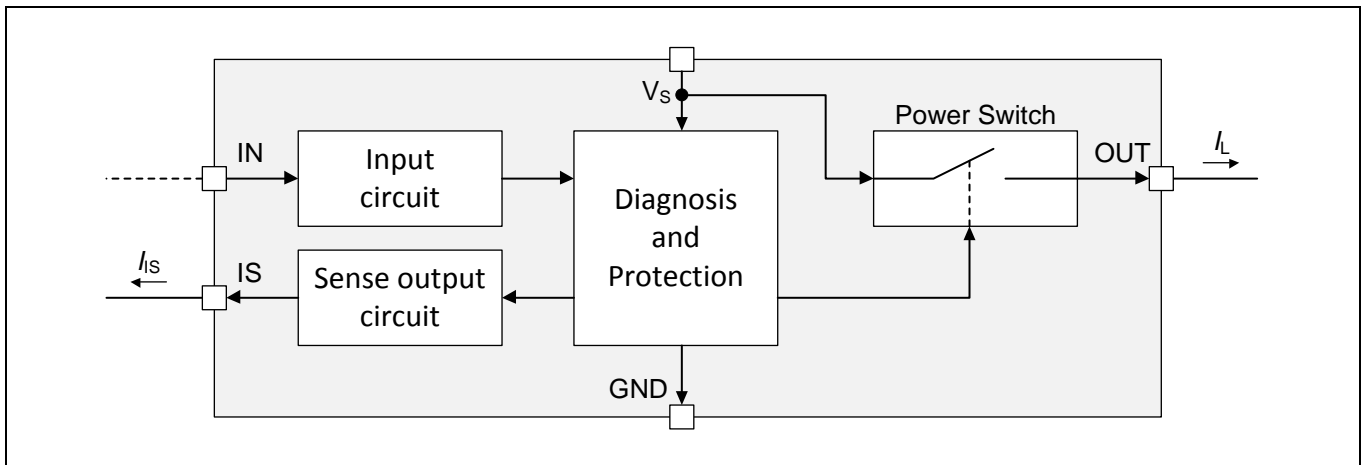


Figure 7 High-level block diagram for a conventional high-side power switch

The ideal relationship between the sense current I_S and the load current I_L is shown in Figure 8(a). In reality, however, there may be slope (steepness) error as illustrated in Figure 8(b). Such slope errors are mainly dependent on part-to-part production variation, and their effects are more pronounced at higher load currents.

Meanwhile, the sense offset error – which is introduced by the internal amplifier offset voltage – 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. Also, in the case of a negative offset error, the current sense capability may become disabled below a certain load current threshold, as illustrated by the horizontal portion of the solid green line in Figure 8(c).

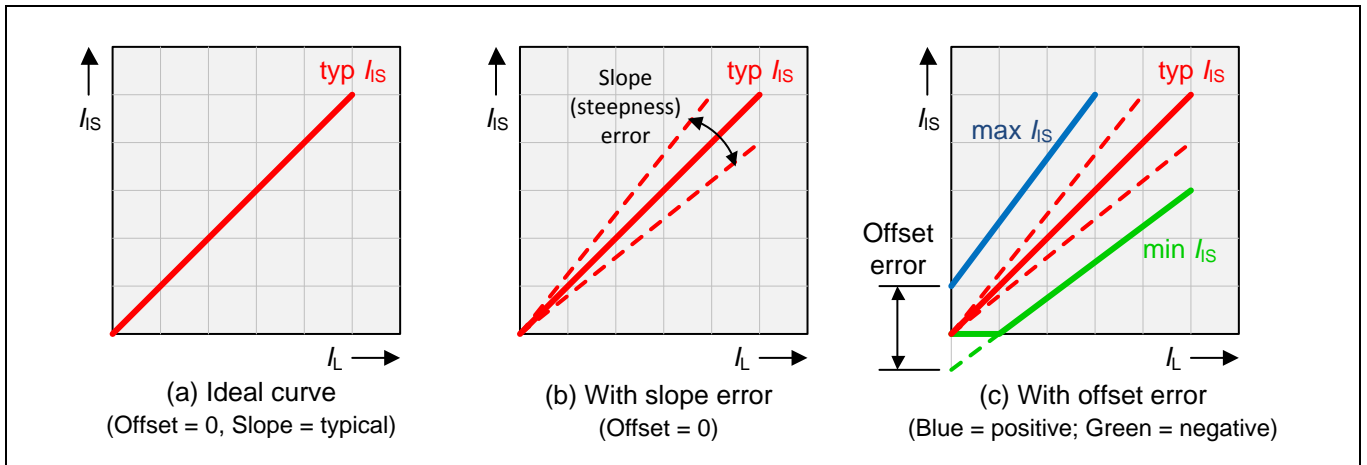


Figure 8 Relationship between I_{IS} and I_L in conventional devices

The relationship between the sense current I_{IS} and the load current I_L in a high-side power switch can be expressed using Equation (4).

$$\text{Equation (4)} \quad I_{IS} = \left(\frac{1}{k_{IS}} \times I_L \right) + I_{IS(OFFSET)}$$

The sense current I_{IS} in Equation (4) corresponds to y in Equation (1); the load current I_L in Equation (4) corresponds to x in Equation (1); the slope defined by $1/k_{IS}$ in Equation (4) corresponds to m in Equation (1); and the sense offset current $I_{IS(OFFSET)}$ in Equation (4) corresponds to the y -intercept b in Equation (1). The value of k_{IS} is defined in the corresponding device datasheet.

Now consider the information that is available when working with a conventional high-side power switch as illustrated in Figure 9.

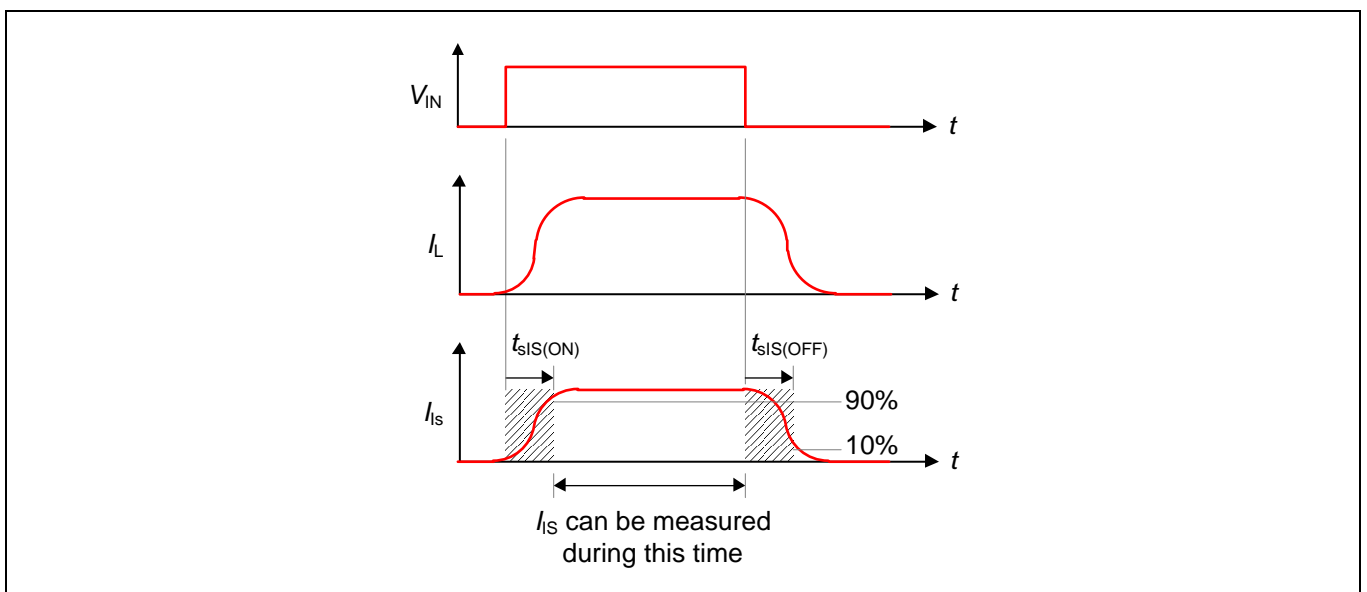


Figure 9 Relationship between I_{IS} and I_L in conventional devices

The shaded areas of Figure 9 (and any equivalent illustrations later in this application note) indicate the times when the I_{IS} output is transitioning between ON/OFF states. These transition times, which are represented by $t_{sIS(ON)}$ and $t_{sIS(OFF)}$, are the 90% I_{IS} and 10% I_{IS} current sense settling times, respectively. The analog sense current signal is invalid during the current sense settling times.

As can be seen in Figure 9, the only value that is available is the sense current I_{IS} . There is no way to calibrate the sense current offset or the slope from a single reading. The only way to calculate these values is to use a 2-point calibration technique, which involves switching in two separate loads during manufacturing test as illustrated in Figure 10.

