AN5386

Application note

STSPIN830: measuring negative voltages on sense resistors

Introduction

The STSPIN830 is a three-phase motor driver with an integrated power stage. The current sensing is performed using shunt resistors connected between the low-side MOSFETs and ground.

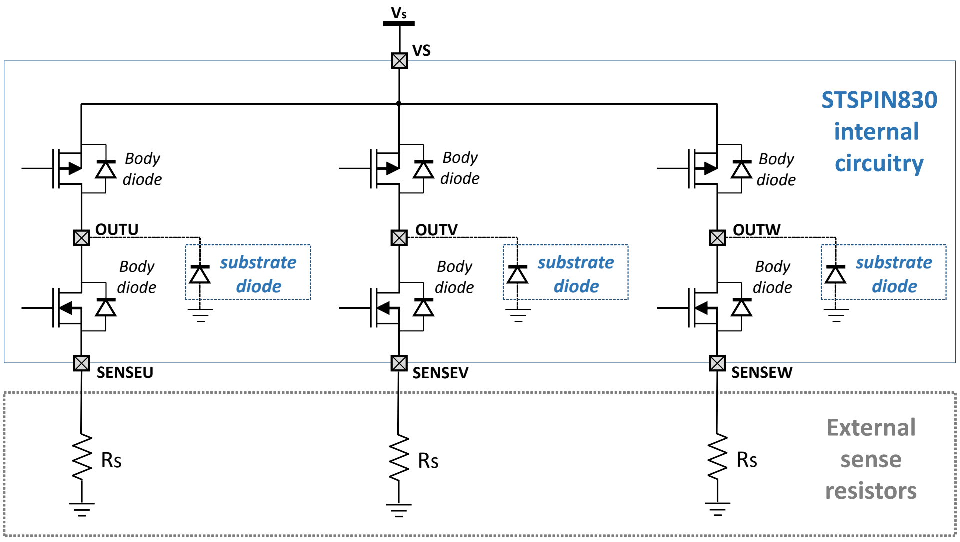
According to the direction of the current, the voltage on the sense resistor can be positive or negative. Some applications and algorithms, such as Field Oriented Control, require measuring both positive and negative voltages.

This document describes how to select the shunt resistors' value in order to properly sense currents generating a negative voltage. The relation between the sensing accuracy and the current flowing in the motor is then explained.

1 STSPIN830 power stage

The STSPIN830 integrates the power stage, shown in Figure 1, composed of three half-bridges. Each low side has a dedicated pin on which a resistor, named sense resistor or shunt resistor, can be connected for current sensing purpose. In addition to the body diode of each MOSFET, there is a substrate diode between each of the output pins (OUTU, OUTV and OUTW) and device ground.

Figure 1. Substrate diodes in STSPIN830 power stage



When the low side of one phase is on, the phase current flows into the respective shunt resistor and it can be measured reading the voltage drop. This is true only if all the current flowing through the OUTx pin is equal to the one flowing through the respective SENSEx pin.

However, when an output pin sources the current, the output voltage can fall below the ground (see Figure 2). If the negative voltage is strong enough, the substrate diode turns on taking a part of the current. Consequently, the current flowing through the sense resistor is no more equal to the one in the OUTx node, thus in the motor phase. This can lead to an error in current measurement: the higher the current flowing through the substrate diode, the higher this measurement error.

