

# 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

1	Introduction .....	2
2	Three-Phase Motor .....	2
3	Challenges With Inline Motor-Control Current Sensing.....	6
4	INA240 in a Motor Application .....	8

## List of Figures

1	Simplified Block Diagram of a Three-Phase Motor.....	2
2	Low Side Implementation of Current Sensing Amplifiers.....	3
3	High Side Implementation of a Current Sensing Amplifier .....	4
4	Inline Implementation of Current-Sensing Amplifiers (Only One Phase Shown).....	5
5	INA240 Output vs 40-V Common-Mode Step Input.....	6
6	Competitor 1 Output vs 40-V Common-Mode Step Input .....	7
7	Competitor 2 Output vs 40-V Common-Mode Step Input .....	7
8	INA240 Output vs PWM Input.....	8
9	Competitor 1 Output vs PWM Input .....	9
10	Competitor 2 Output vs PWM Input .....	9

## List of Tables

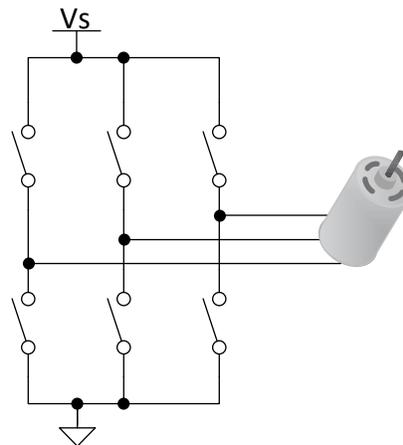
1	Summary Comparison of Implementation Methods .....	5
---	--	---

## 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.

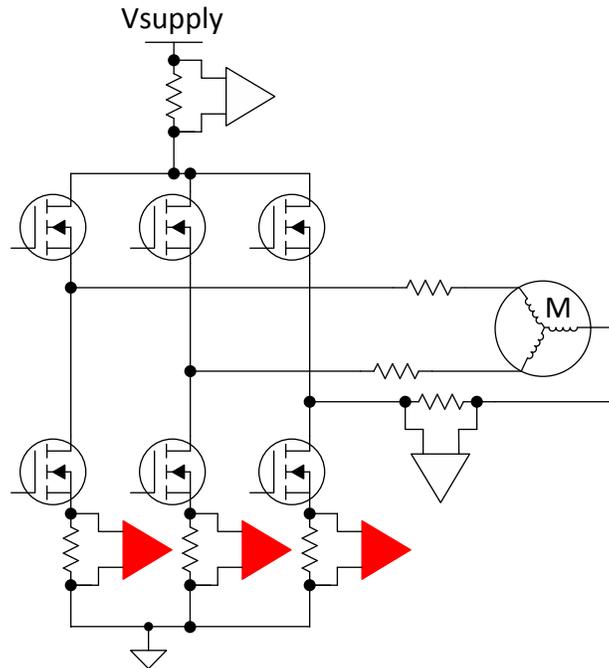


Figure 2. Low Side Implementation of Current Sensing Amplifiers

## 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 ( $V_{supply}$  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.

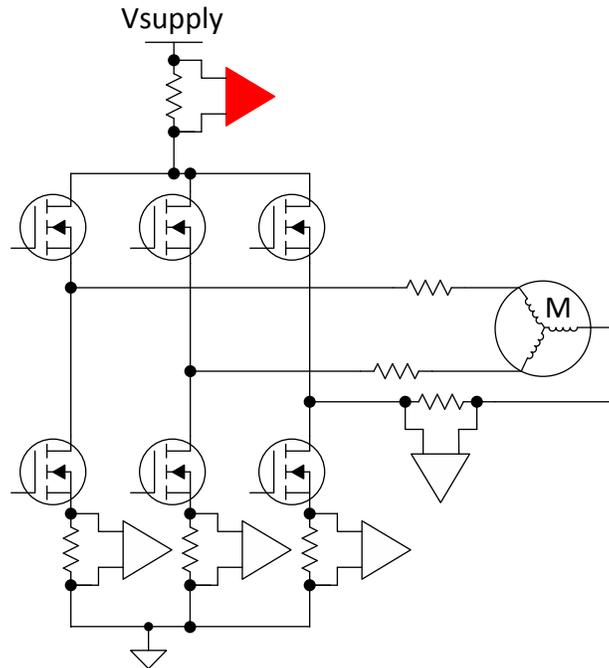
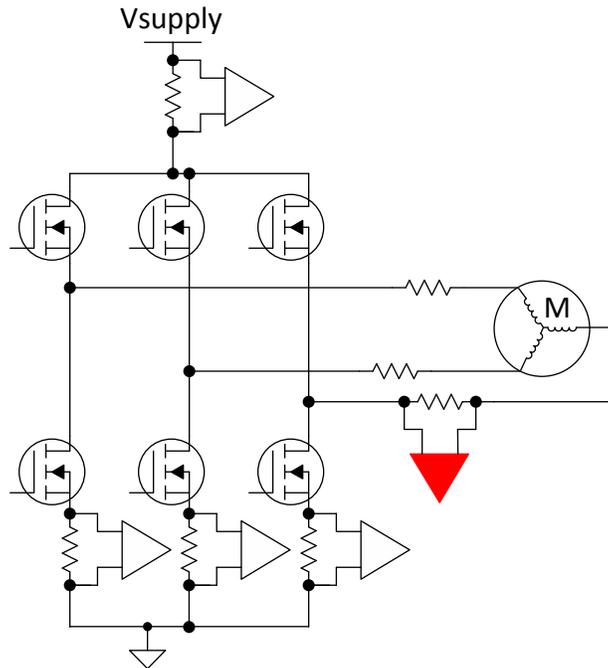