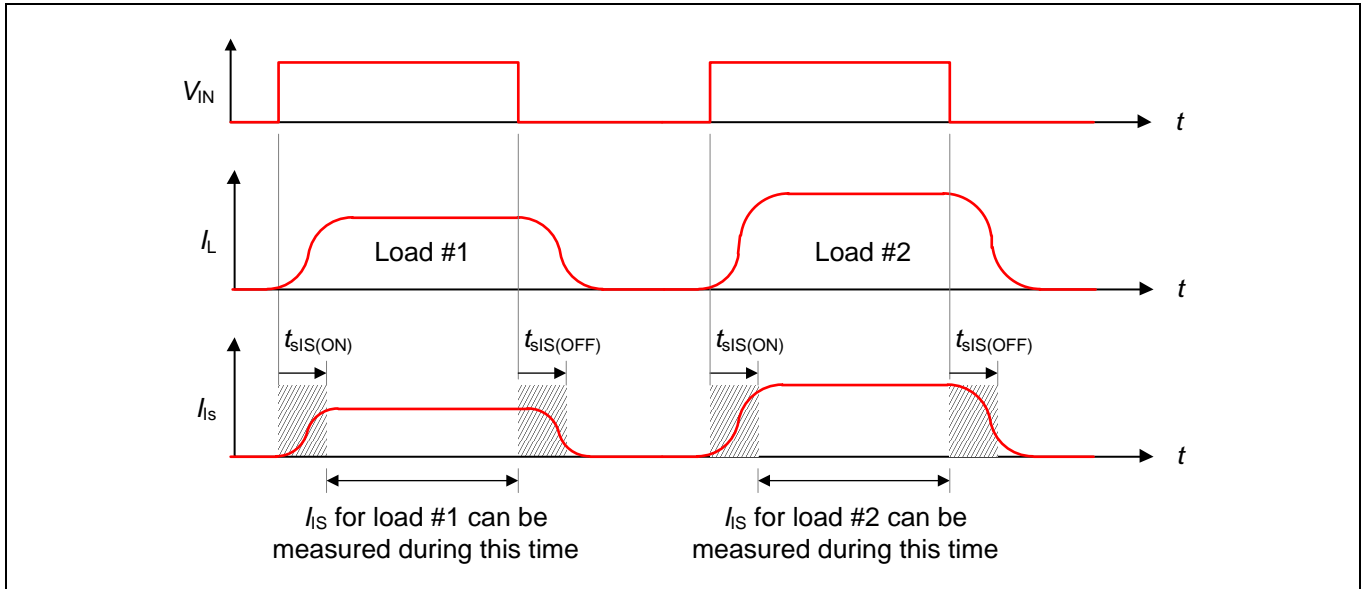


Figure 10 Measuring two loads using conventional devices

The value of k_{IS} may now be calculated using Equation (5), where I_{L1} and I_{L2} are the two different load currents and $I_{IS}(I_{L1})$ and $I_{IS}(I_{L2})$ are the corresponding sense currents.

$$\text{Equation (5)} \quad k_{IS} = \frac{I_{L1} - I_{L2}}{I_{IS}(I_{L1}) - I_{IS}(I_{L2})}$$

Once the slope has been determined, this value can be used to calculate the sense current offset value by picking the (I_L, I_{IS}) values for any point and solving for $I_{IS(OFFSET)}$ using Equation (6).

$$\text{Equation (6)} \quad I_{IS(OFFSET)} = I_{IS} - \left(\frac{1}{k_{IS}} \times I_L\right)$$

Both of these values may be stored in the microcontroller's non-volatile memory to be used by the application software.

The end result is that, using conventional techniques, the steepness of the slope is difficult to measure by end-of-line calibration. This is due to the fact that it requires the use of a full 2-point calibration technique, which involves switching in two separate loads during manufacturing test. Furthermore, the sense current offset cannot be measured dynamically by the application during operation, which means that the temperature dependency associated with the offset will remain in the application.

2.7 Advantages of ADVANCED SENSE Technology

A high-level block diagram for a high-side power switch enabled with Infineon's ADVANCED SENSE technology is illustrated in Figure 11.

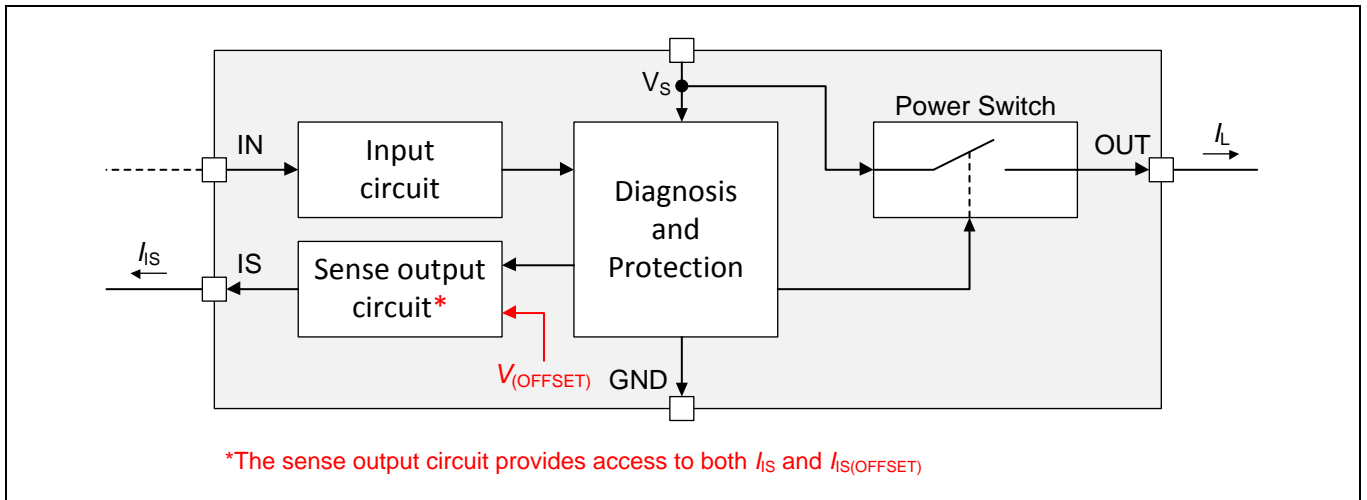


Figure 11 High-level block diagram for an ADVANCED SENSE enabled high-side power switch

As can be seen, there are two main differences between this block diagram and that for the conventional high-side power switch, which was illustrated in Figure 7. The first difference is the use of special circuitry to introduce a voltage bias called $V_{(OFFSET)}$, which ensures the offset error is always positive as illustrated in Figure 12(b).

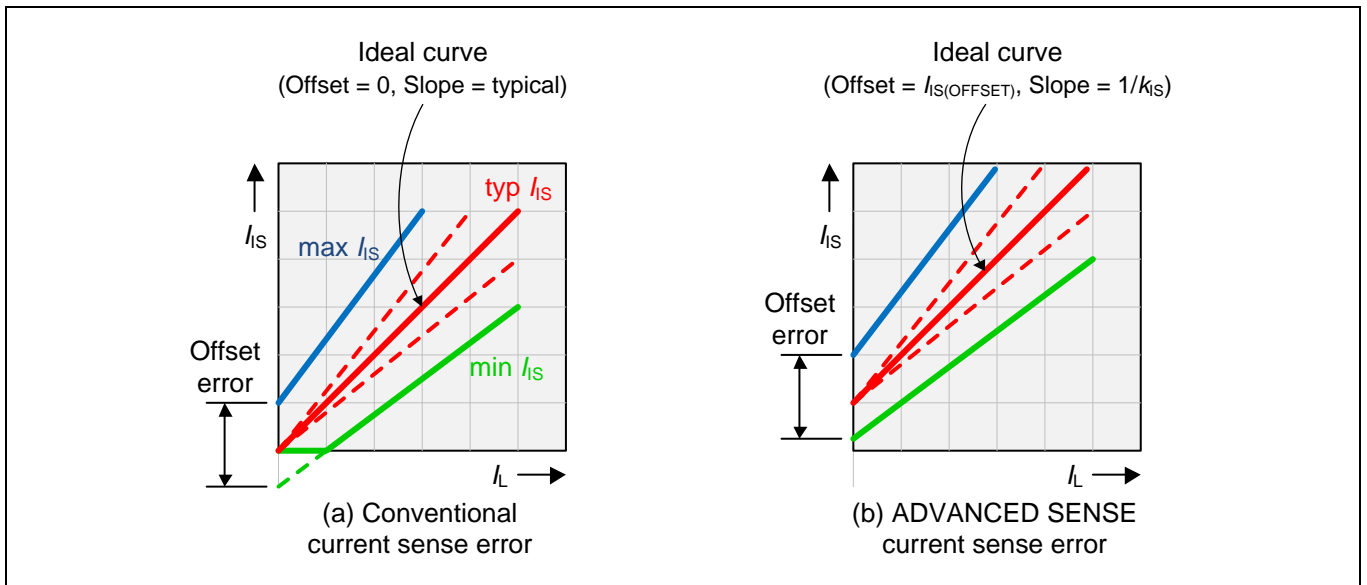


Figure 12 Comparison between conventional and ADVANCED SENSE enabled devices

The fact that the offset error is always positive significantly simplifies the relationship between the sense current I_s and the load current I_L . Knowing that the offset error is always positive means that it can always be subtracted from the measured sense current I_s so as to determine the actual amount of sense current that is associated with the load. It also means that the I_s sense current output always shows a meaningful value, even when the current load I_L is small. This “always positive” offset error is one of the major benefits of ADVANCED SENSE because it significantly reduces both manufacturing test software and application software overhead when calibrating for increased accuracy.

The second difference and major advantage of an ADVANCED SENSE enabled device is that it provides direct access to the sense current offset as illustrated in Figure 13.