1.1 Current sensing with negative SENSEx voltages

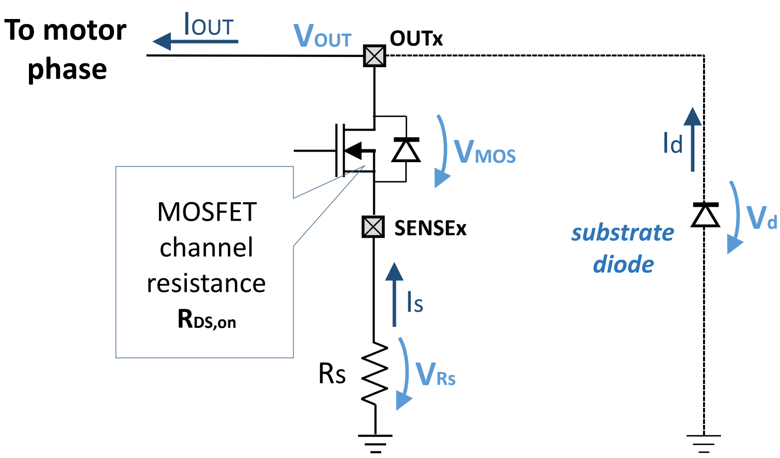
The condition under investigation is when a negative voltage is present on the SENSEx pins. This condition occurs when:

- the current is sourced by the OUTx pin
- the low-side MOSFET on that phase is on

Consequently, a negative voltage is present on the OUTx pin and the substrate diode is forward biased. A part of the output current flows through the substrate diode and not in the sense resistor.

Note: For positive voltages on R_S and on OUTx pins, the substrate diodes are completely turned off: in this case no errors are introduced in the current sensing.

Figure 2. **Current representation in one half-bridge low side for negative OUTx voltage**



Referring to Figure 2 , the error ε in current reading can be expressed as:

Equation 1

$$\varepsilon = \frac{I_d}{I_{OUT}} \qquad (1)$$

where I_d is the substrate diode's current and I_{OUT} is the output current.

The substrate diode's current (I_d) depends on the forward voltage (V_d) that is actually the opposite of the output voltage V_{OUT} on the OUTx pin (see Eq. (2)). The Id – and therefore the error ε – is negligible when the voltage Vd is below the turn-on threshold of the diode, as shown in Figure 3 in Section 1.2

Equation 2

$$V_d = -V_{OUT} = V_{Rs} + V_{MOS} = I_S \cdot (R_S + R_{DS,on}) \qquad (2)$$

where $R_{DS,on}$ is the channel resistance of the low-side MOSFET and R_S is the value of the sense resistor.

In order to reduce the current I_d and so the error ε for a given current of the target application, a reduction of the sense resistor is needed. Similarly, the effect on the substrate diodes are more evident in higher current applications.

1.2 Diodes characteristics

The typical characteristics of the substrate diode and the body diode have been measured at room temperature (T_{amb} about 25°C) and they are represented in Figure 3. According to these measurements, the turn-on threshold of the substrate diode (about 0.8V) is higher than that of the MOSFET body diode, which is about 0.6V. For STSPIN830, the typical low-side $R_{DS,on}$ of the N-channel low side is around 340 mΩ at T_{amb}. Considering a sense resistor in the application Rs = 330 mΩ, the current flowing in the substrate diode is negligible when the phase current I_{OUT} is less than 1A. In this condition, it is possible to assume that $I_{OUT} \approx I_S$ (the output current is almost equal to the current flowing in the sense resistor).

The evaluation of the current sensing error is shown in Figure 4 at different levels of current in the phase of the motor and at 25°C. The measurements of Figure 4 are done mounting on the evaluation board three different sense resistors: 330 mΩ, 100 mΩ and 50 mΩ with ±1% tolerance, which determines a non-zero error at lower currents.

Using the 330 mΩ resistor, the measurement error is 6% at 1.5A, while it is negligible decreasing the resistor below 100 mΩ. According to the maximum reading error allowed by the application, a suitable sense resistor value should be chosen, as explained in Section 2

