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A Four-Decade, Integrated Current-Sensing Solution With Extended Supply Range

by Bich Pham and Ashwin Badrinarayanan, Maxim Integrated, San Jose, Calif.

Measuring current in a system is a fundamental, yet powerful tool in monitoring the system's state. With advanced technology, electronic or electrical systems are shrinking tremendously in physical size, reducing power dissipation and cost with not much tradeoff in terms of performance. Every electronic device is monitoring its own health and state, where these diagnostics provide vital information needed to manage the system and even dictate its future design upgrades.

There is a growing need to measure a wide range of current in a system from miniscule current levels up to several amperes of current. In some cases, the current measurement is not the goal but rather a necessary step for determining power consumption. The following application examples illustrate why it is necessary to measure current and/or power consumption over a wide dynamic range:

- Applications where sleep/inactive currents are important, and must be measured in addition to current measurement during normal operation, to determine the overall loading performance and battery/supply power estimation.
- ATE/testing environments needed to handle miniscule/low-microamp current levels up to ampere levels of current as part of R&D or production-level testing.
- Production floor environments to catch production problems (flux trapped under ICs, unwanted solder shorts or open circuits) along with normal operating function tests.
- Industrial equipment monitoring: The power dissipation during on and off times provides the health of the equipment such as normal and leakage currents monitored in equipment to determine its wear and tear over time.

Current-sense amplifiers used in combination with external sense resistors are a traditional choice for measuring current in these types of applications. However, there are performance limitations associated with this option, particularly with respect to dynamic range.

This article introduces a resistorless, greater than four-decade dynamic range current-sensing solution and describes a simple method to extend its supply voltage range from 6 V up to 36 V using only a Zener diode and two MOSFETs. The MAX40016 is featured as an example with schematic and test results. However, the technique is a generic one that can be used to extend the common mode for any current-sense amplifier, particularly those versions with current output.

Although the technique described here is not new, applying it to the MAX40016 offers a solution that achieves the extended supply range while also providing wide dynamic range and high accuracy. These last two design criteria are usually in conflict with traditional current-sense amplifiers with an external sense resistor, but can be obtained by using the resistorless solution provided by the MAX40016. In place of the external sense resistor, the MAX40016 relies on the R_{ON} of an internal pass transistor.

Current Solution

In the presence of higher voltage (common-mode) applications up to 80 V, a current-sense amplifier (CSA) with an external sense resistor offers a solution to most problems when measuring current (Fig. 1). This circuit solution is simple on the outside, but relies on a complex integrated circuit design with an architecture catered to precision and accuracy.

CSAs come with best-in-class accuracy and precision to tackle microampere current levels and still maintain better signal-to-noise ratio (SNR) performance to provide the resolution of measurement sought by the system design.

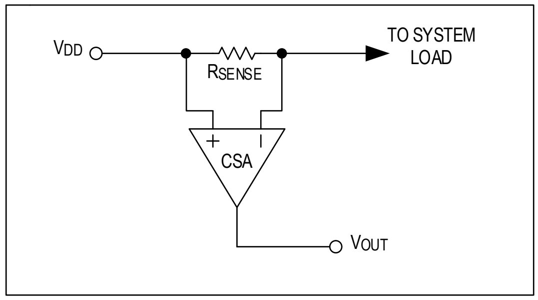

Fig. 1. CSA + sense resistor.

However, it is not an easy task when selecting an optimized CSA for designers. There are tradeoffs to consider (Fig. 2) including available supply, minimum detectable current (which translates to how low the input offset voltage (V_{OS}) of the device is), maximum detectable current (which translates to the maximum input sense voltage (V_{SENSE})) and allowable power dissipation on the R_{SENSE}.

