Application Brief

High Speed Single Shunt Current Sensing in Motor Control

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Introduction

Permanent Magnet Synchronous Motor (PMSM) and AC induction motor (ACIM) are two of the most commonly used motor types for position and velocity control applications. These are multi-phase motors and require external coil excitation which generally comes in a 3-phase configuration. Such motors are commonly used in various applications ranging from industrial motion control to home appliances. The most popular example is in inverter compressor drives. To receive the best possible efficiency and performance from these motors we need to control the current in all the three phases of the coil winding. To control the current there are various techniques which can be implemented like Trapezoidal control, Sinusoidal control, and Field-oriented control (FOC). For the application inverter compressor drive where high torque and efficiency is required with minimum torque ripple and audible noise over wide range of motor speed, FOC control is the best one. Like the other control scheme, FOC implementation also requires real-time feedback of the currents in all the three phase and rotor position to control the torque and this can be done using the following methods listed:

- Inline current sensing
- Inverter leg current sensing
- DC bus current sensing using a single shunt

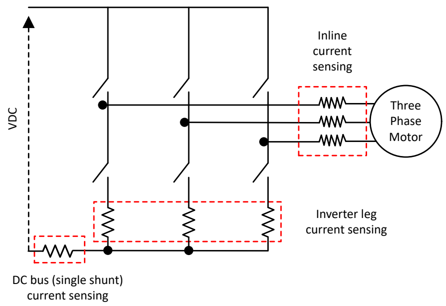


Figure 1. Different Types of Current Sensing

Each of these measurement techniques has pros and cons, however this article mainly focuses on single-shunt current sensing using a high-speed amplifier for FOC control as this is the most cost-effective way of doing so. This article further explains how to select the correct amplifier for this measurement technique.

Single-Shunt Current Measurement in FOC

The single-shunt current measurement technique measures the DC link current and, with knowledge of the switching states, recreates each of the three-phase currents of the motor.

For a better understanding of this technique and to represent the switching state of the inverter, this article defines a switching function Sa for phase A as follows: Sa = 1 when the upper transistor of phase A is ON, and Sa = 0 when the lower transistor of phase A is ON. Similar states can be defined for phases B and C. The explanation of the process assumes that the inverter is fed in complementary mode. The signals in this mode, which control the lower transistors, are in complimentary state of Sa, Sb, and Sc, which control the upper transistors.

The current measurement and switching state must both be considered to properly measure current with the single-shunt technique

An example case is shown in Figure 2.

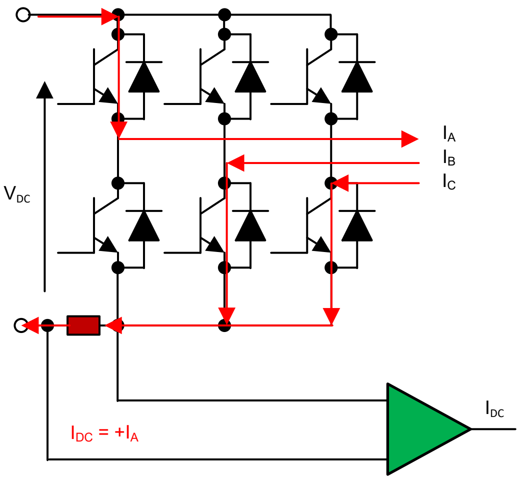


Figure 2. Switching States Sa, Sb, Sc : 1 0 0

Here, the top-side switch of phase A is conducting and the bottom-side switches of phase B and C are conducting. In this switching state, the DC bus current measurement gives the phase A current and is positive (+I_A). The direction of current in phase A is toward the motor winding. Similar to the preceding explanation, there are eight different switching options in SVM (space vector modulation) PWM. Table 1 explains the switches conducting in each space vector switching state and phase current which can be measured in that state.

Table 1. SVM Switching States

Switch State	AH	BH	CH	MEASURE
0	0	0	0	Offset
1	1	0	0	I_A
2	1	1	0	$-I_C$
3	0	1	0	I_B
4	0	1	1	$-I_A$
5	0	0	1	I_C
6	1	0	1	$-I_B$
7	1	1	1	Offset

The six switching states from 1 to 6 are known as active vector.

With the switches in states 0 and 7, only circulating current is present and during these states measuring current with the single-shunt technique is impossible.

To have at least possible distortion in the current of the motor winding, the minimum active vector duration needs to be zero, but in reality, this is practically not possible to achieve because of the sensing and loop delay. A non-zero, minimum-vector duration creates distortion in the winding current which causes torque ripples and creates audible noise, unless compensated in the software algorithm (which is very complex and difficult to achieve).