Figure 3. Substrate diode IV curve at room temperature

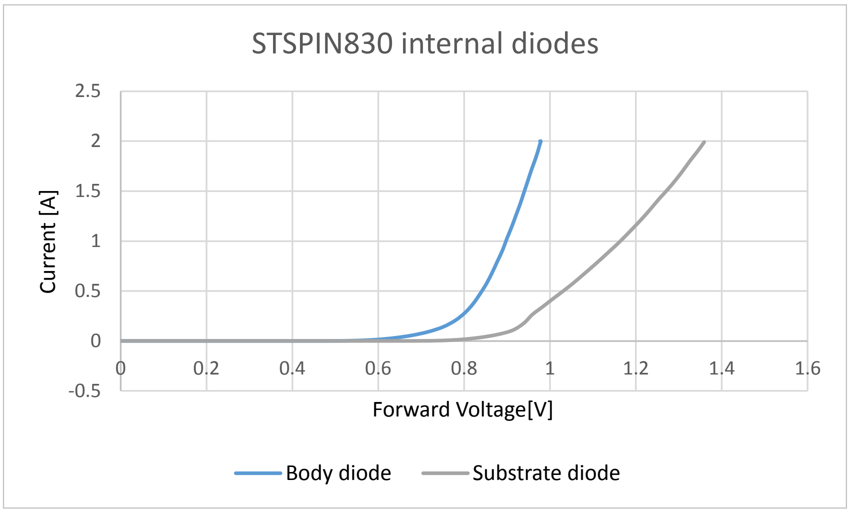
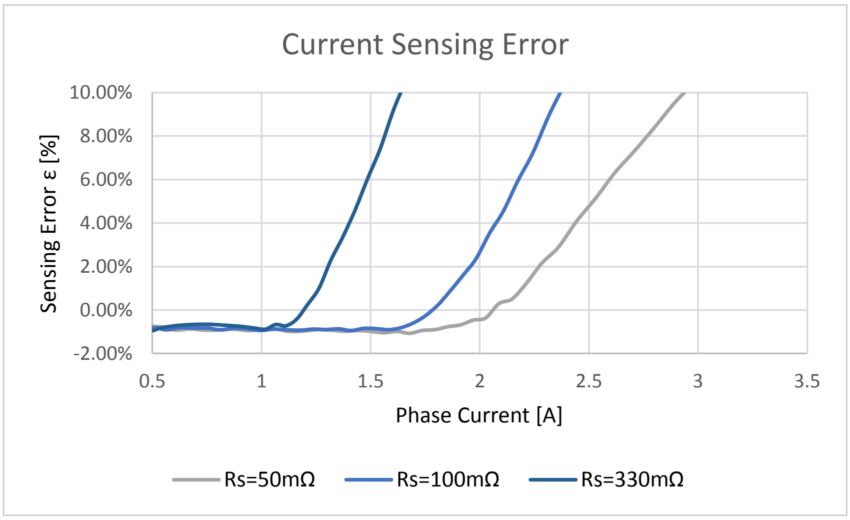


Figure 4. Measurement error on the sense resistor with respect to the output current



2 Sense resistor sizing

The sizing of the sense resistors must be evaluated according to the maximum current of the application. A proper sense resistor must be chosen in order to minimize the negative voltage drop and avoid the turn-on of the substrate diode. On the other side, a smaller sense resistor requires a higher gain of the external amplification and its signal to noise ratio is worse. Table 1 provides the trade-off between high and low values of the sense resistor.

Table 1. Comparison between high and low values of the sense resistor

	Advantages	Disadvantages
Higher R_S values	Higher signal on sense resistor; smaller amplification required	Bigger error when negative voltages are present on OUTx pins; higher power dissipation
Lower R_S values	Smaller error when negative voltages are present on OUTx pins reduced power dissipation	Smaller and more noisy signal on sense resistor; higher amplification required

Another point to consider is the temperature of the power stage; when high currents are involved, the temperature will increase, introducing two different effects:

