Current Sensing for Inline Motor-Control Applications

Jason Bridgmon and Carolus Andrews

ABSTRACT

Modern control systems require good feedback accuracy and signal integrity in order to perform well in the areas of system control and stability, to correctly drive system responses such as speed and torque, and to help provide system stability inside the system dynamic range. An ideal amplifier for inline measurements only amplifies the differential signal, with complete rejection of the common-mode transients present because of PWM cycling. Inline measurements in three-phase, motor-control systems are often accomplished with isolated, discrete components in order to decrease sensitivity to these transients. High-bandwidth amplifiers with fast settling times are also used to try to reject common-mode transients. The INA240 from Texas Instruments uses enhanced PWM rejection in the design of the device that suppresses transients, and provides a clean differential signal measurement for feedback and control.

Contents

List of Figures

List of Tables

1 Introduction

There are essentially three ways to measure current in a motor-control system: high side measurements, low side measurements, and inline measurements. When a pulse-width modulated (PWM) signal is used to drive the motor, inline measurements are the most difficult from which to obtain accurate measurements because there is corresponding error due to the common-mode transients (dV/dt). In an inverter system that requires feedback to correctly operate, phase-current measurements are also required.

2 Three-Phase Motor

In a three-phase motor, a series of PWM polyphase signals drive the load through the creation of magnetic fields, as shown in Figure 1. Generally, a brushless motor is more efficient than a brushed dc counterpart. This efficiency increase is due to several factors, the largest of which is the absence of brushes; the motor is electrically commutated rather than mechanically. This electrical commutation leads to advantages in several areas, such as increased product life as a result of the absence of mechanical wearing parts, and the fact that brushless motors do not spark like their brushed counterparts; ideal in volatile applications. However, the advantages outlined here come with a cost. The opportunity cost for these advantages is a more complex motor that requires control electronics to achieve maximum efficiency, and these controls are normally implemented through the current signals being passed through the motor.

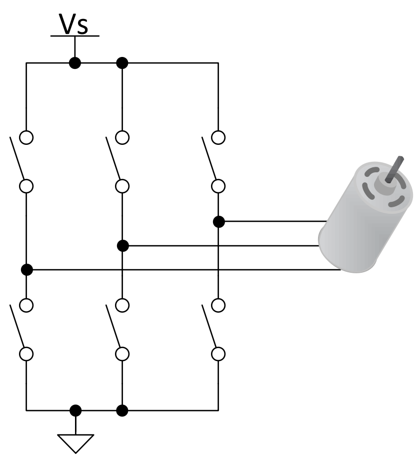

Figure 1. Simplified Block Diagram of a Three-Phase Motor

2.1 Low-Side Implementation

In low-side current sensing, an amplifier is added to the low side of the gate-driving FETs with a shunt resistor placed in line with each switching leg, as shown in Figure 2. The advantage in low-side sensing is in the simple solution. Being on the low side of the load, the common-mode voltage at the shunt is approximately zero; therefore, the robustness of the amplifiers is not an important factor. However, this solution comes at the cost of ground variation, and places additional resistance between the load and the path to ground. Additionally, this resistance removes the ability to detect faults in the load if the load becomes shorted to ground.