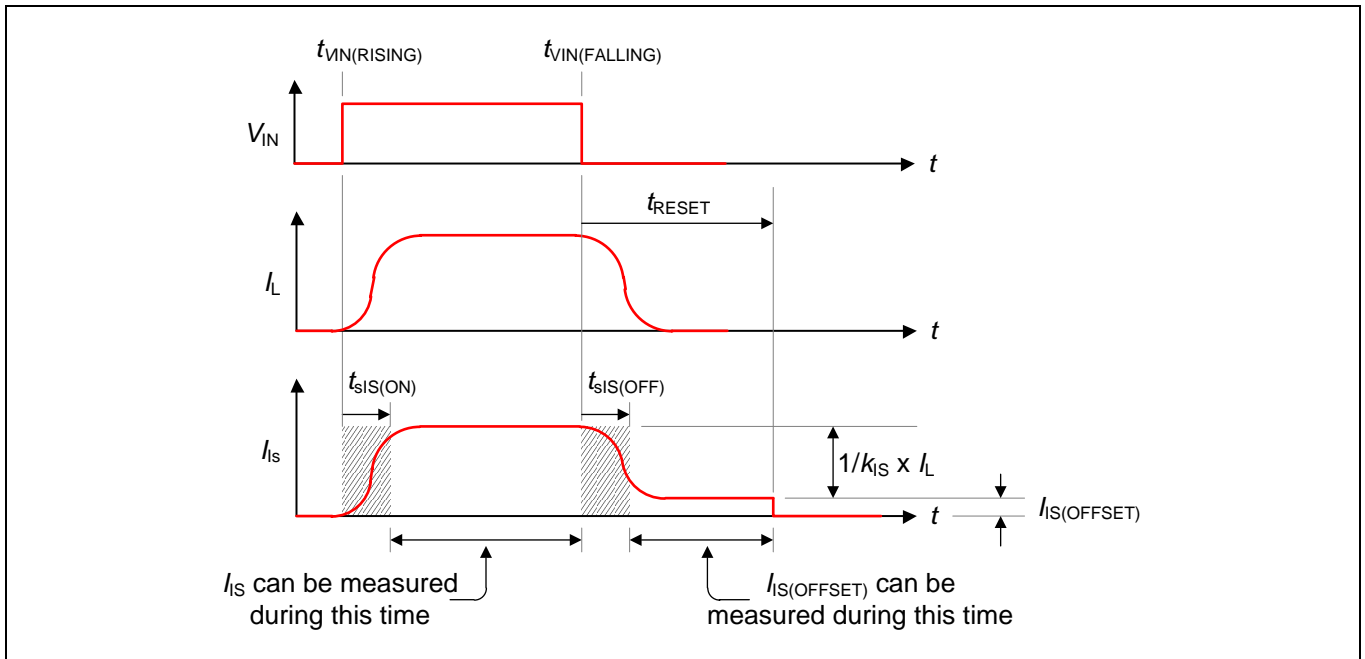


Figure 13 Measuring $I_{IS(OFFSET)}$ with an ADVANCED SENSE enabled device

As is illustrated by Figure 13, the difference between reading I_{IS} and $I_{IS(OFFSET)}$ is dependent on the state of the V_{IN} input and the time since the V_{IN} input transitioned from a LOW to a HIGH state, or vice versa (definitions for HIGH and LOW can be found in the parameter tables of the respective device datasheet):

The output of the IS pin is I_{IS} when $t_{SIS(ON)} < t < t_{VIN(FALLING)}$

The output of the IS pin is $I_{IS(OFFSET)}$ when $t_{SIS(OFF)} < t < t_{RESET}$

This feature means that a *Virtual 2-Point Calibration* can be performed by manufacturing test using only a single load as discussed later in this application note. Furthermore, having direct access to the sense current offset in this way means that the application software can compensate for any temperature dependency associated with the offset.

3 Calibrating ADVANCED SENSE Enabled Devices

3.1 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).

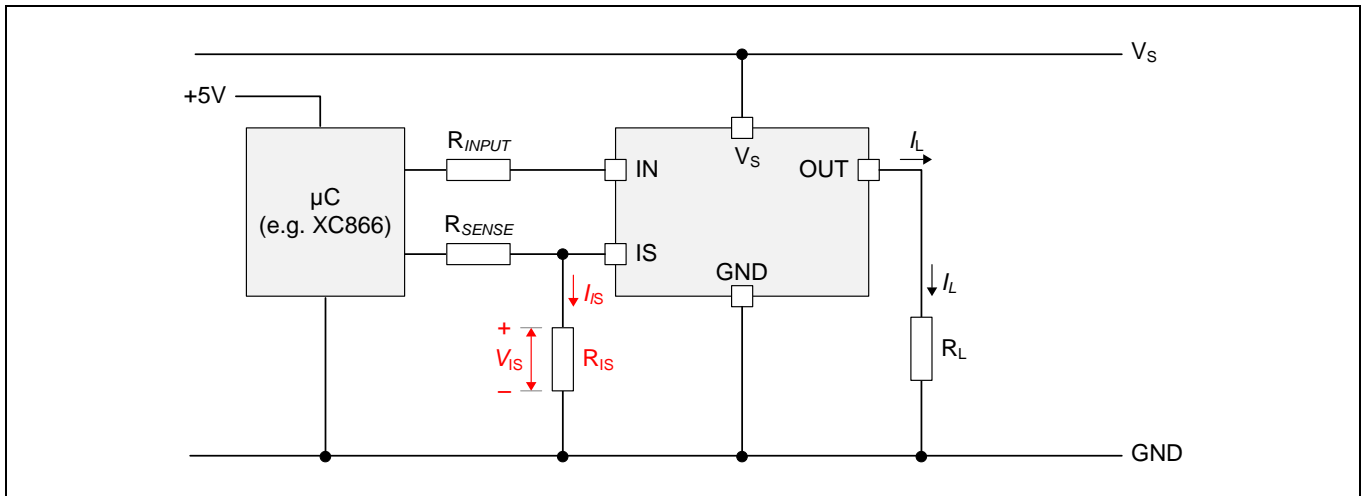


Figure 14 Reference circuit for calibration nomenclature

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 (7).

$$\text{Equation (7)} \quad V_{IS} = I_{IS} \times R_{IS}$$

Also, remembering that the offset current $I_{IS(OFFSET)}$ can also be directly read through the IS pin as discussed in the previous section, the potential $V_{IS(OFFSET)}$ is determined as shown in Equation (8).

$$\text{Equation (8)} \quad V_{IS(OFFSET)} = I_{IS(OFFSET)} \times R_{IS}$$

With the exception of the *No Calibration* scenario discussed later in this application note, the initial values for k_{IS} and $V_{IS(OFFSET)}$ 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 $V_{IS(OFFSET)}$ (the voltage value in ADC counts) in the microcontroller's non-volatile memory; that is, it is assumed that manufacturing test will NOT store $I_{IS(OFFSET)}$ (the current value).

From Figure 10 and Equation (5), k_{IS} is traditionally calculated using a 2-point calibration technique, which involves switching in two separate loads during manufacturing test. From Equation (7), $I_{IS} = V_{IS} / R_{IS}$, so substituting for I_{IS} in Equation (5) allows k_{IS} to be calculated as shown in Equation (9).

$$\text{Equation (9)} \quad k_{IS} = \frac{I_{L1} - I_{L2}}{\left(\frac{V_{IS(I_{L1})}}{R_{IS}}\right) - \left(\frac{V_{IS(I_{L2})}}{R_{IS}}\right)}$$

Figure 13 illustrated that one of the major benefits of an ADVANCED SENSE enabled device is that it provides direct access to the sense current offset. This means that Virtual 2-Point Calibration can be performed by manufacturing test using only a single load as illustrated in Figure 15.

