Extend Supply Voltage Range of a 4-Decade, < 300uA to 3A Resistor-less Current Sensing Solution

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Abstract: This article introduces a resistor-less, greater than 4-decade dynamic range current sensing solution and describes a simple method to extend its supply voltage range up to 6V-36V using only a Zener diode and two MOSFETs. The MAX40016 is featured as an example with schematic and test results.

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 tremendously shrinking 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 to several Amperes of current. For example, ascertaining the high dynamic range of current flowing or consumption in a system can be seen in the following cases:

1. Sleep/ Inactive currents to determine the overall loading performance and battery/ supply power estimation in addition to normal operation.
2. ATE/Testing environments need to handle miniscule/low micro-amp current levels to ampere levels of current to necessitate R&D or production level testing
3. Production floor environments to catch production problems (flux trapped under IC's, unwanted solder shorts or open circuits) along with normal operating function tests.
4. Industrial equipment monitoring, the power dissipation during ON and OFF times provide the health of the equipment, e.g., normal and leakage currents monitored in an equipment to determine its wear and tear over time.

In presence of higher voltage level (common-mode levels) applications up to 80V, a simple current sense amplifier (CSA) on the outside (but a complex integrated circuit design with architecture catered towards precision and accuracy) and a sense resistor is the solution to most of the problems when measuring current. Current sense amplifiers currently come with best in class accuracy and precision to tackle the demand of realizing micro-ampere current levels and still maintain better signal-to-noise ratio (SNR) performance to provide the resolution of measurement the system design is looking for.

However, it is not an easy task when come to selecting an optimized CSA for designers. There are tradeoffs that should be taken into considerations (Figure 2):

1. Available supply

2. Minimum detectable current (translates to how low the input offset voltage (V_{OS}) of the device is)
3. Maximum detectable current (translates to the maximum input sense voltage (V_{SENSE}))
4. Power dissipation allowable on the 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 range of the sensed current is reduced (I_{MIN} : I_{MAX}).

Reducing the R_{SENSE} value is more beneficial as it reduces power dissipation of the resistor, increases the sensed current range. Reducing the R_{SENSE} value reduces the SNR (which may be improved with averaging to average the noise at the input). It should be noted that during this scenario the offset of the device affects the accuracy of the measurement. Oftentimes, calibration at room temperature is done to improve system accuracy, cancelling out the offset voltage with addition of test cost for 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 equation below:

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

$V_{SENSE-RANGE}$ is typically 100mV for most CSAs with an input offset voltage of approximately 10µV. Note that If V_{SENSE_MIN} is chosen to be a 10xV_{OS} factor, this provides 3 decades at best for a ±10% errors in an un-calibrated system. Similarly, if a 100xV_{OS} is selected, a ±1% error range can be achieved but then the dynamic range is shrunk to 2 decades. As a result, there is a tradeoff between dynamic range and accuracy: tightening the accuracy budget reduces the dynamic range dictated by the V_{SENSE_MIN} and vice versa.

A point to note is that in a CSA + R_{SENSE} system, R_{SENSE} (tolerance and temperature coefficient) is usually the bottleneck of total accuracy of the system. This is still the industry's efficient practice to monitor/measure currents in a system thanks to its simplicity, reliability and reasonable costs compared to other alternatives such as Fuel gauges, CSA's with integrated chip resistor, discrete implementation of difference amplifiers using Op-Amps. Higher grade tolerance and temperature coefficient sense resistors can be found 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}.

Resistor-less Sensing Solution:
When it comes to applications that require higher dynamic range of currents to be measured from a couple of hundreds of microamperes to several amperes, an integrated current sensing device (U1) shown in Figure 3 below is highly useful, effective solution. The solution meets the bill in the following criteria:

1. Integrated sensing element (resistor-less)
2. Greater than 4-decade current sensing dynamic range
3. Current output feature (along with 160Ω LOAD provides 0-1V V_{OUT}, compatible with all ADC/Micro-controller inputs for current realization).

Figure 3: 2.5V to 5.5V Current Sensing System with Integrated Current Sensing Element

Instead of an external sense resistor, an integrated sensing device is present across V_{DD} input and load (LD) output, capable of measuring the system load current (I_{LOAD}) from 100uA to 3.3A. An internal gain block with the gain of 1/500 provides the output current at ISH, which is $\frac{I_{LOAD}}{500}$. A 160Ω resistor connecting from ISH current output to GND, converts to V_{ISH} voltage output from 0V to 1V.

The drop across V_{DD} and LD on the sensing element device is approximately 60mV at 3A of load current (Plot 1), equivalent to a mere 180mW power dissipation while at lower current values, the total error observed to sense 100µA range is in the region of 10% (Plot 2). Together with less power dissipation at higher current loads and still maintaining improved error budget at lower current levels, this scheme prevails the traditional sense circuit of Figure 1. Hence, applications requiring wider current sensing ranges up to 3A of sensing can benefit from this scheme.