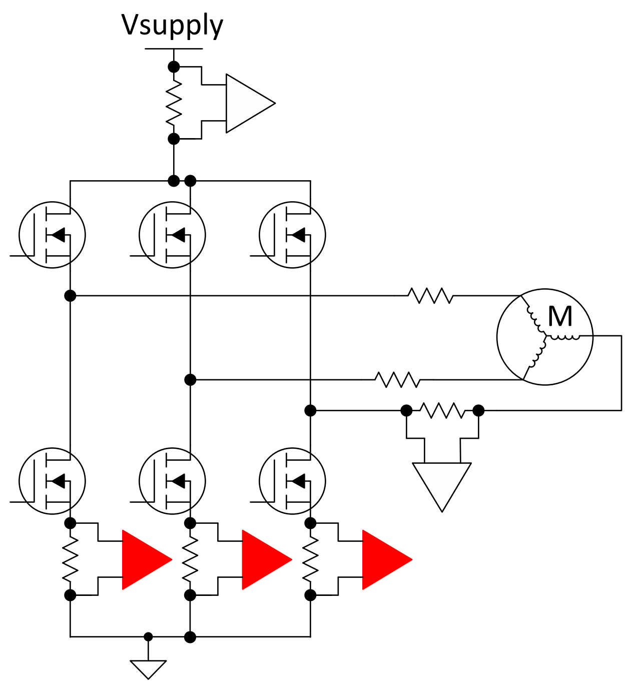

Figure 2. Low Side Implementation of Current Sensing Amplifiers

2.2 High-Side Implementation

For high-side current sensing, a shunt is placed inline immediately following the supply voltage of the FET matrix, as shown in Figure 3. Use this method to deal with low-side measurements issues. The system regains the ability to detect ground faults, and the load path to ground is no longer impeded. However, the common-mode voltage experienced by this amplifier is approximately that of the supply voltage (Vsupply in Figure 3), and requires a much more robust amplifier to handle the potentially high-voltage requirement. Usually, special differential amplifiers and current shunt monitors are required in order to implement the system.

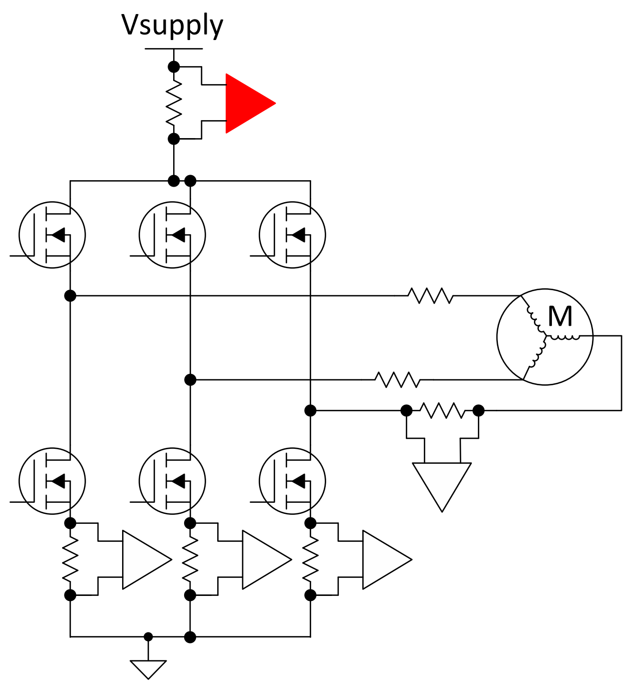

Figure 3. High Side Implementation of a Current Sensing Amplifier

2.3 Inline Implementation

The inline current measurement method implements shunt resistors directly into the FET switching network, as shown in Figure 4. Here, the current being passed across the motor is measured and used in feedback and control calculations. During the slew of the PWM signal, the inputs of the amplifier are exposed to a signal that is quickly moving approximately between ground and a large input voltage (Vsupply in Figure 4). This exposure leads to large common-mode transients being injected into the amplifier; nonideal for a device attempting to pass a precise measurement for the purposes of feedback control.

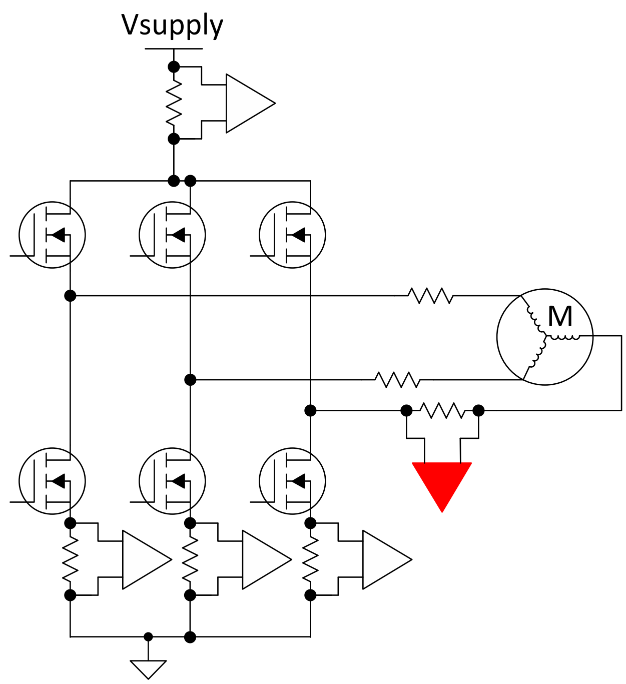

Figure 4. Inline Implementation of Current-Sensing Amplifiers (Only One Phase Shown)