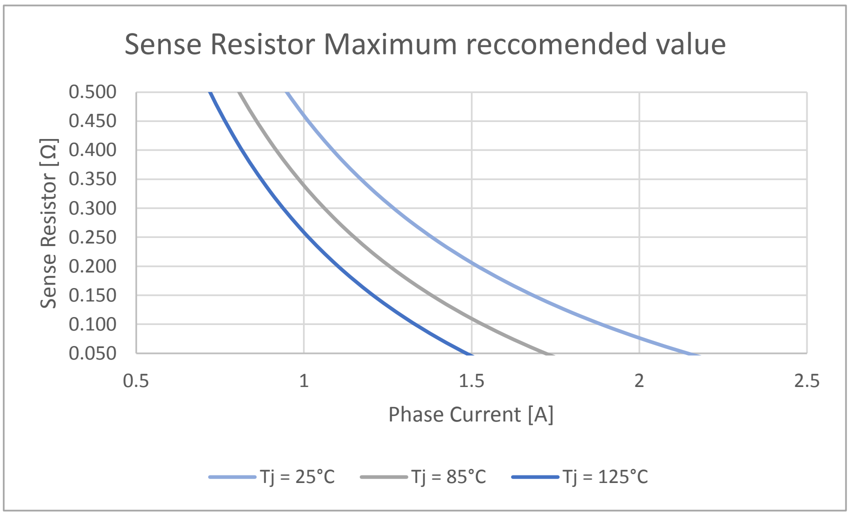
- The low-side MOSFET resistance increases.
- At the same value of the forward voltage V_d, the diode brings more current

Increasing the MOSFET channel resistance implies a high voltage drop, the OUTx pin becomes more negative, so the forward voltage of the substrate diode is higher. Moreover, there is a further contribution in the substrate diode current, given by the higher temperature. The sensing error ε increases with temperature: this effect must be evaluated when sizing the sense resistor value.

Knowing the substrate diode characteristic, and its thermal coefficient and knowing the values of the $R_{DS,on}$ of the low side MOSFET and its thermal behavior, it is possible to determine a relation between the phase current of the motor and the sense resistor to be used, in order to keep the reading error ε limited to a given percentage of the total current.

A set of suggested R_S values, at three different junction temperatures, are represented in Figure 5. The values are not measured but are estimated using a simplified model, which does not consider the body diode of the MOSFET. The curve in the chart determines the maximum suggested values with respect to the target current: Then a lower value can be selected considering the trade-off reported in Table 1. The curves are calculated in order to limit the reading error up to 1% of the target current.

Figure 5. **Sense resistor value with respect to the maximum target current**



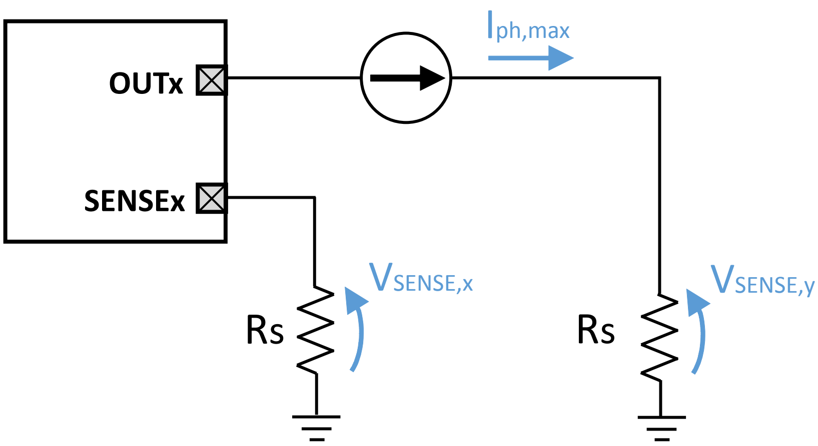
The sense resistor should range between 0.5Ω and 0.05Ω. The upper limit is to avoid undesired power dissipation on the sense resistors; below the lower limit, there is no appreciable advantage on the sensing error reduction: for lower sense resistors the sensing accuracy is limited by the $R_{DS,on}$ of the low-side MOSFET.