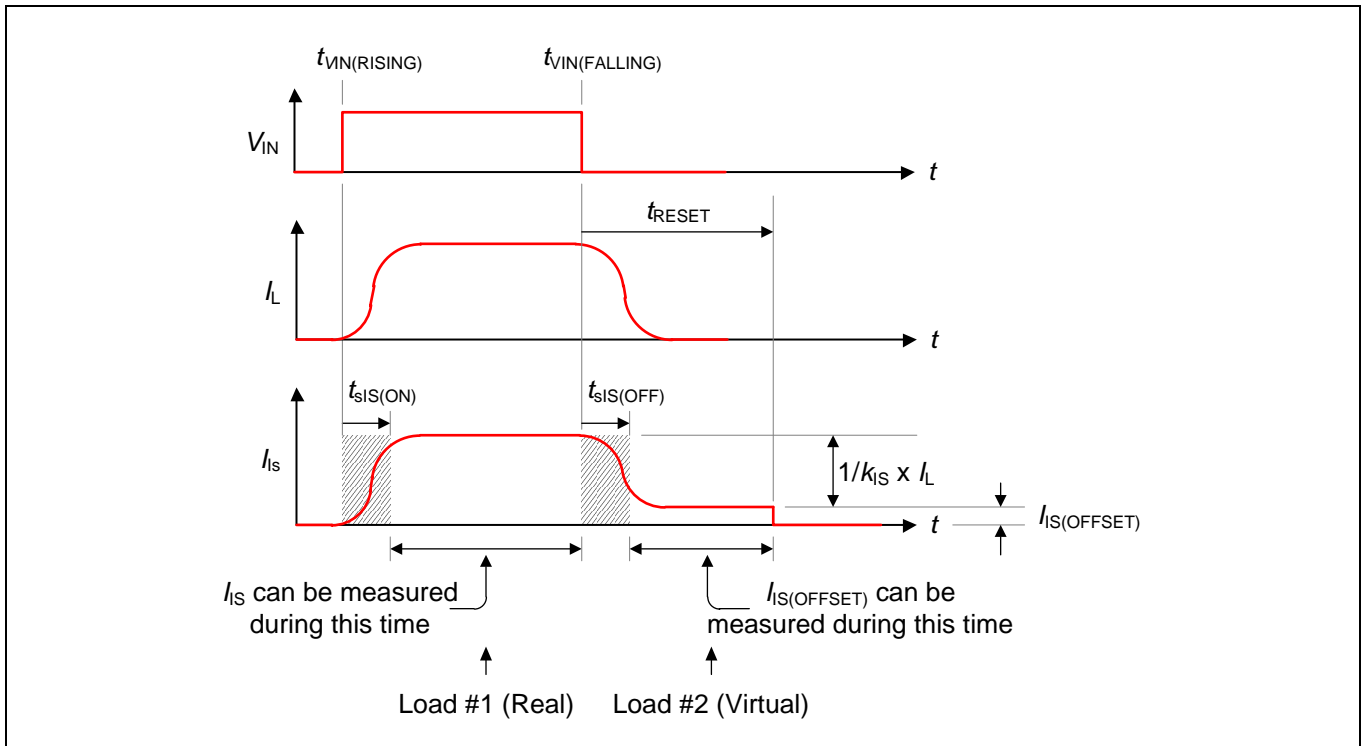


Figure 15 Performing Virtual 2-Point Calibration using only a single load

The single real load, shown as Load #1 in Figure 15, equates to I_{L1} in Equation (9). The virtual load, shown as Load #2 in Figure 15, equates to I_{L2} in Equation (9); this is equivalent to a no load (open load) condition, which means that $I_{L2} = 0$ in Equation (9).

From Figure 15, the sense current associated with Load #2 is $I_{IS(OFFSET)}$. From Equation (8), $I_{IS(OFFSET)} = V_{IS(OFFSET)} / R_{IS}$, so substituting this in Equation (9) gives the formula used by manufacturing test to calculate k_{IS} as shown in Equation (10).

$$\text{Equation (10)} \quad k_{IS} = \frac{I_{L1}}{\left(\frac{V_{IS}(I_{L1})}{R_{IS}} \right) - \left(\frac{V_{IS}(I_{IS(OFFSET)})}{R_{IS}} \right)}$$

From Equation (4), $I_{IS} = (1/k_{IS} \times I_L) + I_{IS(OFFSET)}$, which means that the load current I_L can be calculated as shown in Equation (11).

$$\text{Equation (11)} \quad I_L = k_{IS} \times (I_{IS} - I_{IS(OFFSET)})$$

From Equation (7) and Equation (8), $I_{IS} = V_{IS} / R_{IS}$ and $I_{IS(OFFSET)} = V_{IS(OFFSET)} / R_{IS}$, so substituting these values into Equation (11) yields Equation (12).

$$\text{Equation (12)} \quad I_L = k_{IS} \times \left(\frac{V_{IS}}{R_{IS}} - \frac{V_{IS(OFFSET)}}{R_{IS}} \right)$$

Factoring Equation (12) allows the application software to calculate the load current I_L as shown in Equation (13).

$$\text{Equation (13)} \quad I_L = \frac{k_{IS}}{R_{IS}} \times (V_{IS} - V_{IS(OFFSET)})$$

3.2 Types of Calibration

The various types of calibration that may be performed using ADVANCED SENSE enabled devices are summarized in Table 3.

Table 3 Types of calibration supported by ADVANCED SENSE enabled devices

Calibration	Performed By	Used By
No Calibration	N/A	Application Software
Offset-Only	Manufacturing Test	Application Software
Virtual 2-Point	Manufacturing Test	Application Software
Running Offset	Application Software*	Application Software

Note: * The application software is dynamically updating the 25C value written to NVM by manufacturing test.

3.3 No Calibration (No Cal)

With this calibration option, no calibration is performed by manufacturing test; thus, no values for $V_{IS(OFFSET)}$ and k_{IS} are stored in the microcontroller’s non-volatile memory. Instead, the application developer simply uses typical values for $V_{IS(OFFSET)}$ [calculated using Equation (8)] and k_{IS} as specified in the datasheet. 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 16 summarizes the process used by the application software when the *No Calibration* option is being used.

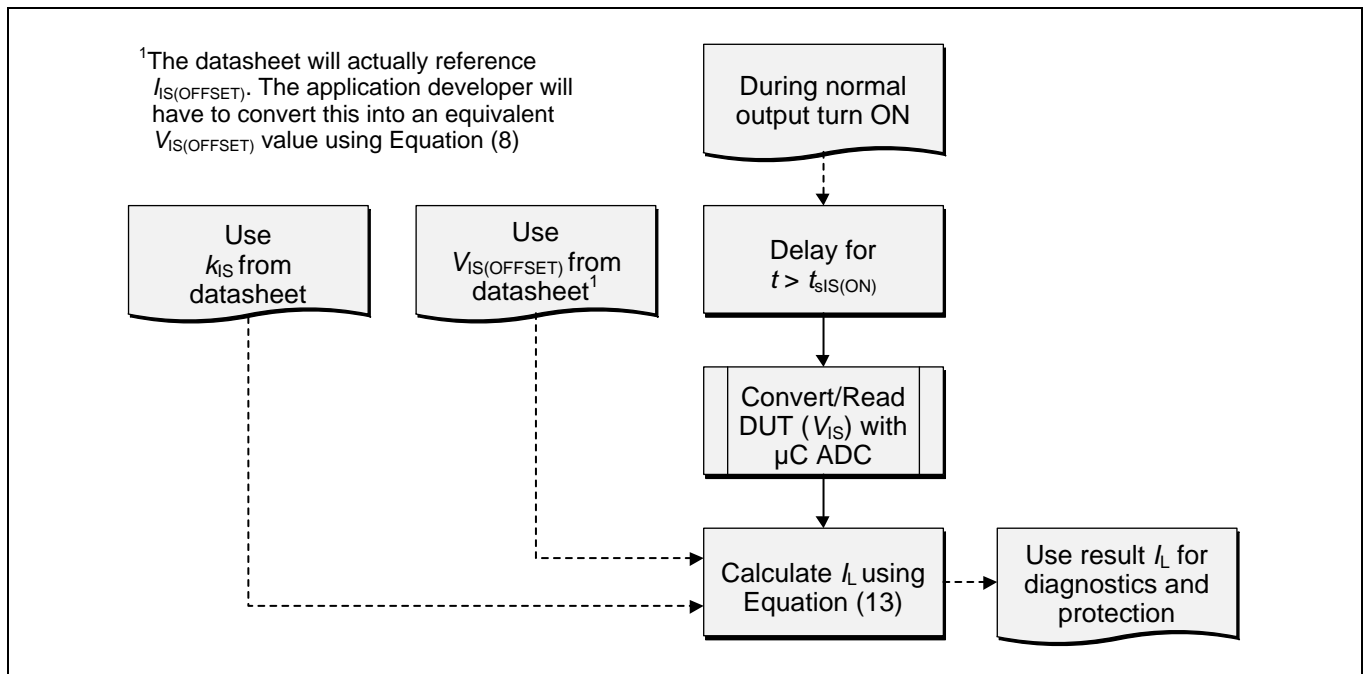


Figure 16 Application software procedure for No Calibration option

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 k_{IS} and $V_{IS(OFFSET)}$ to calculate the load current I_L using Equation (13).

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.)

3.4 Offset-Only Calibration

With this calibration option, manufacturing test measures the value of $V_{IS(OFFSET)}$ at an ambient temperature of 25°C. This measured value will be stored in the microcontroller’s non-volatile memory along with the typical datasheet value of k_{IS} , and 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. To determine the value and polarity of the offset, additional points above and beyond the single-point calibration must be performed.

With ADVANCED SENSE enabled devices, the offset is provided by the device under the conditions described in Figure 13; switching a known load is not required. Furthermore the offset value with ADVANCED SENSE enabled devices is always positive, which means that it is always subtracted and always easily measured.

There are two ways in which the measurement of $I_{IS(OFFSET)}$ (in the form of $V_{IS(OFFSET)}$) may be performed in the manufacturing test environment using ADVANCED SENSE enabled devices. The typical technique is illustrated in Figure 17.