Table 1. Summary Comparison of Implementation Methods

High-Side Implementation	Low-Side Implementation	Inline Implementation
	Pros	
Stable high common-mode voltage	Low common-mode voltage	
Fault detection	Low voltage amplifiers acceptable	Know the true phase current
Robust amp requirements	Low cost	Gain the ability to monitor the system
No ground disturbances		
	Cons	
Drive current ≠ phase current	Unable to detect faults	Sense amp must support high common-mode rejection
	Drive current ≠ phase current	

3 Challenges With Inline Motor-Control Current Sensing

One of the largest challenges in inline current sensing is the presence of common-mode transients in the output. Depending on the internal topology of the current shunt monitor, the ability to handle the common-mode input as it quickly toggles between large and small voltages is compromised. To evaluate this ability, a common-mode voltage test is applied to several amplifiers whose shunts are placed in line with the load of a single PWM signal. A 40-V, 10-ns signal generator tied to both terminals of these current-sense amplifiers creates a step response not unlike those seen in a PWM circuit. The output of the Texas Instruments INA240 is shown in Figure 5. Ideally, the amplifier disregards the signal, because the signal is present on both inputs. Therefore, in this case with no differential signal, the output remains at 2.5 V.

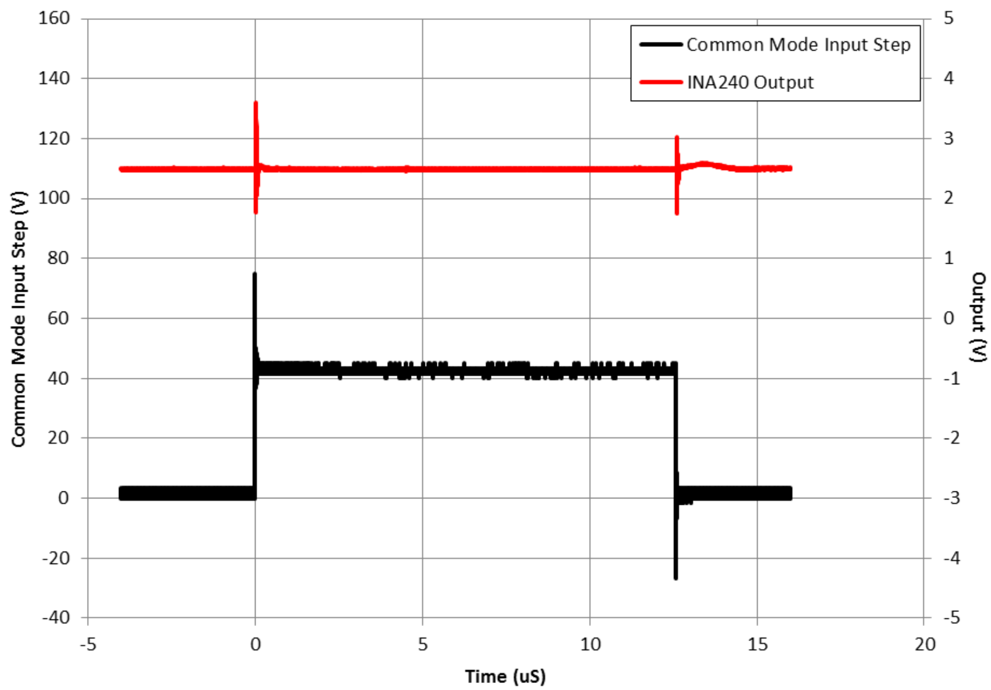

Figure 5. INA240 Output vs 40-V Common-Mode Step Input

Common-mode transients may create overshoot and undershoot phenomena that can cause several issues with feedback, including false activations for flag or overcurrent triggers, ripples in control gain, and reductions in overall system efficiency because of issues including torque ripple. Torque ripple refers to the periodic change in torque output as the motor rotates. Torque ripple can be caused by several factors, a key factor being slight inconsistencies in the individual windings of each phase. Other than a precise construction of the actual motor, a good way to handle this phenomenon is through a dynamic control system. However, the response of these controls is limited by the accuracy of the measured current to adjust torque accordingly to the correct value. Common-mode transients require more work by the control system to keep torque in line, and lead to a decrease in efficiency.

Capturing data through the same setup used for Figure 5, competitive devices were also tested and the output results are shown in Figure 6 and Figure 7. In these cases, the rapid dV/dt creates distortions in the output of the amplifier.