Resistor-less Sensing Solution with Extended Line/Input Voltage:
Figure 4 is an input voltage range extension of Figure 3, where the supply voltage for U1 can now accept the line voltage higher, up to 6V to 36V. The Zener diode (D1) maintains the voltage across V_{DD} and gate of the PFET (M1) to 5.6 V. The bulk of the high voltage line is absorbed by M1 with the M1's source clamped to approximately 4V-4.5V away from the V_{DD} input voltage, thus maintaining the U1 operating voltage (V_{DD}-V_{SS}) within its normal operating range (Plot 3). This M1's source voltage is then biasing the gate voltage for M2 PFET. M2 PFET source is at V_{SS} (U1) + V_{TH} (M2) making sure U1 ISH output is within acceptable voltage levels. The ISH current output and R1 generates 0 to 1V output with respect to GND.

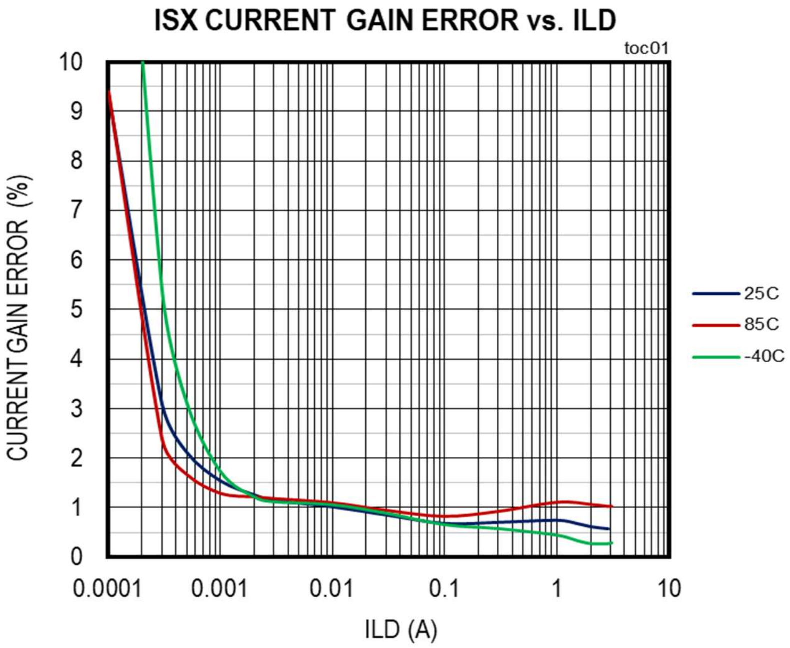
Figure 4. A 6V to 36V Current Sensing System with Integrated Current Sensing Element

Reference	**Device**	**Description**
D1	CMFZ4690	5.6V Zener
M1	BSP322PH6327XTSA1	MOSFET P-CH 100V 1A SOT-223
M2	BSP322PH6327XTSA1	MOSFET P-CH 100V 1A SOT-223
U1	MAX40016ANL+	Four Decade Resistor-less CSA in WLP Package

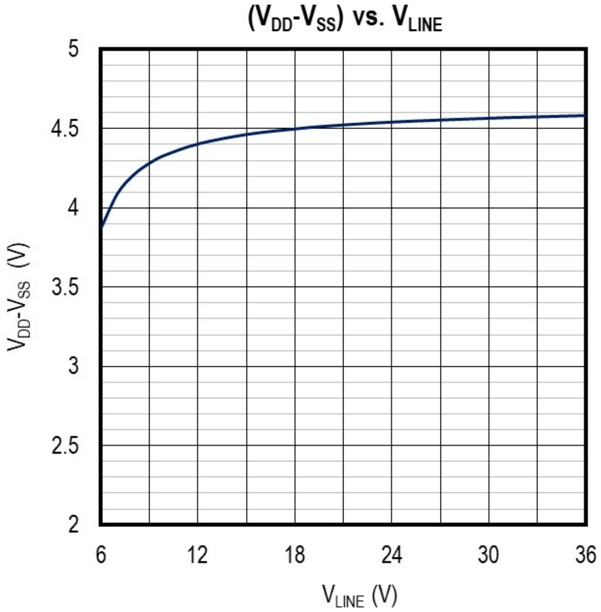
Experimental Results:

Below are experimental results from the circuit of Figure 4.

Plot 1: Voltage Drop across the Internal Sense Element vs. Load Current



Plot 2: Gain Error at ISH output vs. Load current at different temperatures



Plot 3: Function of MAX40016 Supply Voltage (V_{DD}-V_{SS}) vs. V_{LINE}

Conclusion:

With the resistor-less sensing solution using MAX40016, a 4-decade current sensing solution is realized with extended operating range up to 36V.

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