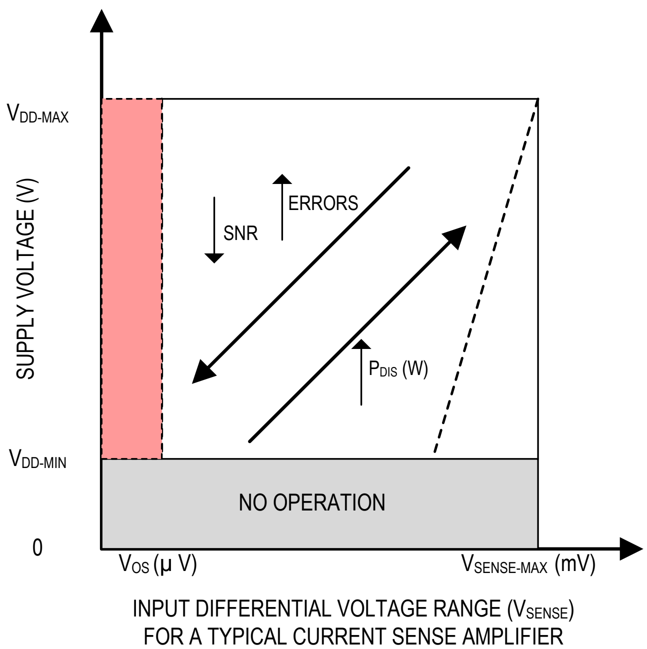

Fig. 2. Design constraints to consider when using a CSA and R_{SENSE}.

Since the differential voltage range is set by the choice of the current-sense amplifier, increasing the R_{SENSE} value improves the accuracy of the measurements for lower values of the current. But, the power dissipation is higher at higher current and that may not be acceptable. Also, the dynamic range or ratio of the sensed currents (I_{MAX} /I_{MIN}) is reduced.

Rather than increasing its value, it’s more beneficial to reduce the R_{SENSE} value as the lower resistance value lowers the power dissipation of the resistor and increases the sensed current range. However, the lower R_{SENSE} value comes at the expense of reduced SNR (which can be improved with averaging of the noise at the input).

Note that with this scenario (a lower R_{SENSE} value), the offset (V_{OS}) of the device affects the accuracy of the measurement. Often, calibration at room temperature is done to improve system accuracy, cancelling out the offset voltage but adding cost in the testing of certain systems.

Also, the input differential voltage range (V_{SENSE}) is dependent on the supply voltage or the internal/external reference voltage and the gain:

$$V_{SENSE} = \frac{V_{DD}\ or\ V_{REF}}{GAIN}$$

In any application realizing high current ranges, the goal is to maximize the dynamic range for a targeted accuracy budget, which is typically estimated by the following equation:

$$Dynamic\ Range\ (decade) = LOG\left\{\frac{V_{SENSE-RANGE}}{V_{SENSE\_MIN}}\right\}$$

$V_{SENSE-RANGE}$ is typically 100 mV for most CSAs with an input offset voltage of approximately 10 µV. Note that if V_{SENSE_MIN} is chosen to be a 10 x V_{OS} factor, this provides three decades at best for ±10% errors in an uncalibrated system. Similarly, if a 100 x V_{OS} is selected, a ±1% error range can be achieved, but then the dynamic range is shrunk to two decades. As a result, there is a tradeoff between the dynamic range and accuracy: tightening the accuracy budget reduces the dynamic range dictated by the V_{SENSE_MIN} and vice versa.

Note that in a CSA + R_{SENSE} system, R_{SENSE} (tolerance and temperature coefficient) is usually the bottleneck in the total accuracy of the system. However, this is still the industry's preferred practice to monitor/measure currents in a system thanks to its simplicity, reliability, and reasonable costs compared to other alternatives such as fuel gauges, CSAs with integrated chip resistors, and discrete implementation of difference amplifiers using op-amps.

Higher grade tolerance and temperature coefficient sense resistors are available, but only at steeper prices. The total error budget of the application over temperature needs to be equivalent to the error emerging from the R_{SENSE}.