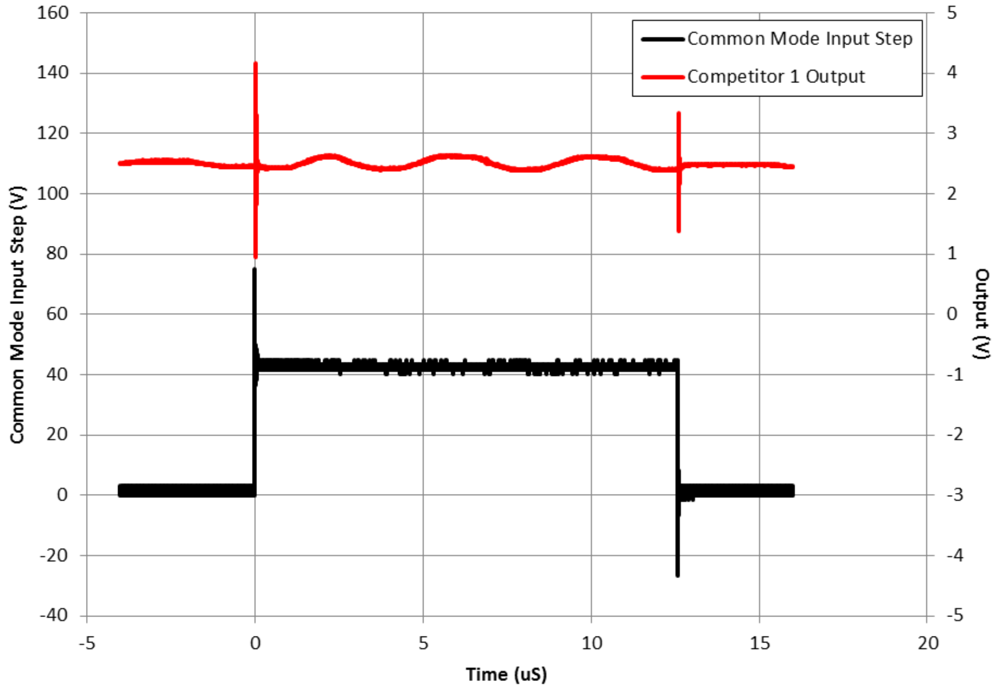

Figure 6. Competitor 1 Output vs 40-V Common-Mode Step Input

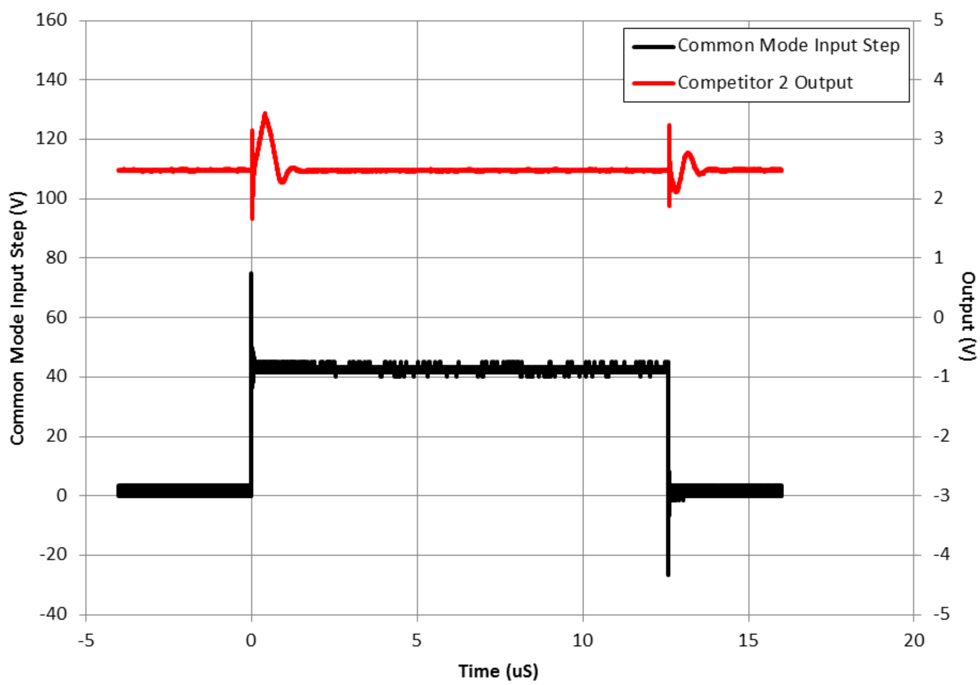

Figure 7. Competitor 2 Output vs 40-V Common-Mode Step Input

4 INA240 in a Motor Application

The INA240 was specifically designed to thrive inside motor applications. Using an Anaheim Automation BLWS231S-36V BLDC motor alongside an MDC100-050101 motor controller, tests were performed to examine signal integrity across a few competitive current-shunt monitor products. Figure 8 shows the performance of the INA240 in this motor application. Figure 9 and Figure 10 show some competitive-product outputs for comparison.