2.1 Testing setup

The following setup represented in Figure 6 measures the error introduced on the current sensing for a given value of sense resistor R_s and for a given maximum target current:

1. Turn on the low-side MOSFET
2. Sink the maximum current $I_{ph,max}$ expected from the application, from one OUTx pin
3. Measure the drop on the sense resistor $V_{SENSE,x}$ (actually it is a negative voltage)

Figure 6. **Test circuit for sensing error evaluation**



The reading error of the phase current is calculated using the following formula:

Equation 3

$$\varepsilon = 1 + \frac{V_{SENSE,x}}{I_{ph,max} \cdot R_S} = 1 + \frac{V_{SENSE,x}}{V_{SENSE,y}} \quad (3)$$

The sign of the voltages in Eq. (3) should be considered referring to Figure 6.

The block diagram reported in Figure 6 can be implemented as shown in Figure 7. This example considers two phases OUTU and OUTV while OUTW is left in high impedance.

The current is forced in the inductive load by the PWM signal applied on OUTU pin, while OUTV is always low. The error can be calculated as reported in Eq. (3), using $V_{SENSE,x} = V_{SENSE,U}$ and $V_{SENSE,y} = V_{SENSE,V}$. The voltages $V_{SENSE,U}$ and $V_{SENSE,V}$ must be sampled when the PWM signal is low, otherwise $V_{SENSE,U}$ is zero.

A diagram showing the signals involved in the test setup of Figure 7 is represented in Figure 8. Since the OUTV low side is always on, the voltage $V_{SENSE,y}$ follows the profile of the current I_{ph}; the voltage $V_{SENSE,U}$ instead follows the profile of the current only when the OUTU low side is on. When the PWM is high, so the high side is on, the current flows from the Vs to the load so no drop can be seen on the SENSEU pin.

Figure 7. Applicative implementation of the test setup

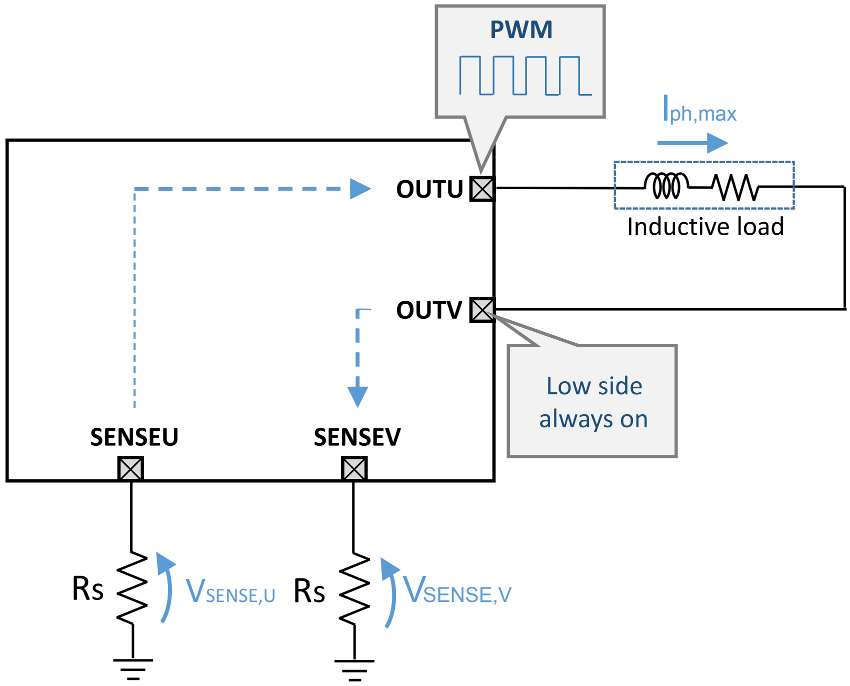
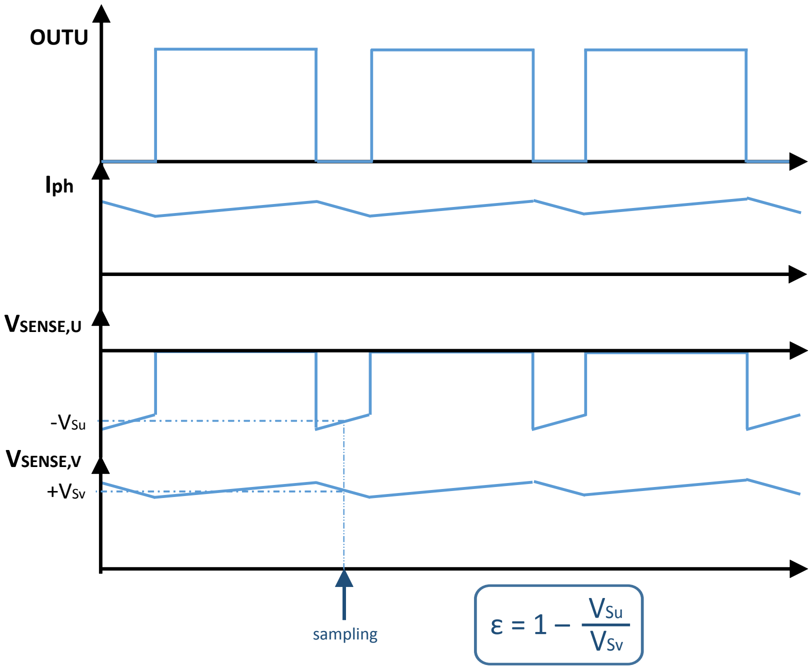