Figure 3. High Side Implementation of a Current Sensing Amplifier

### 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 ( $V_{supply}$  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.



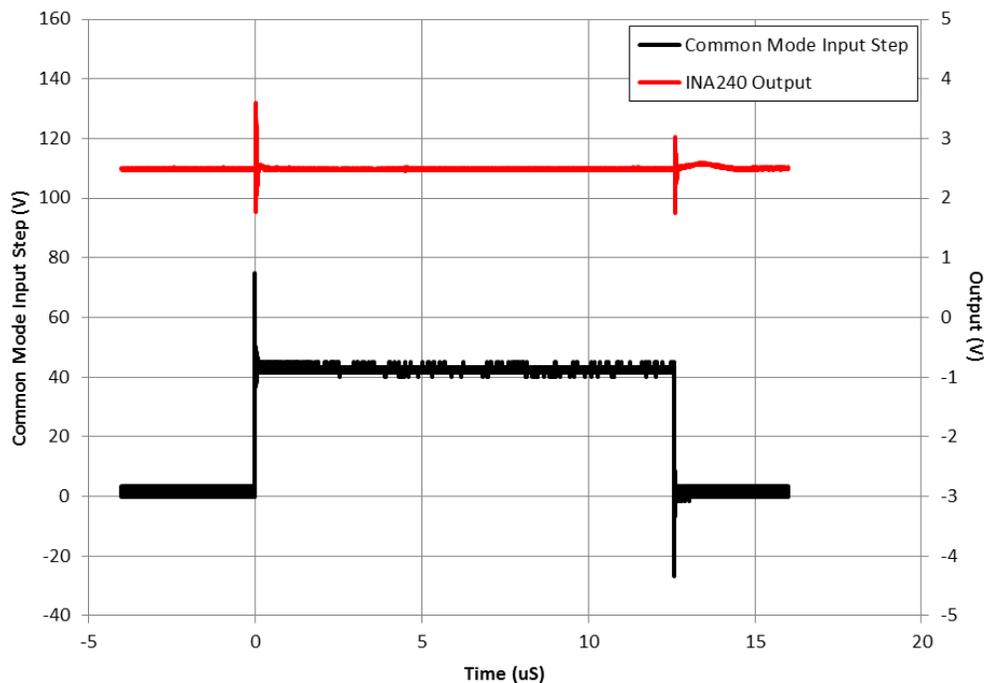
**Figure 4. Inline Implementation of Current-Sensing Amplifiers (Only One Phase Shown)**

**Table 1. Summary Comparison of Implementation Methods**

High-Side Implementation	Low-Side Implementation	Inline Implementation
<b>Pros</b>		
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		
<b>Cons</b>		
Drive current $\neq$ phase current	Unable to detect faults	Sense amp must support high common-mode rejection
	Drive current $\neq$ 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.

