Low-Drift, Low-Side Current Measurements for Three-Phase Systems

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There are multiple locations in the drive circuitry for a motor where the motor's phase currents can be measured. How the current information will be used by the system controller plays a large role in determining the measurement location that aligns best. The four most common locations to measure current in a three-phase motor are shown in Figure 1. There are trade-offs associated with each of the measurement locations such as the measurement accuracy capability, high-voltage circuitry requirements, and signal response time. The complexity of the measurement circuitry to provide adequate system control varies for each location.

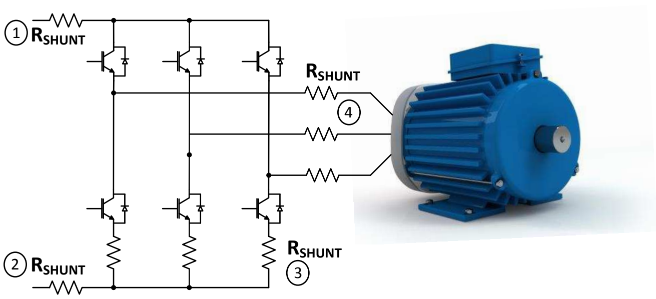

Figure 1. Measurement Locations In A Three-Phase System

Measurement locations one and two from Figure 1 are useful when the detection of faults is necessary rather than needing to provide information on the actual motor current back to the system controller. Extracting individual phase current information from these locations is challenging making them more ideal for comparisons of the total system currents to detect ground shorts, leakages, or other out-of-range conditions.

A common location to implement current sensing for motor control in three-phase systems is in the low-side of each phase leg (measurement location 3 from Figure 1) due to the limited requirement on the common-mode voltage level. In a low-side configuration it is important to note that current only flows through each phase leg when that phase's low-side transistor is turned on. The pulsed characteristic of the current in the low-side phase measurements is unlike the continuous current at the in-line location (measurement location 4 from Figure 1). Measuring the differential signal across a current sensing resistor at location 4 allows for a continuous signal directly proportional to the motor's phase current. However, with the PWM motor drive circuitry creating large common-mode voltage level changes at this in-line location, specific current sense amplifiers capable of handling and rejecting these high dv/dt transitions are required.

In the low-side phase leg configuration the current flows through the shunt resistor only when that particular low-side transistor is on requiring the amplifier to change output levels quickly as the current is pulsed off and on. When this transistor turns on and begins to conduct current, the result is a stepped input signal. The amplifier must be able to respond quickly in amplifying the signal to allow the output to follow the input signal. A processor can then take the switched output waveform from the amplifier and re-combine the phase current information to extract the current signal that will be used in the motor's control algorithm.

A critical requirement for the current sense amplifier measuring low-side phase leg current is to be sufficiently fast to accommodate the small measurement time window determined by the PWM drive circuitry's switching frequency and duty cycle. The amplifier output must transition and settle before the measurement is sampled to provide an accurate proportional waveform to the actual phase current for the processor to use in the control algorithm.

The bandwidth, output drive and settling requirements are determined by the application's switching frequency and duty cycle range. PWM switching frequencies in the range of 20kHz to 30kHz are common in order to stay above the audible frequency band. For example, a 25kHz switching frequency with a 50% duty cycle and a sampling point taken at the midpoint of each half cycle requires the output of the current sense amplifier to settle within 10µs to ensure an accurate measurement. The processor is unable to create proportional waveforms for the control algorithms to properly control the motor if the amplifier's output is unable to reach the output level and sufficiently settle within the available time period.

The settling time period will change and vary as the duty cycle needed to control the motor is varied as shown in Figure 2. Lower motor speeds require a lower duty cycle creating a challenge for the current sense amplifier to provide accurate measurements with smaller timing periods. The duty cycle required to provide the necessary control capability in the motor's control algorithm will determine the necessary bandwidth and settling time characteristics of the current sense amplifier.