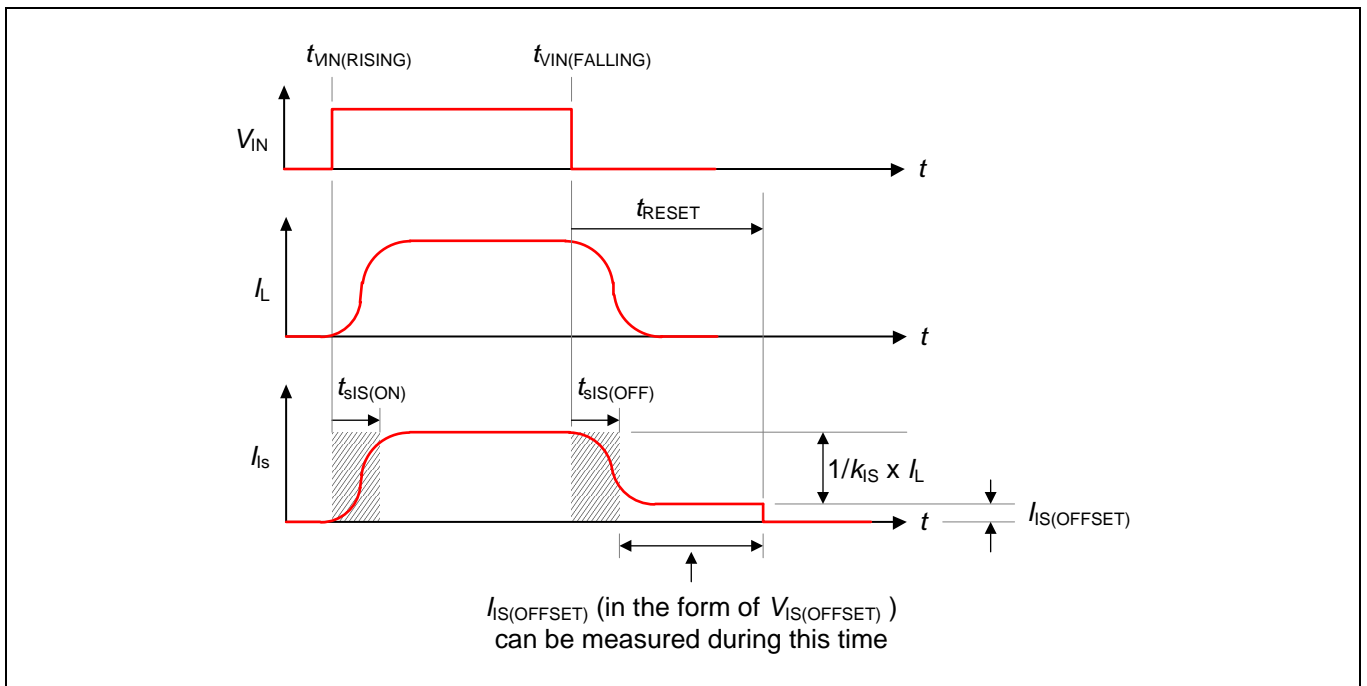


Figure 17 Typical technique for measuring $I_{IS(OFFSET)}$

In this case, the measurement is performed at time t , where t is defined by Equation (14) and the values for $t_{IS(OFF)}$ and t_{RESET} may be determined from the appropriate device datasheet:

Equation (14)
$$t_{IS(OFF)} < t < t_{RESET}$$

A more efficient technique may be performed in the case where no load (open load) is applied to the manufacturing test setup as illustrated in Figure 18.

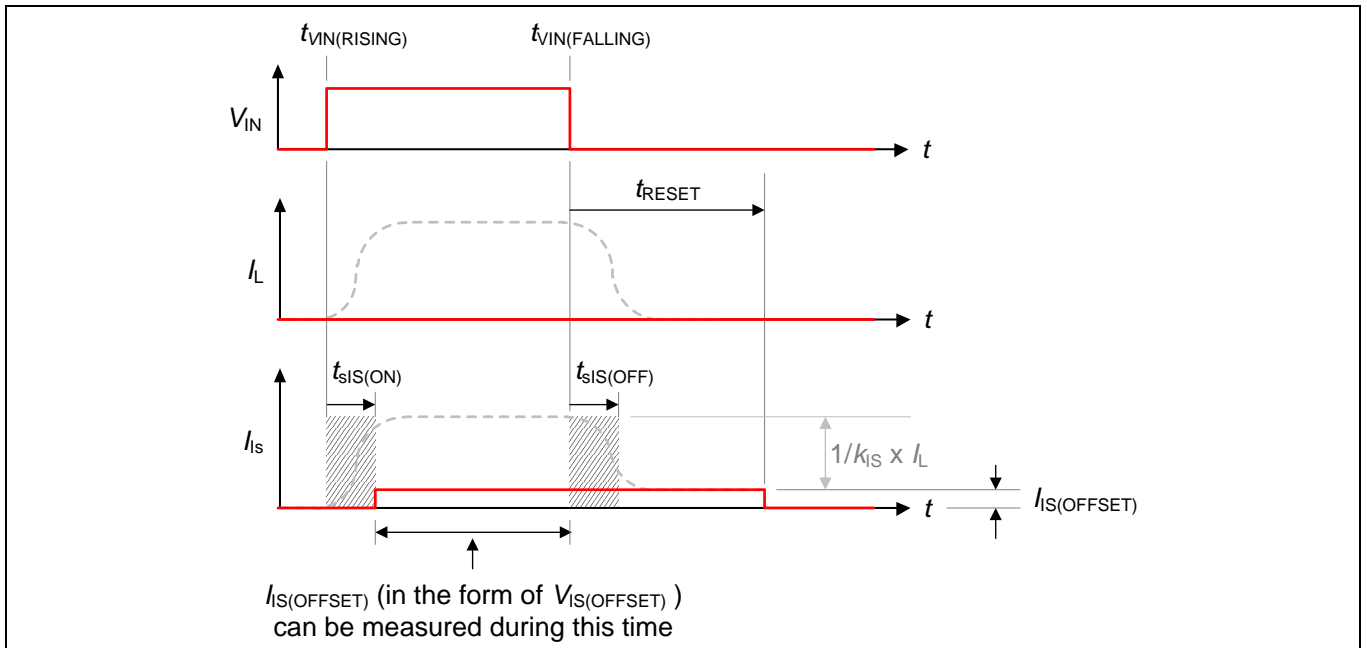


Figure 18 More efficient technique for measuring $I_{S(OFFSET)}$

In this case, the measurement is performed at time t , where t is defined by Equation (15), the value for $t_{SIS(ON)}$ may be determined from the appropriate device datasheet, and the value for $t_{VIN(FALLING)}$ is defined by the manufacturing test program:

$$\text{Equation (15)} \quad t_{SIS(ON)} < t < t_{VIN(FALLING)}$$

This more efficient approach is preferred for *Offset-Only* calibration because it minimizes the amount of time spent on calibration during manufacturing test (this is the approach that will be assumed in the following flowcharts and examples associated with this mode of calibration).

Figure 19 summarizes the process used by manufacturing test when the *Offset-Only* calibration option is being used.

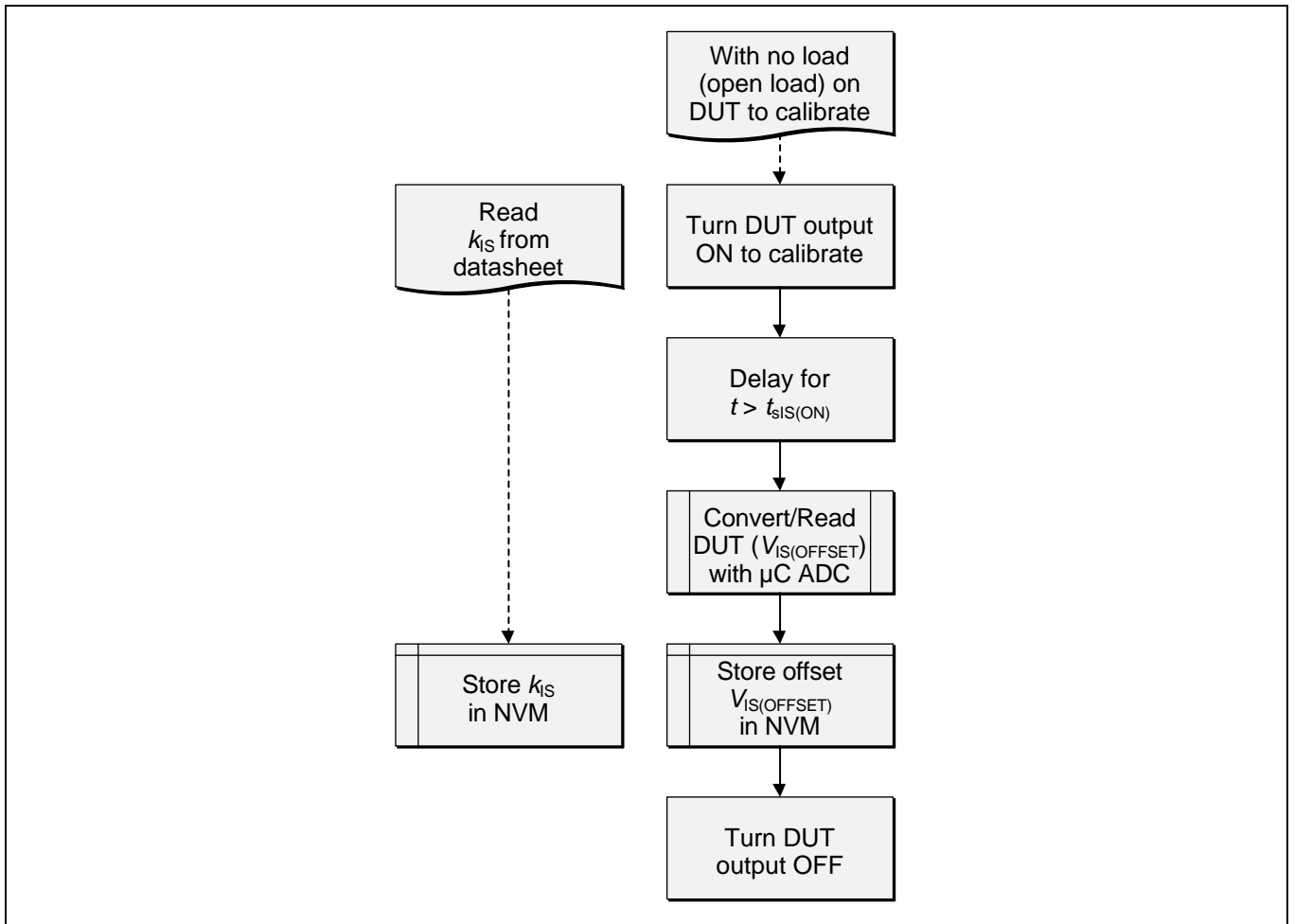


Figure 19 Manufacturing test procedure for the Offset-Only calibration option

The manufacturing test turns the device input ON with no load connected to the device (open load), delays for the current sense settling time, and then reads and stores the $V_{IS(OFFSET)}$ value (along with the typical datasheet k_{IS} value) in the microcontroller's non-volatile memory (NVM).

