

## Redefining a New State-of-the-Art in Microampere Current-Sense Amplifiers

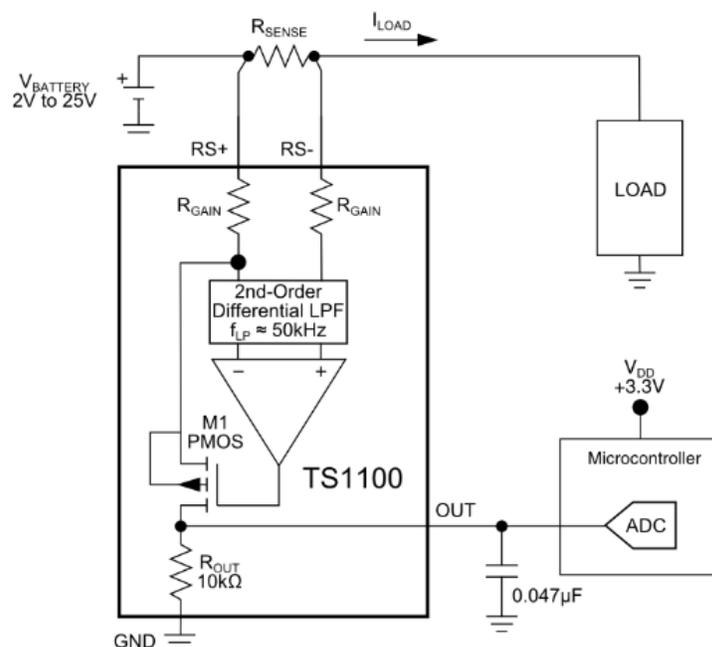
### 1. Introduction

Sensing and controlling supply current flow are a fundamental requirement in most all electronic systems from battery-operated, portable equipment to mobile or fixed-platform power management and dc motor control. High-side current-sense amplifiers (or “CSAs”) are useful in these applications especially where power consumption is an important design parameter. New CSA developments offer even greater benefits in allowing engineers to save power without sacrificing performance.

With the right combination of small form factor, low supply-current operation, wide operating supply-voltage range, low input offset voltage (VOS) and gain errors, and fixed gain options, design engineers now have even more options high-side current-sensing amplification. As a result, new CSA enhancements enable the next generation of battery-powered, hand-held portable instruments addressing power management, motor control, and fixed-platform applications.

### 2. Unidirectional Current Sense Amplifiers

The internal configuration of some unidirectional CSAs is based on a commonly-used operational amplifier (op amp) circuit for measuring load currents in the presence of high-common-mode voltages. In the general case, a CSA monitors the voltage across an external sense and generates an output voltage as a function of load current. Referring to the typical application circuit in Figure 1, featuring the TS1100, the inputs of the op-amp-based circuit are connected across an external RSENSE. At the RS- terminal, the applied voltage is  $I_{LOAD} \times R_{SENSE}$ .