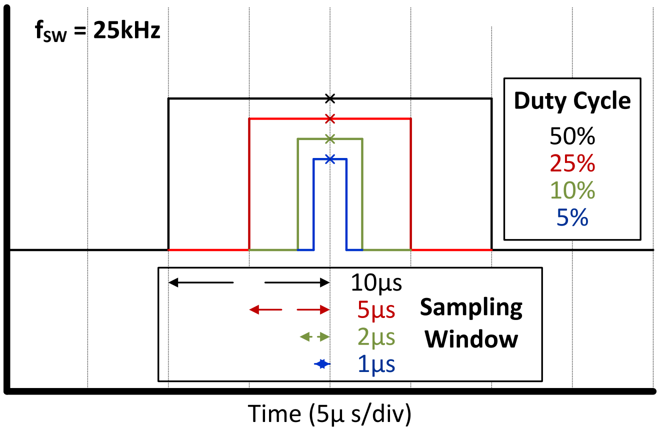

Figure 2. Duty Cycle Impact On Settling Time

An amplifier that is unable to settle within the sampling window will result in a processed waveform that is not proportional to the phase current signal reducing the effectiveness of the motor control algorithms. Figure 3 shows how the output of an amplifier that has insufficient bandwidth and output drive capability will appear. As the input current signal is switching the amplifier's output is unable to reach and settle to the proportional output voltage level resulting in a triangle wave form.

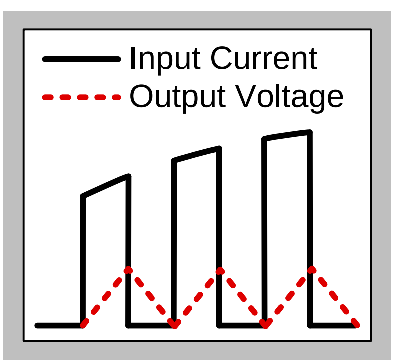

Figure 3. Slew Rate Limited Output

Two amplifier parameters that determine the effectiveness for a given settling time requirement are slew rate and small signal bandwidth. The slew rate specification indicates how quickly the amplifier's output voltage can change in response to a quickly changing input signal. An ideal amplifier's output would match the low-side phase leg's stepped input current signal. The slew rate provides an indication of the amplifier's expected delay in response to the stepped input signal.

The amplifier’s small signal bandwidth also plays a large role in how the output responds to the stepped input condition. An amplifier placed in a high gain configuration has the open-loop bandwidth divided by the corresponding closed-loop gain resulting in a smaller closed-loop small signal bandwidth. Selecting an amplifier with insufficient bandwidth increases the settling time and will result in a more damped output response.

The INA301 is a high-speed current sense amplifier that combines both a high output stage drive capability with a 4V/µs slew rate and a signal bandwidth of 550kHz at a gain of 20V/V. This combination of slew rate and high-speed signal bandwidth, in addition to the on-board over-current comparator make the INA301 ideal for low-side, phase current measurements.

Alternate Device Recommendations

Depending on the necessary system requirement, there may be additional devices that provide the needed performance and functionality. For applications requiring lower measurement accuracy without the additional integrated comparator for over-current detection, use the INA181. For applications requiring current measurements to be taken in-line with the motor phases, use the INA240.

Table 1. Alternate Device Recommendations

Device	Optimized Parameter	Performance Trade-Off
INA181	Package: SC70-6, SOT23-6	Reduced Bandwidth & Duty Cycle Capability
INA240	Enhanced PWM Rejection for In-Line Measurements	Package Size: TSSOP-8

Table 2. Related TI TechNotes

SBOA160	Low-Drift, Precision, In-Line Motor Current Measurements With Enhanced PWM Rejection
SBOA162	Measuring Current To Detect Out-of-Range Conditions
SBOA163	High-Side Motor Current Monitoring for Over-Current Protection
SBOA165	Precision Current Measurement On High Voltage Power Rail
SBOA190	Low-Side Current Sense Circuit Integration

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