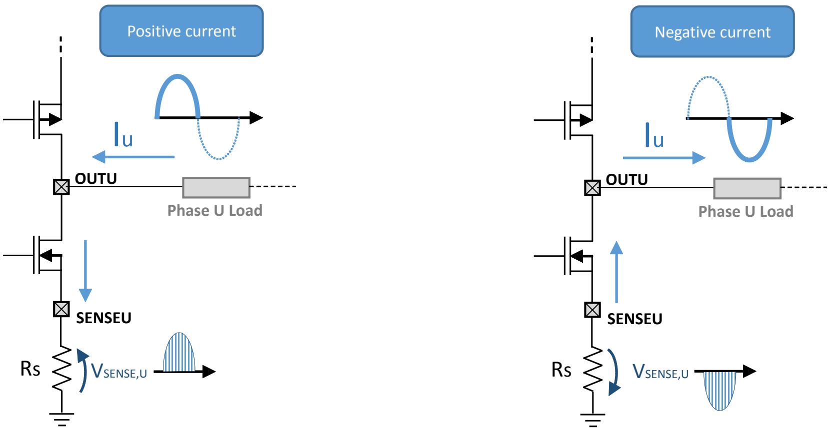
Figure 8. Signals representation of the test circuit of Figure 7



2.2 Example with a sinusoidal current

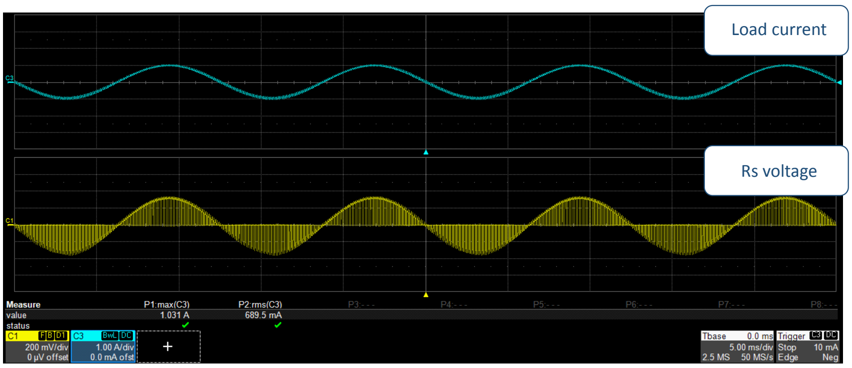
In order to evaluate the effect of the substrate diode, this section reports a typical example, using a sinusoidal current. The example refers to OUTU; anyway it is valid as well as for OUTV and OUTW. The OUTU pin is driven with a PWM signal with a sinewave modulation: its duty cycle ranges from minimum to maximum with a sinusoidal profile. The OUTU is connected to an inductive load and on the other side of the load a PWM signal with a steady duty cycle is applied. Therefore the resulting current is sinusoidal, either sourced or sunk by the OUTU pin; the voltage on the sense resistor is positive or negative as well. Figure 9 represents how the direction of the current and the voltage are considered in the example. Choosing the current sunk by the OUTU pin as positive allows to have the current and the voltage on sense resistor with concordant sign.