Figure 20 summarizes the process used by the application software when the *Offset-Only* calibration option is being used.

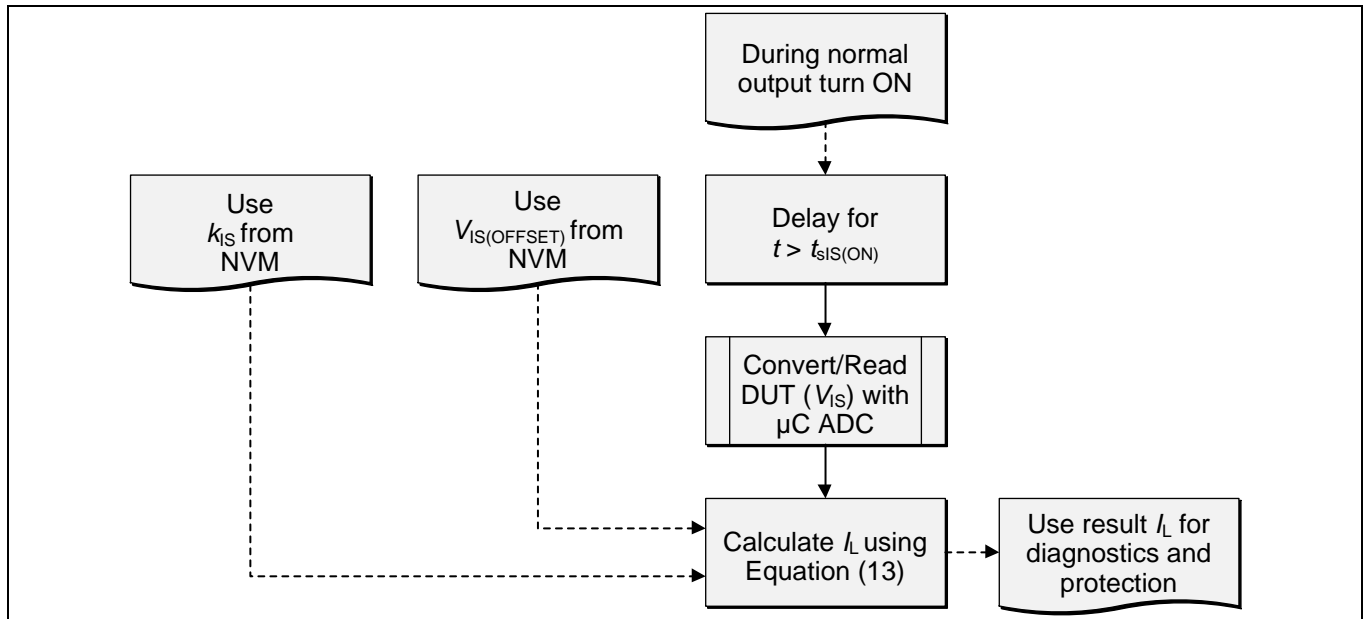


Figure 20 Application software procedure for the Offset-Only calibration option

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 k_{IS} and $V_{IS(OFFSET)}$ stored in the microcontroller's non-volatile memory to calculate the load current I_L using Equation (13). This load current is then compared to normal or faulted threshold limits to determine the condition of the load.

Consider the following example:

Test conditions: Application load resistance $R_L = 1.5\Omega$; manufacturing test supply voltage 13.5V (real load current $I_L = 9A$ under these conditions); manufacturing test temperature 25°C; $R_{IS} = 2k\Omega$; $k_{IS(ACTUAL)} = 14,000$ (but assume that a typical value of 13,000 from the datasheet is stored in the microcontroller's non-volatile memory by manufacturing test).

Manufacturing test measurement stored in non-volatile memory: $V_{IS(OFFSET)} = 0.4V$

Application software measurement from ADC: $V_{IS} = 1.69V$

Application software calculation from Equation (13): $I_L = (13k/2k\Omega) \times (1.69V - 0.4V) = 8.39A$

It can be seen above that the calculated load current is 8.39A while the actual load was 9A. 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.)

3.5 Virtual 2-Point Calibration

With this calibration option, manufacturing test measures the values of $V_{IS(OFFSET)}$ and k_{IS} at an ambient temperature of 25°C. Both of these measured values will be stored in the microcontroller's non-volatile memory to be used by the application software.

The traditional method for determining the value of k_{IS} is called 2-point calibration. This involves switching two known loads at known temperatures, measuring the analog sense current for each load, and then using these measurements to calculate the k_{IS} and $V_{IS(OFFSET)}$ values as discussed in Figure 10 and Equation (5) and Equation (6).

By comparison, in the case of ADVANCED SENSE enabled devices, the offset is given by the device, thereby removing the requirement for switching in two known loads during manufacturing test. As discussed in Figure 15, ADVANCED SENSE technology supports the concept of *Virtual 2-Point* calibration, which means that it is possible for manufacturing test to obtain a true 2-point calibration by measuring at only one load current.

Figure 21 summarizes the process used by manufacturing test when the *Virtual 2-Point* calibration option is being used.

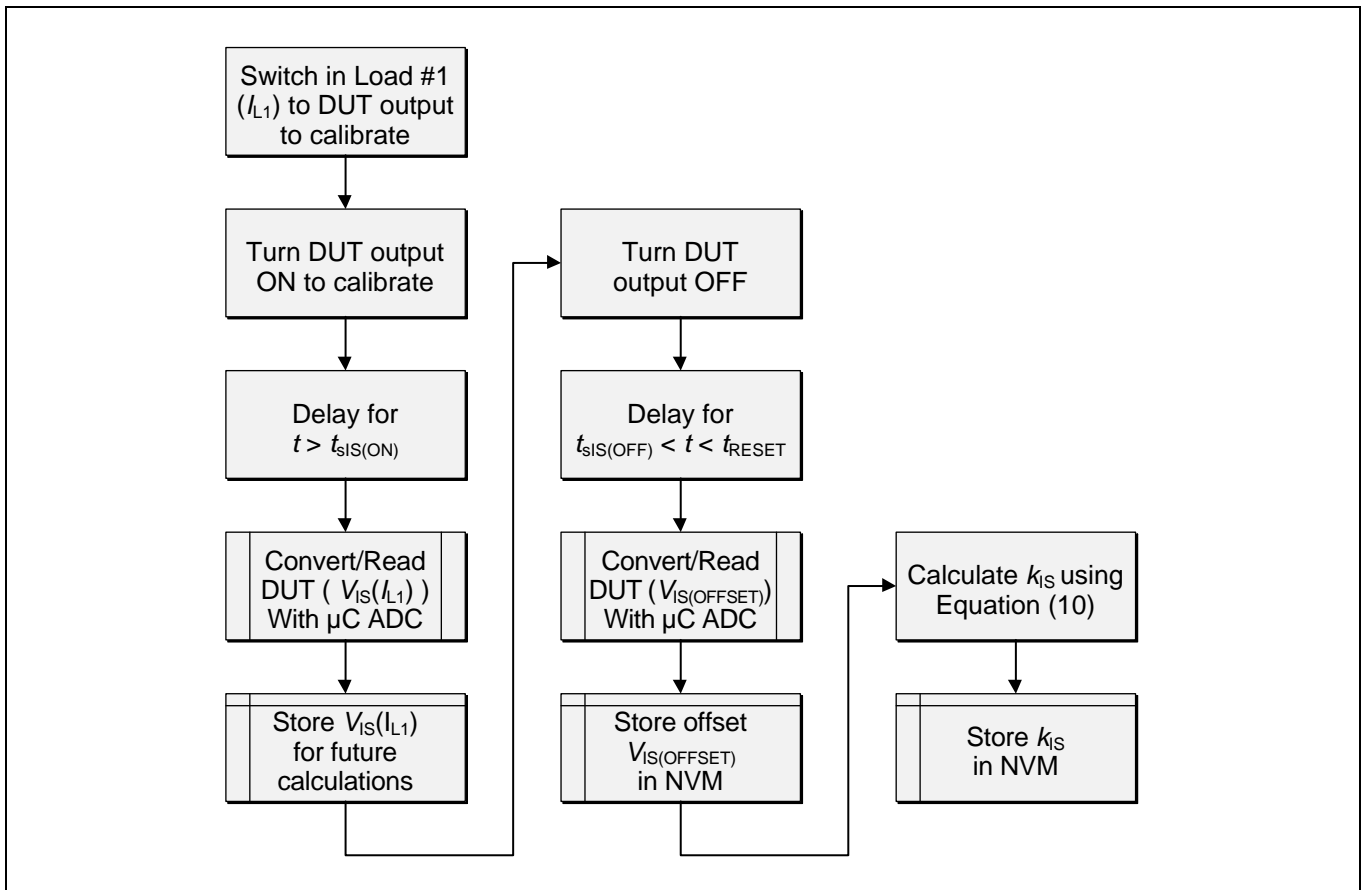


Figure 21 Manufacturing test procedure for the Virtual 2-Point calibration option

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} value. The device input is then turned OFF, the test software delays for the current sense settling time, and then reads and stores the corresponding $V_{IS(OFFSET)}$ value. Finally, the manufacturing test software calculates the slope using Equation (10) and stores both the k_{IS} and $V_{IS(OFFSET)}$ values in the microcontroller’s non-volatile memory (NVM).