Resistorless Sensing Solution

When it comes to applications that require a higher dynamic range of currents to be measured, from a couple hundred microamperes to several amperes, an integrated current-sensing device such as U1 shown in Fig. 3 is a highly useful and effective solution. The solution meets the bill for the following criteria:

- integrated sensing element (resistorless)
- greater than four-decade current-sensing dynamic range
- current output feature, which along with a 160-Ω load provides 0-V to 1-V V_{OUT}, compatible with all ADC/microcontroller inputs used to generate the required digital value for the current.

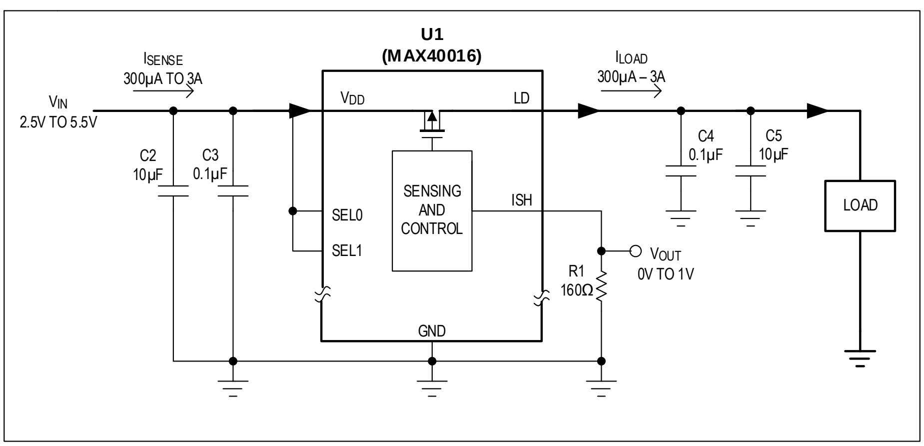

Fig. 3. A 2.5-V to 5.5-V current-sensing system with integrated current-sensing element.

Instead of an external sense resistor, an integrated sensing device (the p-channel MOSFET pictured in Fig. 3) is present across the V_{DD} input and load (LD) output, capable of measuring the system load current (I_{LOAD}) from 100 µA to 3.3 A. An internal gain block with a gain of 1/500 provides the output current at ISH, which is I_{LOAD}/500. A 160-Ω resistor connected from the ISH current output to GND, converts the ISH current to a V_{ISH} voltage output ranging from 0 V to 1 V.

The drop across V_{DD} and LD on the sensing element is approximately 60 mV at 3 A of load current (see Fig. 4), equivalent to a mere 180-mW power dissipation while at lower current values, the total error observed to sense the 100-µA range is in the region of 10% (Fig. 5). By achieving lower power dissipation at higher current loads together with improved error budget at lower current levels, this scheme prevails over the traditional sense circuit of Fig. 1. Hence, applications requiring wider ranges of current sensing up to 3 A can benefit from this scheme.

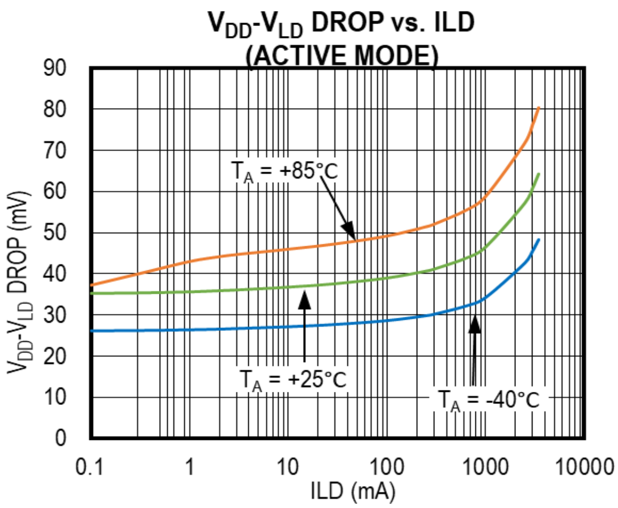

Fig. 4. Voltage drop across the internal sense element of the MAX40016 versus load current.