Figure 8 shows how the INA240 has minimized the error present in the feedback signal, with only a ≈ 500-mV spike on the negative edge of the PWM input signal. The reduced error in the feedback signal reduces not only the effort placed on the control system, but also the copper losses of the system, expressed in Equation 1:

$$P_{cl} = I^2 R_w \tag{1}$$

where

- R_w is the resistance of the copper winding.

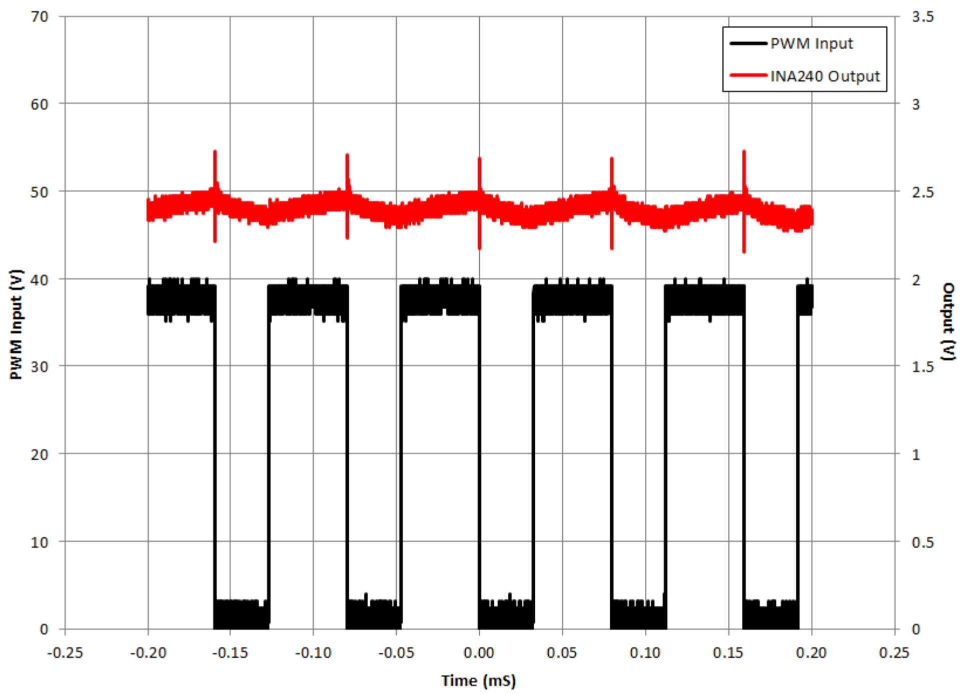

Figure 8. INA240 Output vs PWM Input

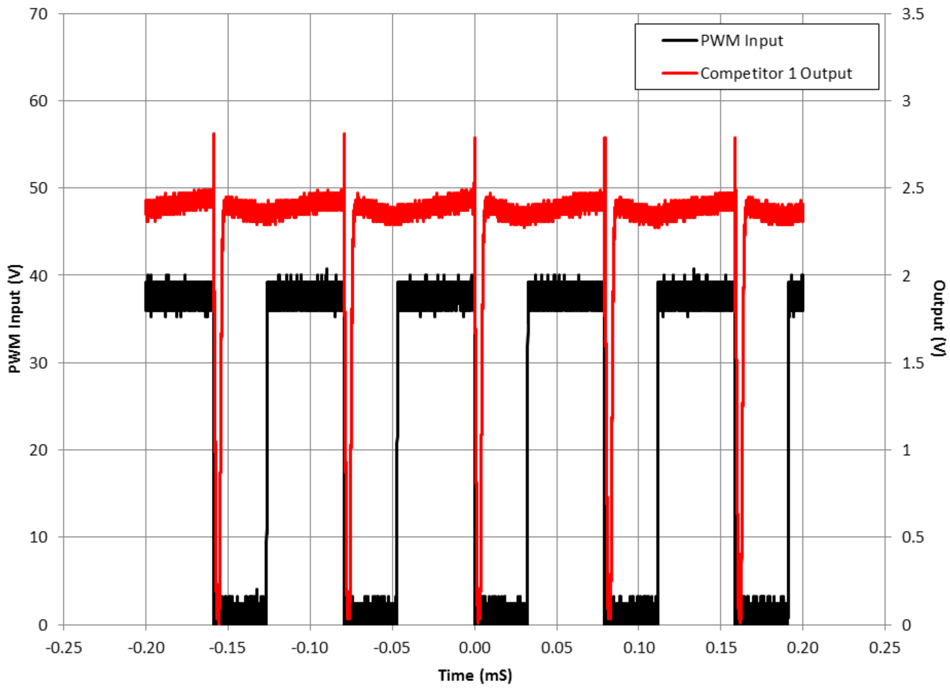

Figure 9. Competitor 1 Output vs PWM Input

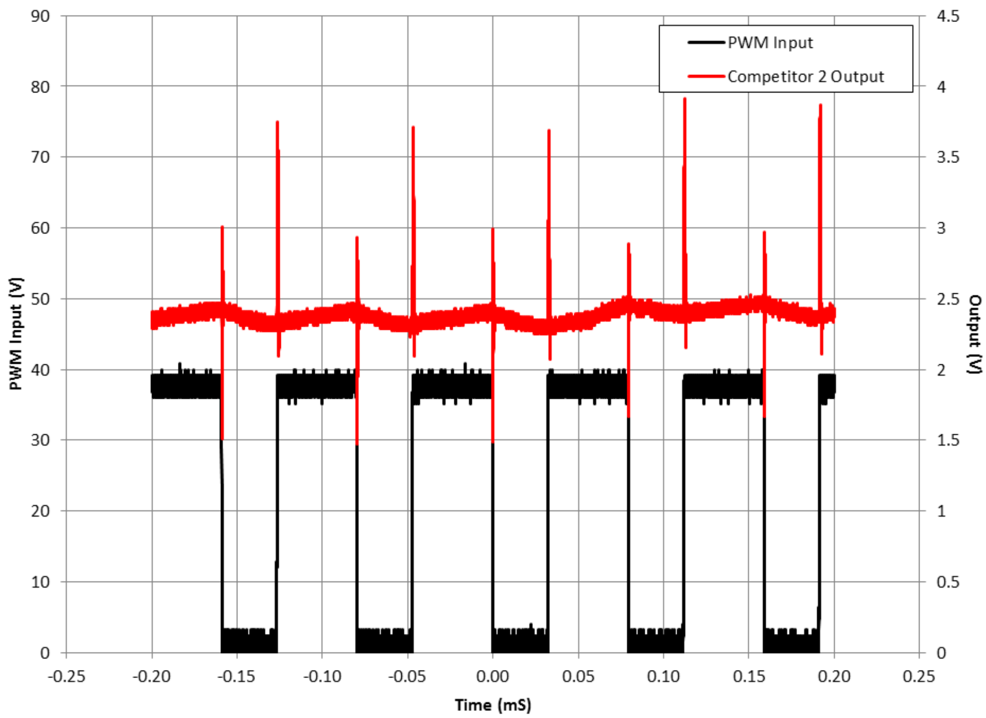

Figure 10. Competitor 2 Output vs PWM Input

Products		**Applications**	
Audio	www.ti.com/audio	Automotive and Transportation	www.ti.com/automotive
Amplifiers	amplifier.ti.com	Communications and Telecom	www.ti.com/communications
Data Converters	dataconverter.ti.com	Computers and Peripherals	www.ti.com/computers
DLP® Products	www.dlp.com	Consumer Electronics	www.ti.com/consumer-apps
DSP	dsp.ti.com	Energy and Lighting	www.ti.com/energy
Clocks and Timers	www.ti.com/clocks	Industrial	www.ti.com/industrial
Interface	interface.ti.com	Medical	www.ti.com/medical
Logic	logic.ti.com	Security	www.ti.com/security
Power Mgmt	power.ti.com	Space, Avionics and Defense	www.ti.com/space-avionics-defense
Microcontrollers	microcontroller.ti.com	Video and Imaging	www.ti.com/video
RFID	www.ti-rfid.com		
OMAP Applications Processors	www.ti.com/omap	**TI E2E Community**	e2e.ti.com
Wireless Connectivity	www.ti.com/wirelessconnectivity		

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265