Application Report
SLVA791–September 2016

TPS65311-Q1 BUCK1 Controller DCR Current Sensing

Krishnamurthy Hegde
MSA-ASP

ABSTRACT

This application report provides guidelines and recommendations for implementing BUCK1 controller current sense using resistance of the inductor (DCR current-sensing method) for TPS65311-Q1 and TPS65310A-Q1 devices. This method was verified on the TPS65311-Q1 device. However, the BUCK1 controller is identical between TPS65310A-Q1 and TPS65311-Q1 devices and the results should be applicable to TPS65310A-Q1 device also.

1 Introduction

BUCK1 controller in the TPS65310A-Q1 and TPS65311-Q1 devices operate using constant frequency peak current mode control. Peak current-mode control regulates the peak current through the inductor such that the output voltage VBUCK1 is maintained to its set value. The error between the feedback voltage VSENSE1 and the internal reference produces an error signal at the output of the error amplifier (COMP1), which serves as target for the peak inductor current. At S1–S2, the current through the inductor is sensed as a differential voltage and compared with this target during each cycle. For applications which require precise current sensing, typically an external shunt resistor is used. But, the external sense resistor could be bulky and also for better efficiency, the resistance of the inductor (DCR) can be used to sense the inductor current. Figure 1 shows the typical block diagram for both current sensing methods.

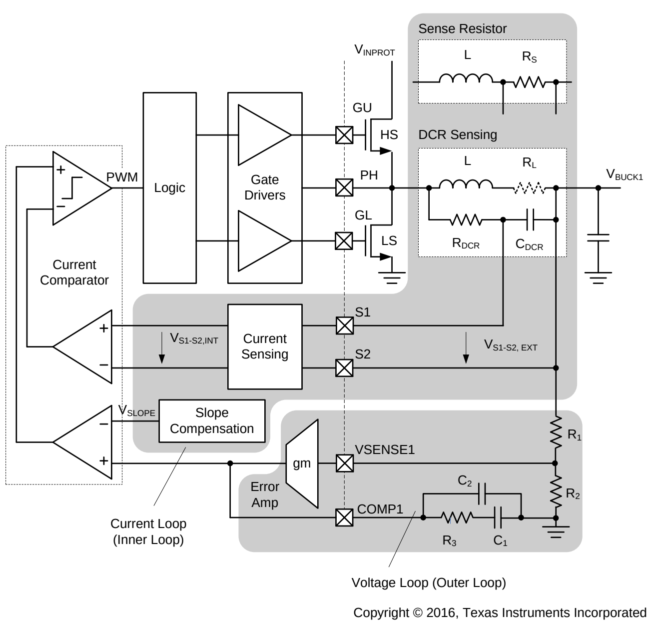


Figure 1. BUCK1 Block Diagram With Current Sensing Using Inductor Resistance-R_L or External Sense Resistor-R_S

2 Sense Resistor Method

As specified in the *TPS65311-Q1 datasheet* (section: *Output Inductor, Sense Resistor and Capacitor Selection for the BUCK1 Controller*), an external resistor-R_S, is used to sense the current through the inductor. The current sense resistor pins, S1 and S2, are fed into an internal differential amplifier which supports the range of VBUCK1 voltages. The sense resistor, R_S, must be chosen so that the maximum forward peak current in the inductor generates a voltage of 75 mV across the sense pins. This specified typical value is for low duty cycles only. At typical duty-cycle conditions around 28% (assuming 3.3-V output and 12-V input), 50 mV is a more reasonable value, considering tolerances and mismatches. Use Figure 2 (*Reduction of Current-Limit vs Duty Cycle*) of the TPS65311-Q1 datasheet to estimate the maximum sense voltage across the sense resistor for different duty cycles.

$$R_S = \frac{50\ \text{mV}}{I_{max\_peak}} \tag{1}$$

Optimal slope compensation which is adaptive to changes in input voltage and duty cycle allows stable operation at all conditions. For the optimal performance of the slope compensation circuit, empirical Equation 2 must be followed while choosing the inductor and the sense resistor.