**Figure 1. Typical Application for a High-Precision Unidirectional Current-Sense Amplifier (TS1100)**

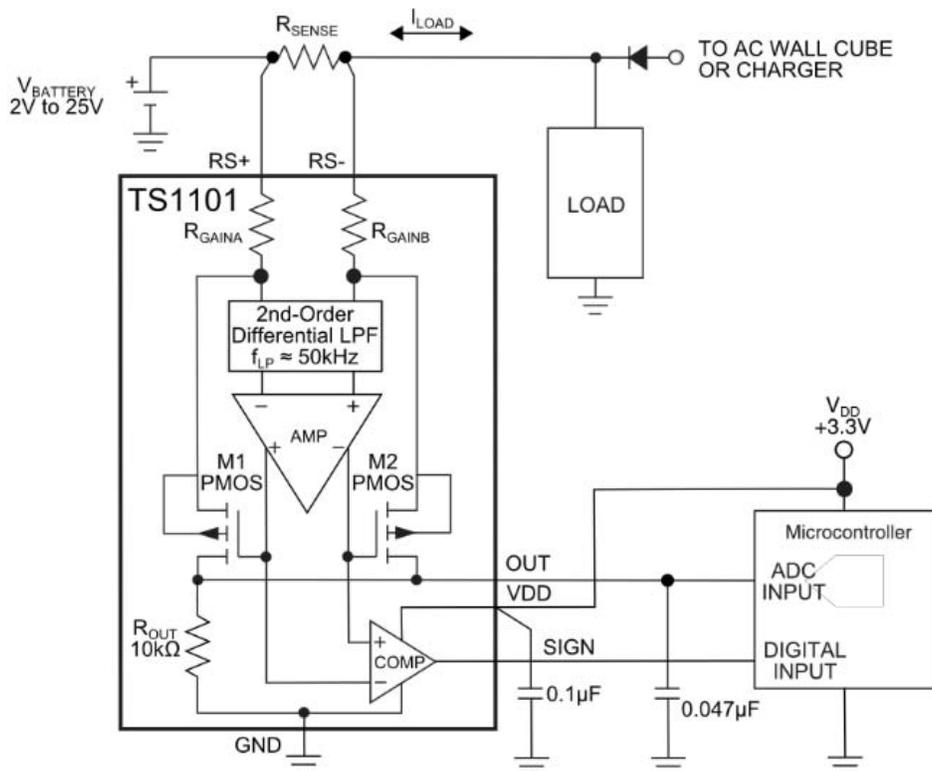
Since the RS- terminal is the non-inverting input of the internal op amp, op-amp feedback action forces the inverting input of the internal op amp to the same potential ( $I_{LOAD} \times R_{SENSE}$ ). Therefore, the voltage drop across RSENSE (VSENSE) and the voltage drop across RGAIN (at the RS+ terminal) are equal. To minimize any additional error because of op-amp input bias current mismatch, both RGAIN resistors are the same value.

## 3. Bidirectional Current Sense Amplifiers

While uni-directional CSAs are primarily used in those applications where current is delivered to a load, there are many applications where it is necessary to measure current in both directions. Some applications where bi-directional current-sense monitoring/amplification are needed include: smart battery packs and chargers, portable computers, super capacitor charging/discharging devices, and general-purpose current-shunt measurements.

Prior to the advent of bi-directional CSAs, uni-directional CSAs were used; however, it was necessary to use two uni-directional CSAs in order to measure current in both directions. The RS+/RS- input pair of CSA #1 is wired normally for measuring current to the load whereas, for CSA #2, the RS+/RS- input pair would be wired anti-phase with respect to CSA #1 for measuring current back to the source. Significant disadvantages to using this configuration besides the cost of two CSAs are that the technique requires twice the printed-circuit-board (pcb) area, ties up two ADC inputs, and requires additional microcontroller coding and machine cycles.

To save on additional computing resources, pcb area, and component costs, a straight-forward modification to the uni-directional CSA configuration yields a bi-directional CSA as shown in Figure 2 for the TS1101.



**Figure 2. Typical Application for a Bidirectional High-Precision Current Sense Amplifier (TS1101)**

As shown in Figure 2, the internal amplifier was reconfigured for fully differential input/output operation and a second low-threshold p-channel FET (M2) was added. The operation of this bidirectional CSA is identical to that of the unidirectional CSA previously discussed when  $V_{RS-} > V_{RS+}$ . In the implementation shown in Figure 2, when M1 is conducting current, the internal amplifier holds M2 OFF. When M2 is conducting current, the amplifier holds M1 OFF. In either case, the disabled FET does not contribute to the resultant output voltage.

For both types of unidirectional or bidirectional CSAs, gain error accuracy is a measure of how well controlled is the ratio of  $R_{OUT}$  to  $R_{GAIN}$ , especially over temperature. In a monolithic implementation, gain error accuracy can be  $<0.5\%$  using novel circuit techniques. In a discrete CSA circuit, it would be quite difficult to achieve this level of performance over temperature with standard 1% tolerance and 100 ppm/°C temperature coefficient resistors. While some CSAs are only available with fixed-gain options, many CSAs offer different gain options tailored to specific application requirements.