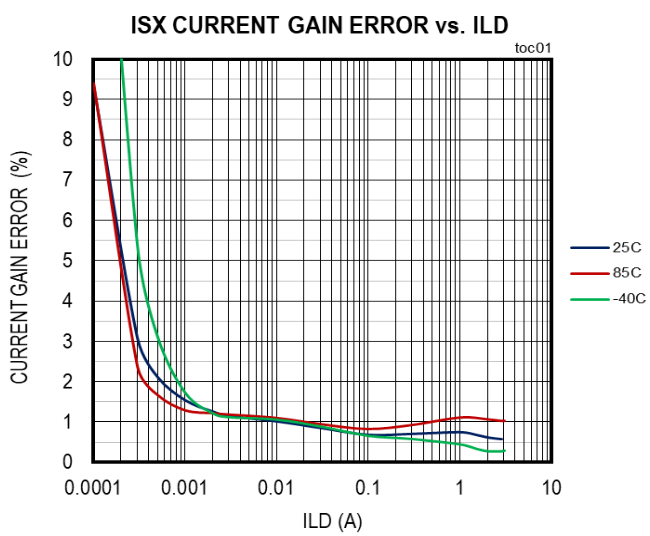

Fig. 5. Gain error at ISH output vs. load current at different temperatures.

Resistorless Sensing Solution With Extended Line/Input Voltage

Fig. 6 is an application circuit that provides input voltage range extension versus what's offered by the standard circuit in Fig. 3. In the new circuit the supply voltage for U1 can now accept a higher line voltage, anywhere from 6 V to 36 V.

The Zener diode (D1) maintains a voltage of 5.6 V across V_{DD} and the gate of the PFET (M1). The bulk of the high voltage line is absorbed by M1 with M1's source clamped to approximately 4 V to 4.5 V away from the V_{DD} input voltage, thus maintaining the U1 operating voltage (V_{DD} - V_{SS}) within its normal operating range (Fig. 7). M1's source voltage is then biasing the gate voltage for M2 PFET. The M2 PFET source is at V_{SS} (U1) + V_{TH} (M2) ensuring the U1 ISH output is within acceptable voltage levels. The ISH current output and R1 generate 0-V to 1-V output with respect to GND.

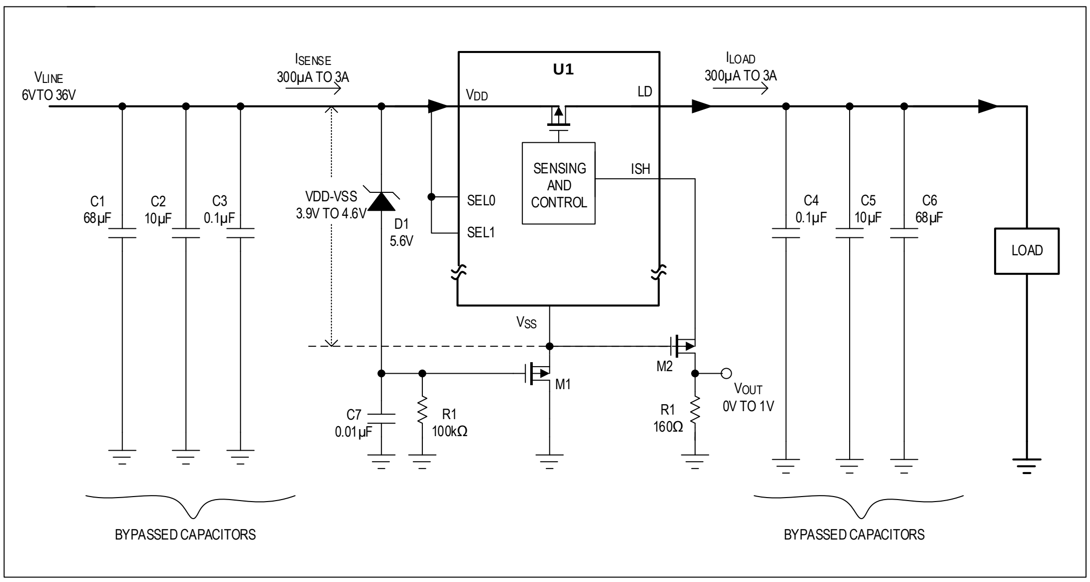

Fig. 6. A 6-V to 36-V current-sensing system with integrated current-sensing element.