$$L = 410 \times R_s$$

where

- L = inductor in µH
- R_S = external sense resistor in Ω (2)

3 DCR Sensing Method

The current sense pins, S1 and S2, are high-impedance pins with low leakage across the VBUCK1 operating range. This allows current sensing using the DC resistance, R_L or DCR of the inductor, for better efficiency and this eliminates the need of additional sense resistor to save cost and PCB space. For DCR sensing method, a RC network, R_{DCR} and C_{DCR}, is used in parallel to the inductor. The voltage across C_{DCR} is sensed using S1 and S2 pins as shown in Figure 1.

When R_{DCR} and C_{DCR} are selected in such a way that the RC time constant is equal to the ratio of inductance and series resistance of the inductor, the voltage across C_{DCR} will be directly proportional to the inductor current (I_L), as expressed in Equation 3 and Equation 4.

$$R_{DCR} \times C_{DCR} = \frac{L}{R_L} \tag{3}$$

$$V\_C_{DCR} = I_L \times R_L$$

where

- R_{DCR}, C_{DCR}= external RC network used in parallel to the inductor
- L= inductor in µH
- R_L = Inductor DC resistance
- V_C_{DCR}= voltage across sense capacitor (4)

A 10-µH inductor with the specification in Table 1 was used for these measurements.

Table 1. Inductor Specification

Part Number	Inductance (µH)	DCR (mΩ)		SRF Typical (MHz)	Isat (A)			Irms (A)	
		Typical	Maximum		10% Drop	20% Drop	30% Drop	20°C Rise	40°C Rise
MSS1260T-103ML	10 ±20%	21.5	23.9	22	6	6.92	7.48	3	4

Based on Equation 3, with L= 10 µH, R_L= 21.5 mΩ, and by assuming C_{DCR} = 220 nF, the result is:

R_{DCR} = 2.11 KΩ

For this experiment, R_{DCR}= 2 KΩ was used as it was the closest available resistor value when compared with 2.11 KΩ.

Different combinations of C_{DCR} and R_{DCR} can also work, but this experiment uses C_{DCR} = 220 nF.

4 Temperature Dependency of Inductor Series Resistance

Inductor series resistance (DCR) is a resistance of copper coil that varies with temperature.

Temperature dependency of inductor series resistance is given in Equation 5:

$$R_L(T) = R_{L\_25C} \times \left[1 + TC\_Copper \times (T - 25)\right] \quad (5)$$

where

- T= temperature of the inductor
- R_{L_25C} = inductor series resistance at room temperature (25°C)
- TC_Copper = temperature coefficient of copper that is equal to 0.00393

5 Measurement Procedure

Since the resistance of the inductor (DCR) varies with temperature, measurements were taken across temperature to check the effect of temperature on the DCR current-sensing method. BUCK1 overcurrent detection causes device reset and RESN is pulled low. DC load current at which the device detects BUCK1 overcurrent (OC) is noted and recorded as the overcurrent detection threshold. However, actual inductor-peak current will be higher than this average DC current and can be estimated based on the differential voltage measured across the current sense resistor, R_S, (when using the Sense Resistor Method) or across C_{DCR} (when using DCR Sensing Method). Since measuring actual inductor current with a current probe requires the inductor to be lifted off the board, this causes accuracy issues and difficulty in measuring the inductor current across temperature.

The scope of this measurement is to check the basic functionality and feasibility of the DCR Sensing Method for this device. These measurements are not intended for optimization of the DCR Sensing Method circuit, nor a reference design for a production application. Any adaption by customers must be validated in customers' own design and environment.