Figure 9. Sign convention in the sinusoidal current test



The waveform reported in Figure 10 is acquired using a sense resistor equal to 330mΩ. The duty cycle is selected in order to have a sinewave ranging from -1A to +1A. The voltage drop on the sense resistor follows the current shape and the error is negligible. The positive and the negative peak of the voltage on R_S are at the same level.

Figure 10. Waveforms acquisition at 1A peak current and a 330 mΩ sense resistor



Increasing the level of the current up to ±2A and keeping the same sense resistor, as shown in Figure 11, results in a distortion on the negative measured voltage, since the substrate diode is clamping the OUTU voltage and consequently the signal on the sense resistor. In order to reduce the distortion, a smaller sense resistor must be used.

Figure 12 shows how the distortion is reduced at the same current of ±2A, when a sense resistor of 50mΩ is used. The drawback is a noisier signal, so an adequate filtering and amplification is required. It is worth noting that the scale of the R_S voltage in Figure 10 and Figure 11 is 200mV/div, while in Figure 12 the scale is smaller (50mV/div.), to properly display the smaller signal.

Figure 11. **Waveforms acquisition at 2A peak current and a 330 mΩ sense resistor**

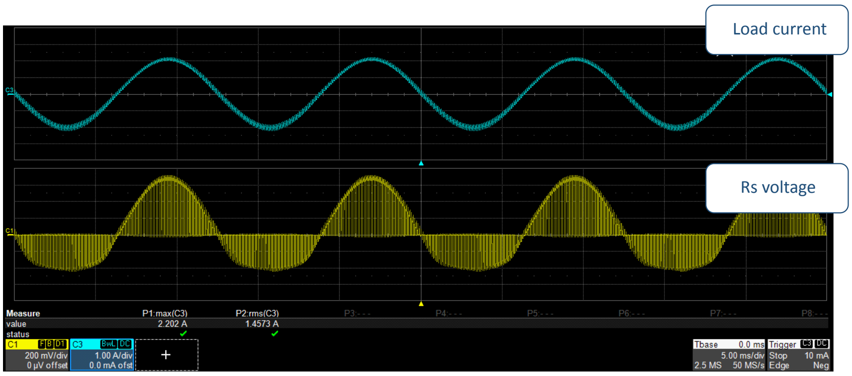
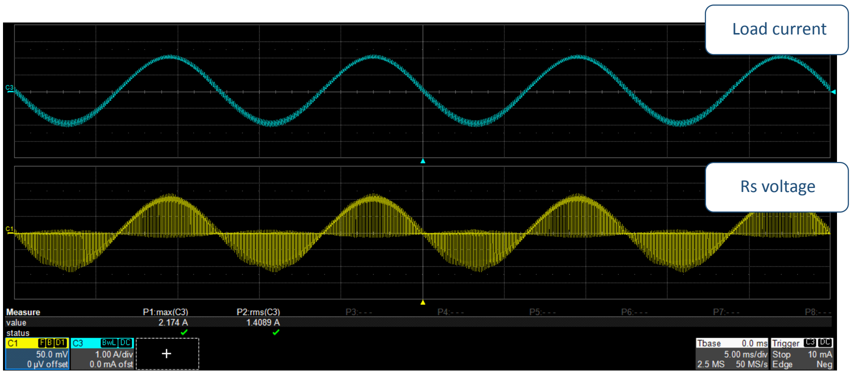


Figure 12. **Waveforms acquisition at 2A peak current and a 50 mΩ sense resistor**



Revision history

Table 2. **Document revision history**

Date	Version	Changes
17-Sep-2019	1	Initial release.

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