Figure 22 summarizes the process used by the application software when the *Virtual 2-Point* calibration option is being used.

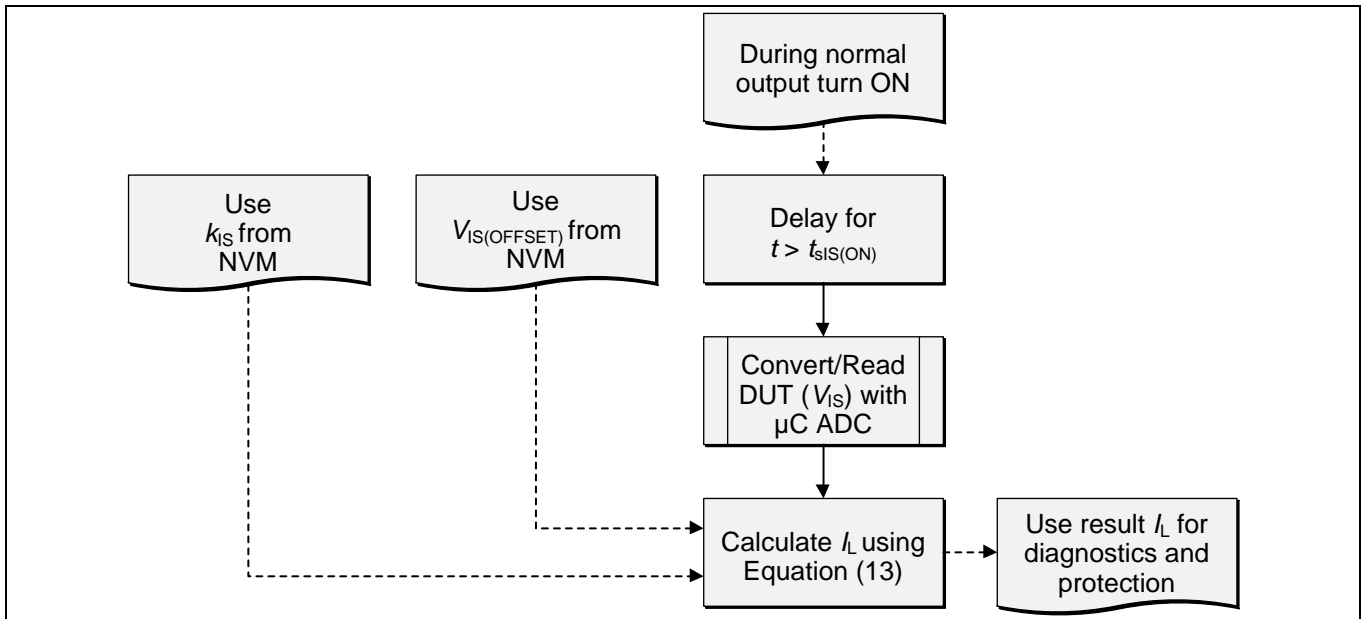


Figure 22 Application software procedure for the Virtual 2-Point calibration option

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 k_{IS} and $V_{IS(OFFSET)}$ stored in the microcontroller's non-volatile memory to calculate the load current I_L using Equation (13). This load current is then compared to normal or faulted threshold limits to determine the condition of the load.

Consider the following example:

Test conditions: Application load resistance $R_L = 1.5\Omega$; manufacturing test supply voltage 13.5V (real load current $I_L = 9A$ under these conditions); manufacturing test temperature 25°C; $R_{IS} = 2k\Omega$; $k_{IS(ACTUAL)} = 14,000$.

Manufacturing test switches in known load: $R_L = 1.35\Omega$

Manufacturing test measurement for known load: $V_{IS} = 1.83V$

Manufacturing test measurement stored in non-volatile memory: $V_{IS(OFFSET)} = 0.4V$

Manufacturing test calculation from Equation (10) stored in non-volatile memory: $k_{IS} = 13,986$

Application software measurement from ADC: $V_{IS} = 1.69V$

Application software calculation from Equation (13): $I_L = (13,986/2k\Omega) \times (1.69V - 0.4V) = 9.02A$

Note: The actual current value is 9A. The result from the application calculation based on Virtual 2-Point calibration (9.02A) is significantly more accurate than the result from the application calculation based on Offset-Only calibration (8.39A).

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.)

3.6 Running Offset Calibration

This calibration option provides the highest accuracy (see also the Accuracy of Different Calibration Options later in this application note).

In fact, *Running Offset* is not really a calibration mode in its own right. There are only two main calibration modes: *Offset Only*, which is traditionally called “single-point calibration,” and *Virtual 2-Point*, which is traditionally called “2-point calibration.”

Running Offset can be performed by the application software to enhance the accuracy of the *Offset Only* and *Virtual 2-Point* calibration measurements performed during manufacturing test. The application software achieves this by updating the sense offset value so as to compensate for temperature changes in the high-side switch’s operating environment. This technique is particularly effective at lower load currents where the effects of the offset are more pronounced.

When launched, the application initially uses the $V_{IS(OFFSET)}$ and k_{IS} values captured during manufacturing test and stored in the microcontroller’s non-volatile memory (NVM). Whenever the application turns the high-side switch OFF, it reads the current offset value, stores this value in the system’s volatile memory (VM), and subsequently uses this new value in its calculations.

In some cases, the application can periodically turn the switch OFF for short periods (measured in milliseconds) without inconveniencing the end-user or disturbing the application load as illustrated in Figure 23. If the application is using PWM operation, the offset current can easily be measured during the off time of the PWM cycle so long as the $t_{sIS(OFF)}$ settling time is met.

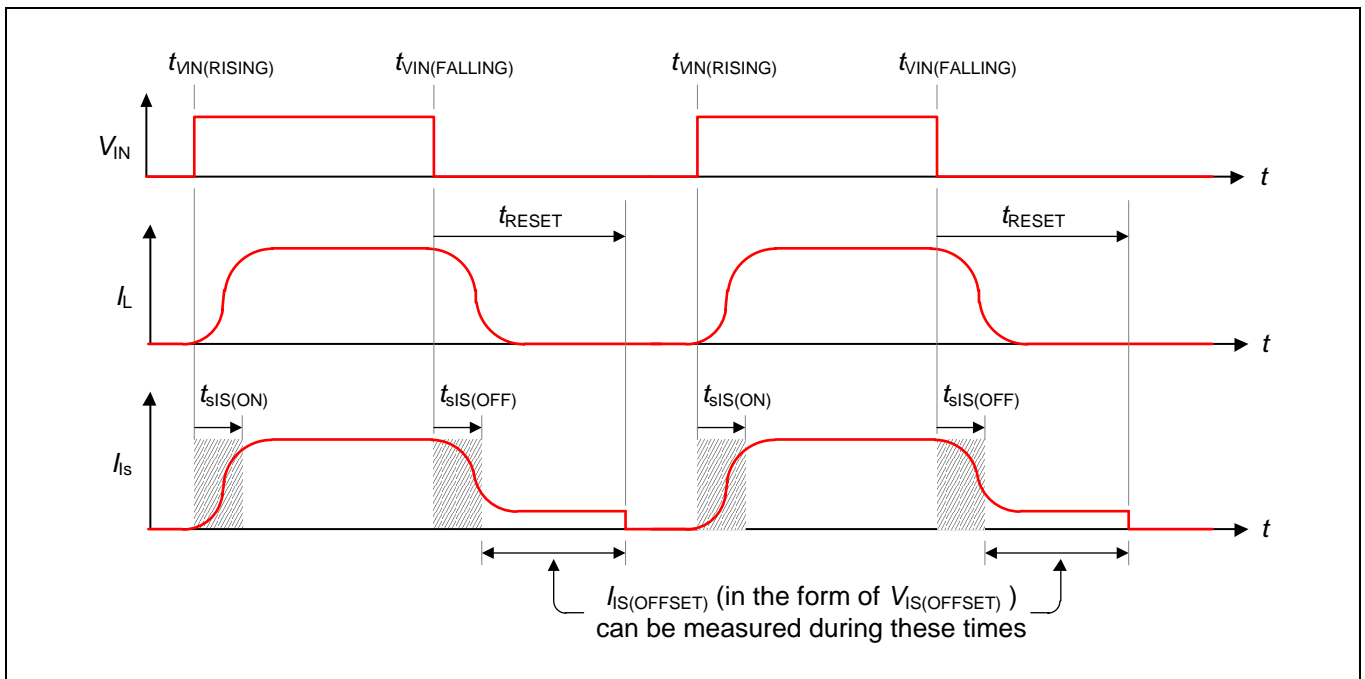


Figure 23 Running Offset calibration timing

Following the first turn-on-off cycle, the application software may simply use the most recently measured value of $V_{IS(OFFSET)}$, or it may keep a running average, or it may use some other technique.

Figure 24 summarizes the process used by the application software when *Running Offset* is being used.