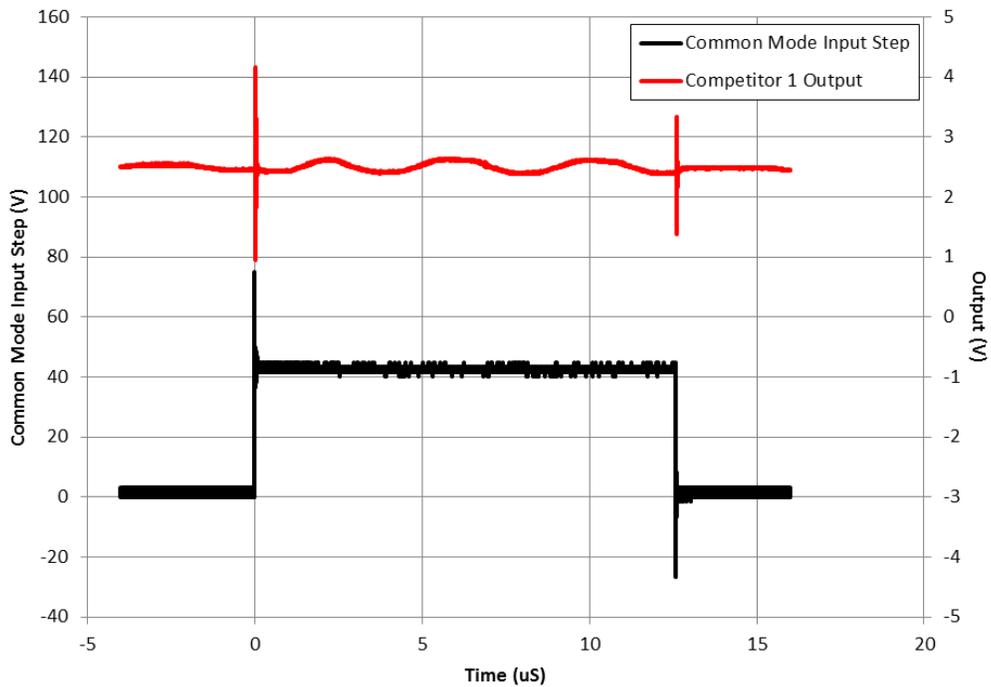


Figure 6. Competitor 1 Output vs 40-V Common-Mode Step Input

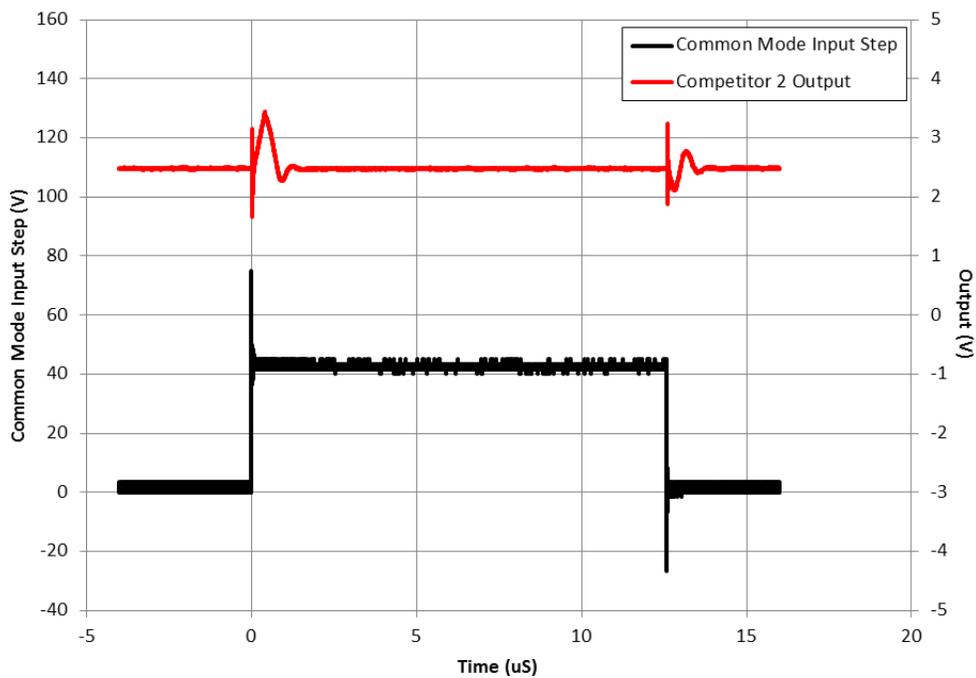


Figure 7. Competitor 2 Output vs 40-V Common-Mode Step Input

## 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  $\approx 500$ -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:

$$P_{cl} = I^2 R_w$$

where

- $R_w$  is the resistance of the copper winding.