Advantages and Challenges in Single Shunt Current Sense

There are several advantages of single-shunt current measurement. Firstly, compared with two-shunt or three-shunt, the single-shunt can reduce the amount of shunt resistor, operational amplifier and ADC, thus reducing the system BOM cost significantly. Also a single comparator can be added across the shunt resistor to implement short circuit protection as well in this sensing scheme

Secondly, the single-shunt can help resolve the system problem of layout for multiple shunts. The compressor drive typically starts from a few hundreds of watts to multi-kW range, so each of inverter leg can need many shunts in parallel, which makes placement or layout difficult. In high-power-rating applications, some designers even choose higher cost magnetic current sensors to avoid such an issue. From this point of view, the single-shunt technique only senses one dc bus current, and therefore, can reduce the number of shunts and help raise the critical current sensing point between shunt-based sensing versus magnetic current sensors.

Also, using a single shunt results in same gain across all the phases as the possibility of gain error across the different phases because of the resistance mismatch is eliminated

Moreover, the single-shunt technique can also avoid many disadvantages of magnetic current sensors, including susceptible to magnetic interference, low accuracy, low bandwidth, poor scalability, and so on.

Nevertheless, implementing single-shunt can bring some design challenges. The sampling points must be carefully selected and the settling time must be as short as possible. For example, to maintain 1.5% total current sensing error, pay attention to the operational amplifier 1% settling time. To have the least distortion in the winding current waveform, the zero active vector duration is needed; but practically, this duration is not possible to achieve. The objective is to minimize this duration to as low as possible; one method is to minimize the current measurement duration using a current sense amplifier with faster settling time.

Need for High-Speed Amplifier for Current Sensing

When using the single-shunt technique, for accurate instantaneous current measurement, current conduction (active vector) duration for each switching state need to be long enough to allow the entire measurement system to settle and for the ADC to have enough time to sample the current. But as explained earlier, larger active vector duration results in the distortion of winding current waveform. The ability to measure current accurately in the least amount of time possible is of utmost importance. This process helps to reduce the current sensing complexity and hence reduces actual current distortion at zero-crossing and sector changes. The process also helps to reduces the software overhead in determining the winding currents during the lower active vector duration. The software algorithm can use mathematical prediction or PWM phase advancing or delaying in such scenarios.

To have the least possible active vector duration, understanding the total loop delay in measurement circuit is also necessary. Figure 3 shows different delay components in the measurement path.

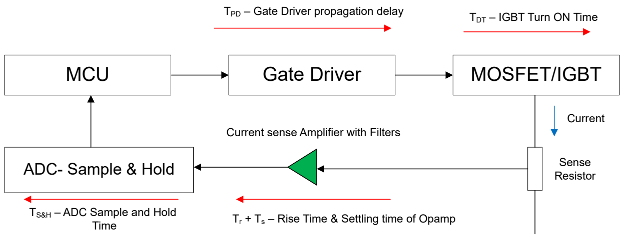


Figure 3. Delay Components in Measurement Path

Each component can have the least possible delay to get the best performance. This process can be achieved by using a fast-current sensing (using a fast amplifier with wide GBP), using a gate driver with minimum propagation delay, using ADC with fast sampling rate, and by optimizing the dead time of MOSFET/IGBT.

The following sections explain how an operational amplifier with high bandwidth and high slew rate results in faster settling in the measurement of DC bus current in single shunt sensing topology thus optimize the delay in sense component.

Circuit Implementation for Single Shunt Current Sensing

Figure 4 shows the OPAMP circuit in differential amplifier configuration used to measure the DC bus current for single-shunt current

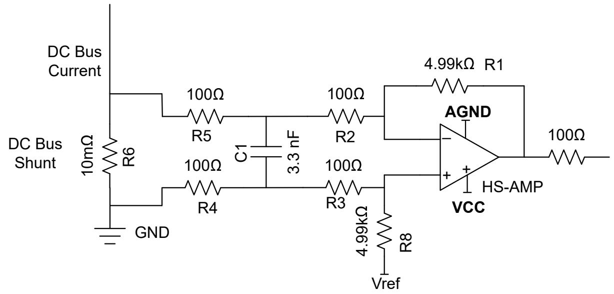


Figure 4. Single-Shunt Current Sensing Circuit

Here, R6 is the sense resistors and the value can be selected based on the peak winding current. The voltage drop across this sense resistor can be calculated by using:

$$V_{SENSE} = I_{SENSE} \times R_{SENSE} \tag{1}$$

This voltage is then amplified using the High-speed op amp used as a differential gain amplifier.