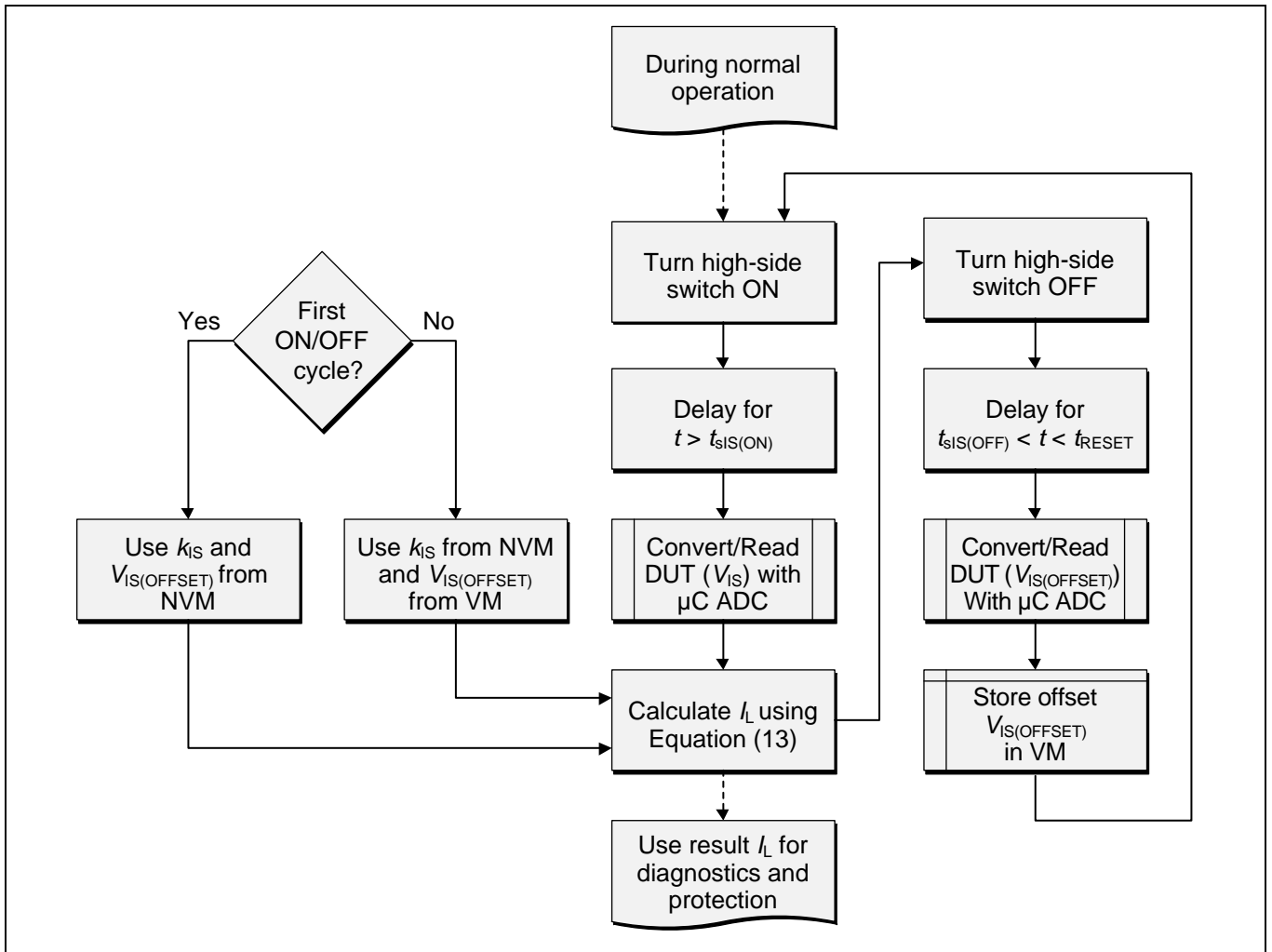


Figure 24 Application software procedure for Running Offset

During normal device/load turn-on cycles, the software reads the IS pin from the ADC after delaying for the current sense settling time. If this is the first turn-on cycle, the application software uses the values for k_{IS} and $V_{IS(OFFSET)}$ from the microcontroller’s non-volatile memory to calculate the load current I_L using Equation (13). This load current is then compared to normal or faulted threshold limits to determine the condition of the load.

During each turn-off cycle, the application software will read the value of $V_{IS(OFFSET)}$ and store it in the system’s volatile memory. For subsequent turn-on cycles, the application software will use the value of $V_{IS(OFFSET)}$ that is stored in volatile memory.

3.7 Accuracy of Different Calibration Options

Figure 25 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.

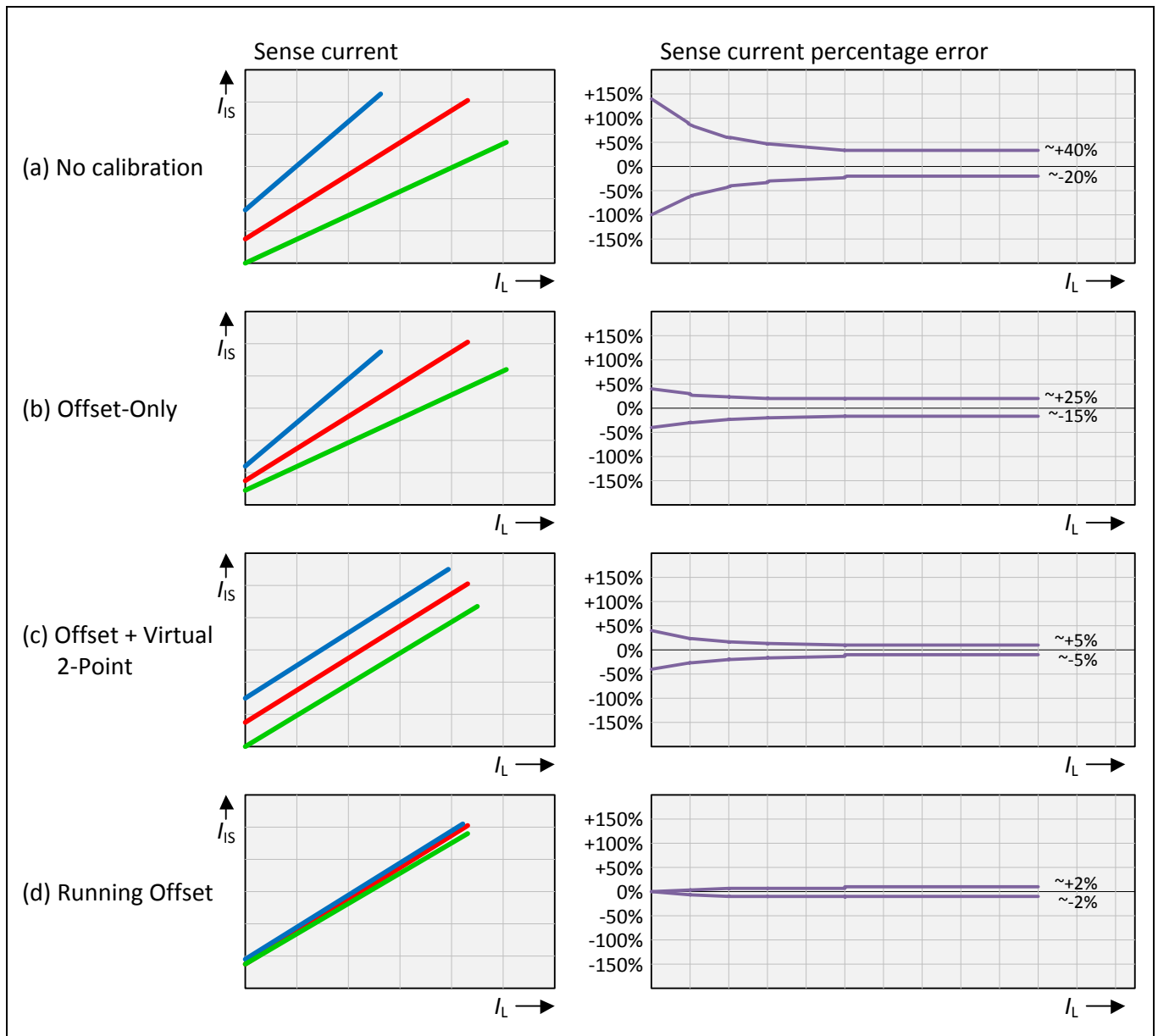


Figure 25 Accuracy of different calibration options

The sense current percentage error graphs clearly show that ADVANCED SENSE technology allows the flexibility to meet the accuracy constraints for many given load requirements. In addition, the calibration effort for both manufacturing test and application software is greatly reduced as compared to traditional and competitive devices.

Note: These graphs are based upon Equation (4) and datasheet parameters for slope (steepness) and offset current including temperature variations. Example datasheet symbols are k_{IS} , $\Delta k_{IS(Temp)}$, $I_{IS(OFFSET)}$, and $\Delta I_{IS(OFFSET)}$. It was assumed for the running offset case that there is no (zero) offset error.

4 Conclusion

Current sensing is a well-accepted feature in high-side power switches. Traditional devices 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. Furthermore, the offset current may only be

calculated at some nominal temperature during manufacturing test; the application software has no way to access or calculate a new offset current value to compensate for changes (such as temperature) in the operating environment.

Infineon's high-side power switches enhanced with ADVANCED SENSE technology addresses both of these issues by moving the offset to an always positive value and by allowing the offset value to be measured by the application software.

ADVANCED SENSE enabled devices also reduce time and cost in manufacturing test by supporting *Virtual 2-Point* calibration, which provides the accuracy of a traditional 2-point calibration for slope while measuring only a single load.

Infineon's ADVANCED SENSE technology enables the compensation of sense current offset and offers high accuracy for load current measurements, all with minimal end-of-line calibration and low application software effort.

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