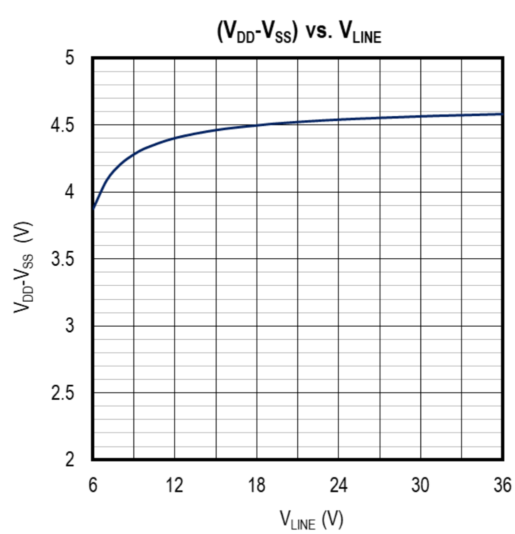

Fig. 7. Function of the MAX40016 supply voltage (V_{DD}-V_{SS}) vs. V_{LINE}.

Experimental Results

DC/Static Characteristic Results

Fig. 5 shows the gain error performance of the application circuit as shown in Fig. 6. Dc load current is varied from 100 µA to 3 A. Since the trends of gain error at different temperatures at lower values of input currents are similar, the designer can calibrate at one temperature.

Fig. 7 shows the supply available across MAX40016 (V_{DD} and V_{SS}) inputs to facilitate normal operation of the device.

Line/Load Transient Characteristic Results

Fig. 8 shows the application circuit's load transient ability from minimum to maximum load current step.

Fig. 9 shows the line transient response with maximum load enabled during power up. During power up, the supply is available to MAX40016 within a few 100-µs intervals, keeping it in normal operation. A resistive load at V_{LD} is connected to draw 3 A from the supply. It can be observed that the output load current tracks the soft start response of the power supply connected to (V_{LINE}/V_{DD}) input.