To achieve their very-low VOS performance over temperature, over wide VSENSE voltages, and over wide power supply voltages, higher-performance CSA incorporate chopper stabilization into the input stage, a commonly-used technique to reduce significantly amplifier VOS. In reducing the CSAs' VOSs to 30  $\mu\text{V}$  (typically) or less, load currents can be resolved to 12-bit resolution or better for full-scale VSENSE voltages equal to and larger than 123 mV. When compared to similar CSAs that exhibit VOSs > 100  $\mu\text{V}$  or more, load current measurements are two times more accurate using CSAs that have implemented chopper-stabilized input stages.

### 3.1. The CSA's SIGN Output Comparator

As was shown in Figure 2, the bi-directional CSA incorporated one additional feature – an analog comparator the inputs of which monitor the internal amplifier's differential output voltage. While the voltage at its OUT terminal indicates the magnitude of the load current, the SIGN comparator output indicates the load current's direction. The SIGN output is a logic high when M1 is conducting current ( $\text{VRS+} > \text{VRS}$ ). Alternatively, the SIGN output is a logic low when M2 is conducting current ( $\text{VRS+} < \text{VRS}$ ).

Note that, unlike other bi-directional CSAs where hysteresis was purposely introduced to prevent comparator output voltage chatter, SIGN comparator exhibits no “dead zone” at ILOAD switchover. With respect to a 50 mV external sense resistor, the load current transition band is less than  $\pm 0.2\text{mA}$ . Other types of CSAs that also utilize an analog OUT/ comparator SIGN arrangement exhibit a SIGN transition band that can range up to 2 mV (or 40 mA referred to a 50 mV sense resistor). On this attribute alone, low-transition band, bidirectional CSAs can be 200 times more sensitive.

### 3.2. Internal Noise Filters

To counter the effects of externally-injected differential and common-mode noise prevalent in any load current measurement scheme, it's always been good engineering practice to add external low-pass filters (LPFs) in series with the CSA's inputs. In the design of discrete CSAs, resistors used in the external LPFs were incorporated into the circuit's overall design so errors because of any input-bias current-generated voltage and gain errors were compensated.

With the advent of monolithic CSAs, utilizing external LPFs in series with the CSA's inputs only introduces additional offset voltage and gain errors. To minimize/eliminate the need for external LPFs and to maintain low offset voltage and gain errors, higher-performance uni-directional and bi-directional CSAs incorporate internal LPFs to further save system cost and improve overall system performance.

### 3.3. Additional Applications Tips

For optimal VSENSE, all parasitic PCB track resistances to the sense resistor should be minimized. Kelvin-sense pcb connections between RSENSE and the CSAs' RS+ and RS- terminals are strongly recommended. The PCB layout should be balanced and symmetrical to minimize wiring-induced errors. In addition, the pcb layout for RSENSE should include good thermal management techniques for optimal RSENSE power dissipation.

A 22 nF to 100 nF good-quality ceramic capacitor from the OUT terminal to GND forms a LPF with the CSAs' ROUT and should be used to minimize voltage droop (holding VOUT constant during the sample interval). Using a capacitor on the OUT terminal will also reduce the CSAs' small-signal bandwidth as well as band-limiting amplifier noise.

In conclusion, a new state of the art in CSA technology has been redefined. Novel CSAs are extremely easy to use, can resolve charging or discharging currents with 12-bit or better resolution, exhibit very low VOS and gain match errors, are self-powered, and consume very little supply current. These higher-performance CSAs mate their electrical performance with pcb-space saving packages (such as SOT23-5 and SOT23-6), are specified to operate over wide or extended industrial temperature ranges, and can operate from 2 to 25 V (and higher) power supplies. See the documentation for the TS1100 and TS1101 Current-Sense Amplifiers. For additional information, contact Silicon Labs.

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