R4, C1, and R5 form the dominant input filter. The input filter cutoff frequency must be selected based on the high-frequency voltage oscillations across the sense resistor during IGBT switching and switching noise from other adjacent switching circuits. By selecting R2 = R3, R4 = R5, and R1 = R8, the signal gain of the amplifier stage is set as,

$$G_{signal} = \frac{R_1}{(R_2 + R_5)} \tag{2}$$

Whereas the noise gain for this configuration is given as

$$G = 1 + \frac{R_1}{(R_2 + R_5)} \tag{3}$$

Selecting the Correct Amplifier for Your Design

The total settling time of the device depends mainly on the setting time of the op-amps and input settling

$$t_{settle} = K_1 \, x \, RC + K_2 \, x \, \tau \tag{4}$$

Where C is the capacitance at the device input

R is the impedance at the input node

K1 and K2 is the constant and depends on % settling,

τ is the time constant for op-amp transfer function

If

$$K_1 \, x \, RC < < K_2 \, x \, \tau = > t_{settle} = K_2 \, x \, \tau \tag{5}$$

For 1% settling k2= approximately 5,

$$t_{settle}(1\%) = 5 \, x \, \tau \tag{6}$$

Assuming the total sampling time available is 1µs (give explanation for 1µs) and out of which 50% (0.5µs) is the acquisition time, the amplifier needs to settle before this duration

For 1% settling of 0.5µs,

$$\tau = \frac{500}{5} = 100ns \tag{7}$$

For High gain configuration, the response of the op-amp can be considered to be of 1st order, hence

$$BW = \frac{1}{2\pi \, x \, \tau} \tag{8}$$

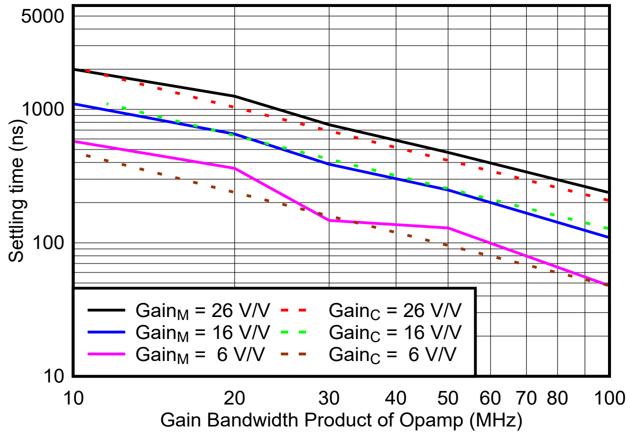
$$BW = \frac{1}{(2\pi \, x \, 100)GHz} = 1.592MHz \tag{9}$$

For selecting op-amps bandwidth

GBW = Bandwidth×Gain,

If gain, G = 26, Required device GBP = 41.4MHz

To account for the variation across devices and the operating temperature, have some margin for GBP while selecting the amplifier. Based on the gain setting and settling time required, the user can infer for the device BW required from the Figure 5, and can accordingly select the device. A few device recommendations are also listed in Table 2.



Gain$_M$ = Measured Gain   Gain$_C$ = Calculated Gain

Figure 5. Settling Time vs Gain Bandwidth Product

Table 2. Recommended Amplifiers for Single-Shunt Current Sensing

Part Number	GBW (MHz)	Slew Rate (V/µS)	I_Q (mA)	Vos (mV)	Rail-to-Rail
OPA835	30	160	0.25	0.5	In to V–, Out
OPA607	50	24	0.9	0.6	In to V–, Out
TLV365	50	27	4.6	1.9	In, Out
OPA863	110	105	0.7	1.3	In, Out
OPA838	300	350	0.96	0.125	In to V–, Out

Conclusion

The use of high bandwidth and high slew rate operational amplifiers helps achieve fast ramp-up and settling even at a high gain. The ramp-up and settling time can be further optimized by using a lower input filter with a very-low inductance shunt resistor.

This reduced settling time enables accurate current sensing even with the active vector duration of less than 1µs, resulting in a less distorted current waveform in the motor winding, and thus helping to minimize the torque ripple and audible noise in motor drives when using single-shunt current sensing.

These high-speed op amps can also directly drive the ADC of MCUs (such as the C2000), and thus eliminate the need for separate ADC drives and reduce the BOM cost.

For a more detailed explanation of design demonstration of fast and accurate current sensing for a three-phase motor drive with sensor-less field-oriented control (FOC), see the *Current Sensing With <1-µs Settling for 1-, 2-, and 3-Shunt FOC Inverter Reference Design*.

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