(1)

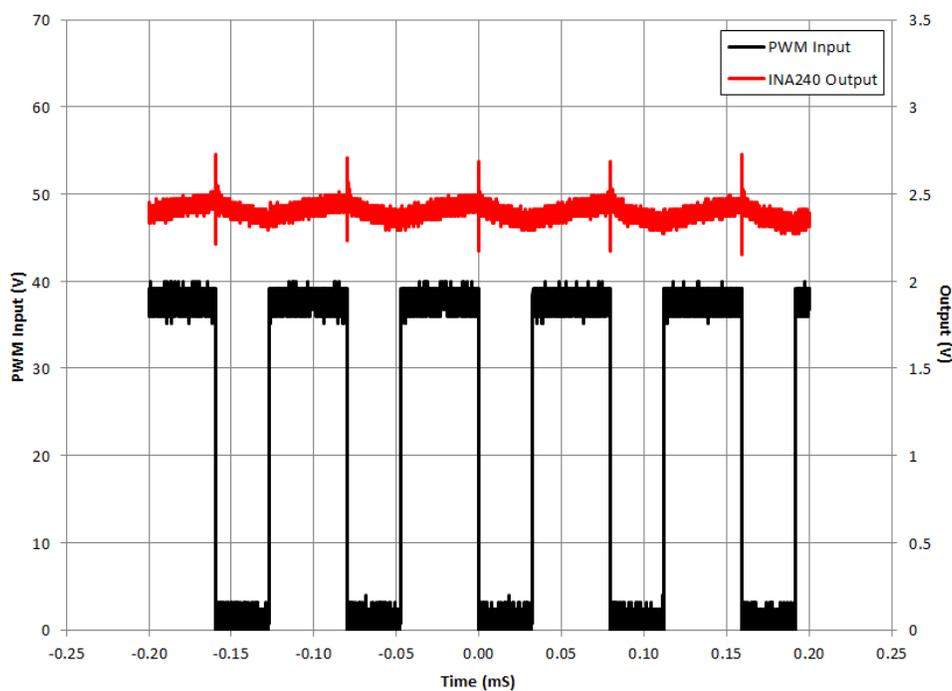


Figure 8. INA240 Output vs PWM Input

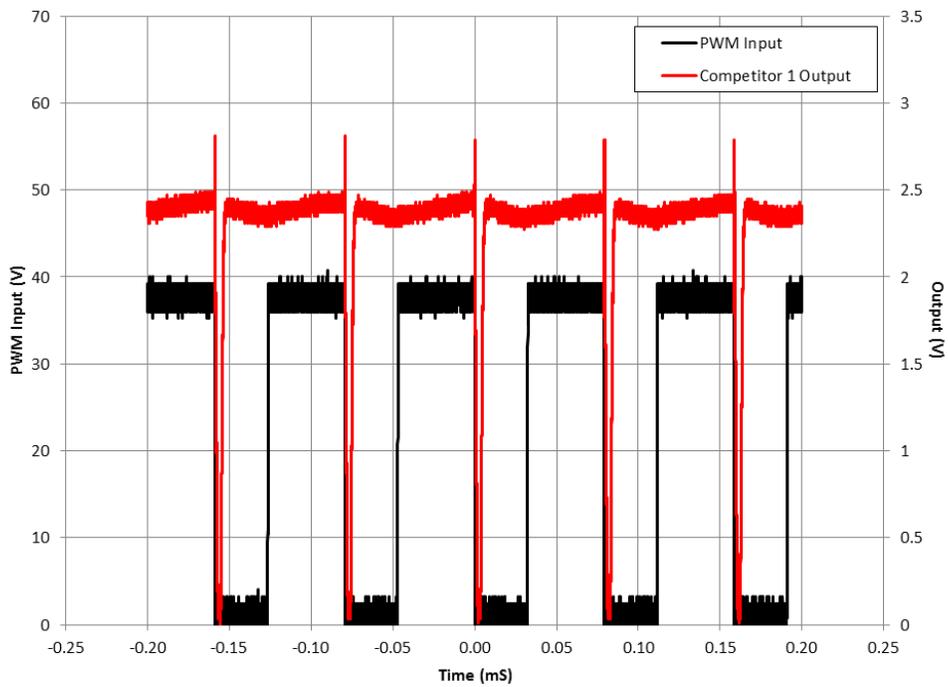


Figure 9. Competitor 1 Output vs PWM Input

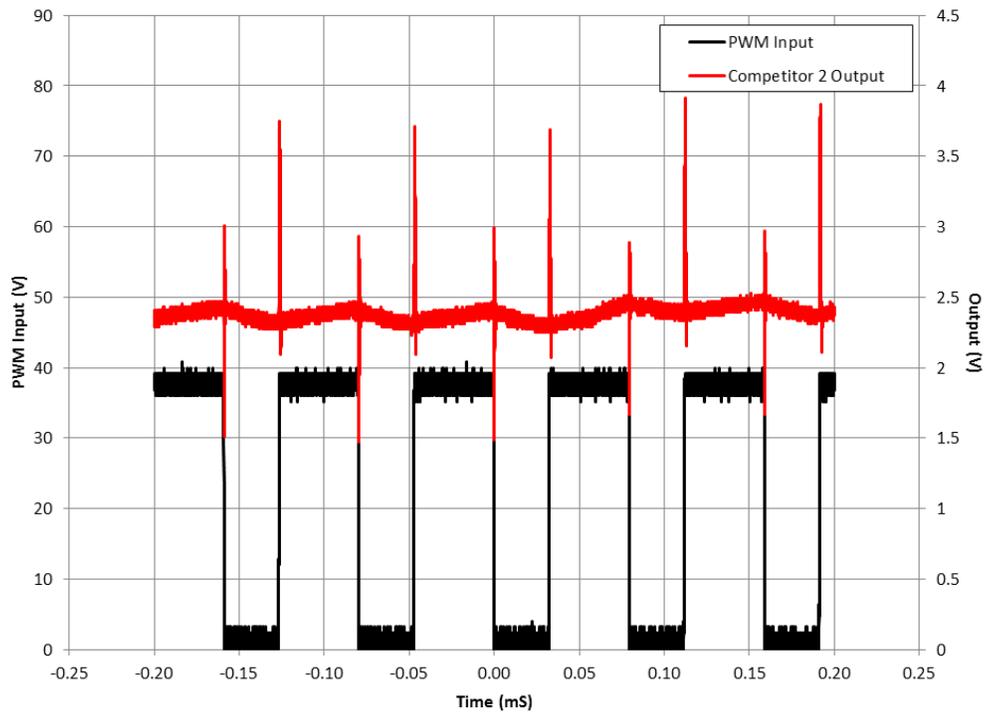


Figure 10. Competitor 2 Output vs PWM Input

## IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as "components") are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI's terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers' products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers' products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI's goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or "enhanced plastic" are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have **not** been so designated is solely at the Buyer's risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

### Products

Audio	<a href="http://www.ti.com/audio">www.ti.com/audio</a>
Amplifiers	<a href="http://amplifier.ti.com">amplifier.ti.com</a>
Data Converters	<a href="http://dataconverter.ti.com">dataconverter.ti.com</a>
DLP® Products	<a href="http://www.dlp.com">www.dlp.com</a>
DSP	<a href="http://dsp.ti.com">dsp.ti.com</a>
Clocks and Timers	<a href="http://www.ti.com/clocks">www.ti.com/clocks</a>
Interface	<a href="http://interface.ti.com">interface.ti.com</a>
Logic	<a href="http://logic.ti.com">logic.ti.com</a>