5.1 Test Conditions

The test conditions are as follows:

- Device Input Supply voltage, VBAT = 12 V (bench-top power supply with 4-A current rating)
- BUCK1 Output Voltage, VBUCK1 = 3.35 V
- Load current on VBUCK1 = Electronic source meter with 3.1 A maximum DC-load current capability
- Case 1, Sense Resistor Method:
  - Reference measurement using 22-mΩ current-sense resistor
  - TPS65311-Q1 EVM with 22-mΩ current-sense resistor for BUCK1 current sensing
- Case 2, DCR Sensing Method:
  - Measurement using DCR current sense using R_{DCR} (2 kΩ), C_{DCR} (220 nF), and 10 µH inductor with 21.5 mΩ DCR

TPS65311 EVM was modified by shorting 22-mΩ current-sense resistor and placing R_{DCR} (2 kΩ) and C_{DCR} (220 nF) across the inductor. Voltage across the sense capacitor was measured using a differential probe. Voltage spikes were observed during the measurements, which could be due to the board modifications that had to be made, such as cutting the trace and blue wiring. However, to demonstrate feasibility, the spikes should be acceptable.

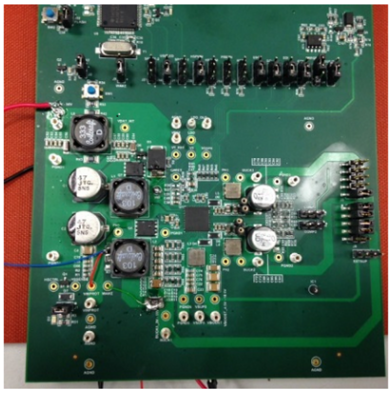


Figure 2. TPS65311-EVM Top View

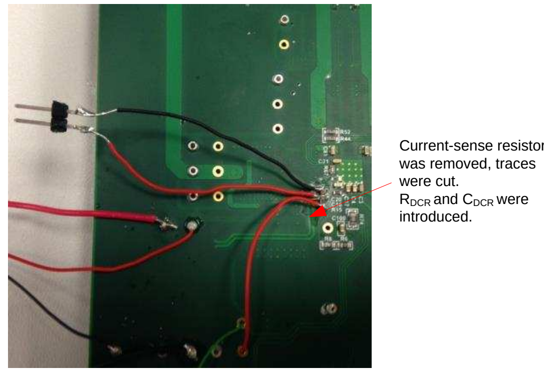


Figure 3. TPS65311-EVM Bottom View

Since the load-current source had a maximum current of 3.1 A, two parallel current-source meters were used in the case where the load current required to detect the overcurrent exceeded 3.1 A (due to limitations of load current source).

Using the DCR Sensing Method, there was a negative offset of approximately 10 mV, which can be adjusted by a slightly different combination of R_{DCR} and C_{DCR} to make the baseline close to 0 mV. This offset could be due to the slight mismatch in the RC time constants according to Equation 4 or due to the blue wiring or measurement setup.

5.2 Measurement Results

All measurement plots taken at room temperature (except Figure 12). The following is the legend for Figure 4 through Figure 12:

- Blue trace: BUCK1 output Voltage
- Green trace: SW1 voltage
- Red trace: Differential voltage measured across sense resistor(Case-1) or Differential voltage measured across C_{DCR} (Case-2)
- Pink trace: Load current on BUCK1