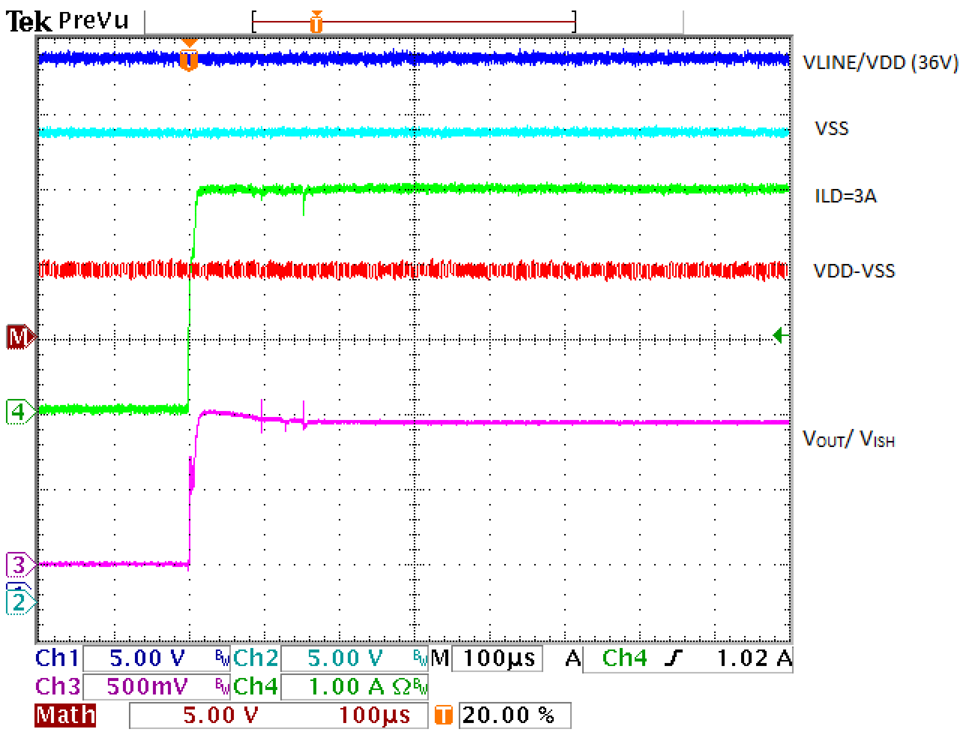

Fig. 8. Load transient response with I_{LOAD} step change from 0 A to 3 A.

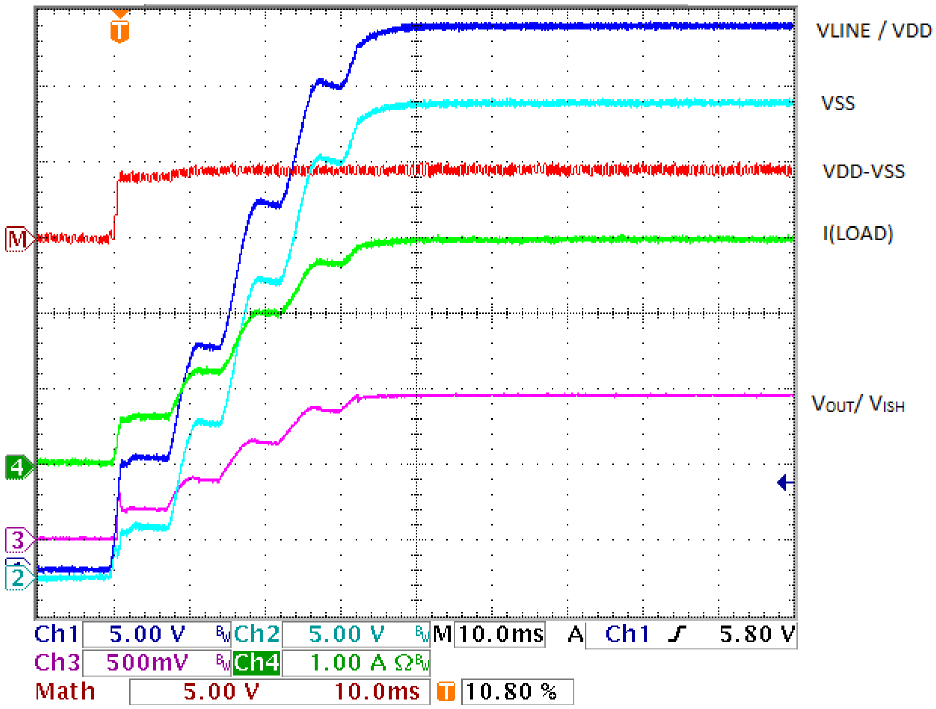

Fig. 9. Power-up transient response with 3-A I_{LOAD}.

Conclusion

The resistorless sensing circuit using the MAX40016 can realize a four-decade current-sensing solution with extended operating range up to 36 V.

About The Authors

Bich Pham joined Maxim Integrated as a customer applications engineer in 2000 and is now a senior member of Technical Staff where he remains focused on helping customers solve real-world design challenges. Bich has a BSEE from San Jose State University in California.

Ashwin Badrinarayanan joined Maxim Integrated as an applications engineer in 2012. He remains focused on new product activities and helping customers solve real-world design challenges in signal chain domain. He has an MSEE from University of Texas at Dallas.

For further reading on current sensing in power electronics designs, see the How2Power Design Guide, locate the Design Area category and select “Test and Measurement”.