Power Mgmt	<a href="http://power.ti.com">power.ti.com</a>
Microcontrollers	<a href="http://microcontroller.ti.com">microcontroller.ti.com</a>
RFID	<a href="http://www.ti-rfid.com">www.ti-rfid.com</a>
OMAP Applications Processors	<a href="http://www.ti.com/omap">www.ti.com/omap</a>
Wireless Connectivity	<a href="http://www.ti.com/wirelessconnectivity">www.ti.com/wirelessconnectivity</a>

### Applications

Automotive and Transportation	<a href="http://www.ti.com/automotive">www.ti.com/automotive</a>
Communications and Telecom	<a href="http://www.ti.com/communications">www.ti.com/communications</a>
Computers and Peripherals	<a href="http://www.ti.com/computers">www.ti.com/computers</a>
Consumer Electronics	<a href="http://www.ti.com/consumer-apps">www.ti.com/consumer-apps</a>
Energy and Lighting	<a href="http://www.ti.com/energy">www.ti.com/energy</a>
Industrial	<a href="http://www.ti.com/industrial">www.ti.com/industrial</a>
Medical	<a href="http://www.ti.com/medical">www.ti.com/medical</a>
Security	<a href="http://www.ti.com/security">www.ti.com/security</a>
Space, Avionics and Defense	<a href="http://www.ti.com/space-avionics-defense">www.ti.com/space-avionics-defense</a>
Video and Imaging	<a href="http://www.ti.com/video">www.ti.com/video</a>

### TI E2E Community

[e2e.ti.com](http://e2e.ti.com)