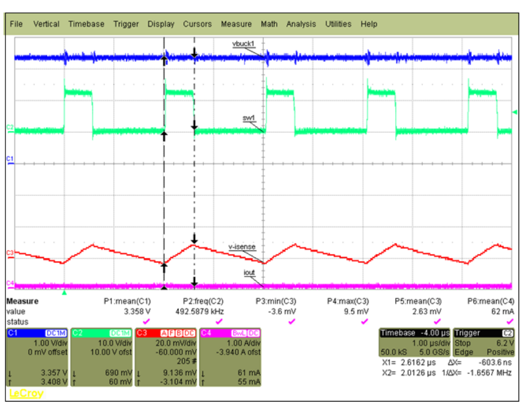


Figure 4. Case 1: Measurement With No Load Condition

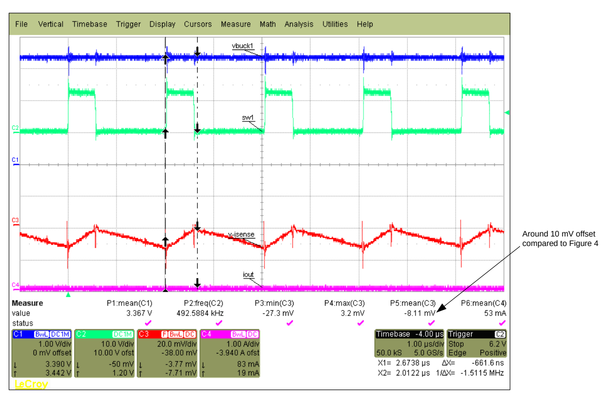


Figure 5. Case 2: Measurement With No Load Condition

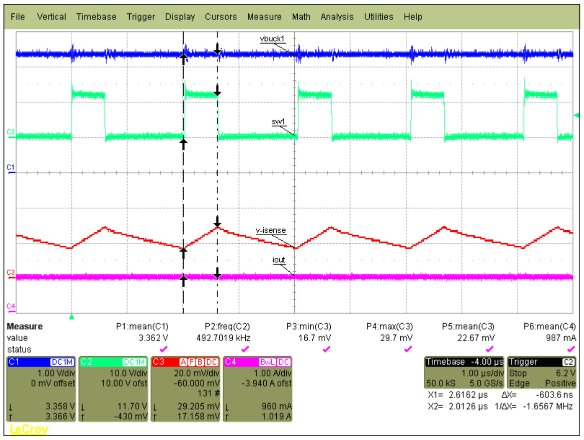


Figure 6. Case 1: Measurement With DC load — 1 A

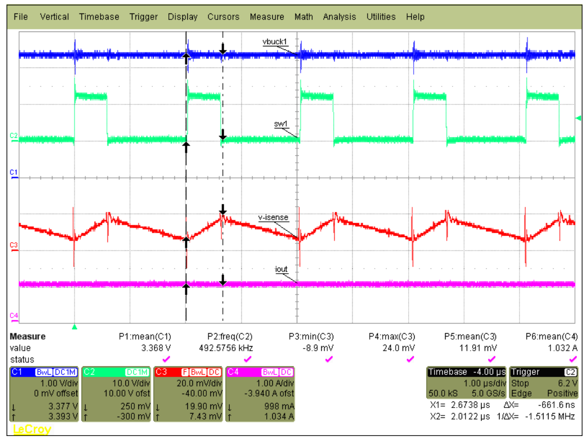


Figure 7. Case 2: Measurement with DC load — 1 A

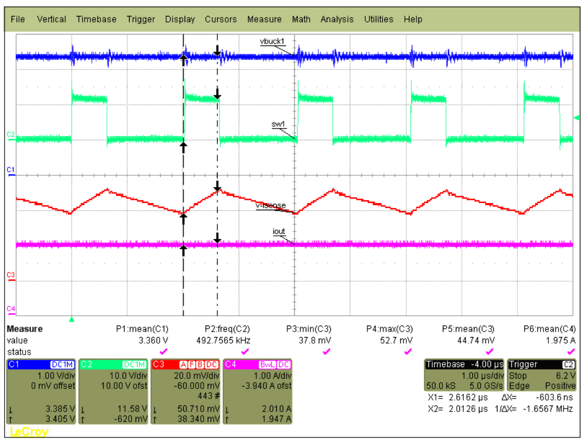


Figure 8. Case 1: Measurement With DC load — 2 A

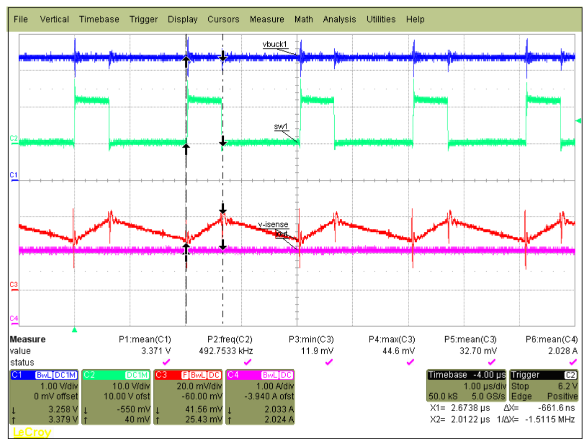
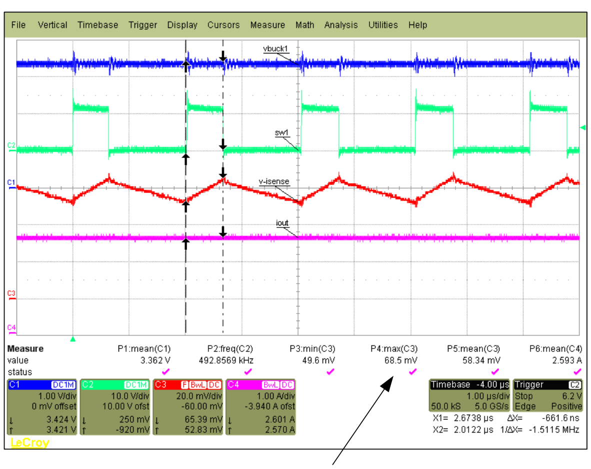


Figure 9. Case 2: Measurement With DC load — 2 A



Device detects OC at around 68 mV

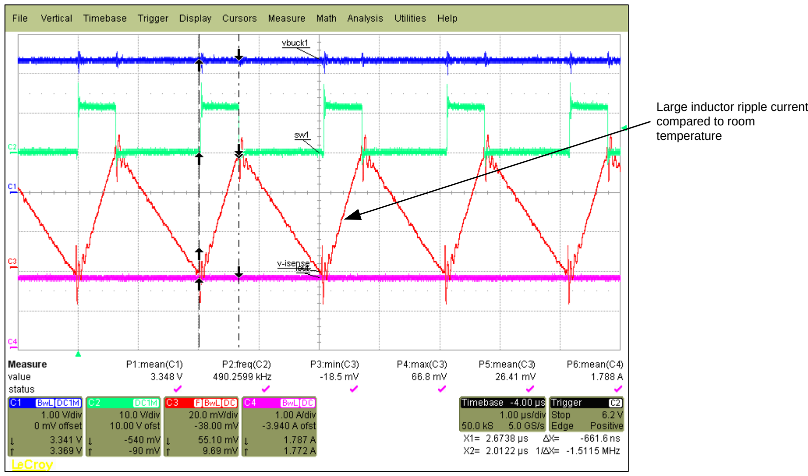
Just before OC Detection

Figure 10. Case-1: Measurement With DC load — 2.6 A

Device detects OC at around 68 mV

Just before OC detection, 0.5 A load current through 2nd source-meter is not shown

Figure 11. Case 2: Measurement With 3.2 A (2.70 A and 0.5 A) Load



Just before OC detection

Figure 12. Case 2: Measurement With 1.8 A Load at +125°C

Table 2. Temperature Measurement Using the Different Current Sensing Methods

Ambient Temperature	DC Load Current When Device Detects OC (A)	
	Case-1, Sense Resistor Method	Case-2, DCR Sensing Method
–40C	2.65	4.0
–25C	2.66	3.9
0C	2.66	3.7
+25C	2.65	3.4
+50C	2.64	3.1
+75C	2.63	2.6
+100C	2.63	2.2
+125C	2.62	1.8

5.3 *Estimation of Peak Inductor Current at Which Device Has Detected Overcurrent (OC)*

Based on Figure 2 of the TPS65311-Q1 datasheet, for Vin = 12 V and Vout = 3.3 V, the current limit voltage (across S1-S2) of approximately 68 mV is almost the same value as observed in the measurement plots. This estimation is done to validate the measurement results by back calculating the average DC current at which device detected the overcurrent threshold.

5.3.1 Case 1, Sense Resistor Method

Based on Figure 10, inductor peak current is calculated as:

$$\text{IL\_max} = \frac{68\ \text{mV}}{22\ \text{m}\Omega} = 3.1\ \text{A} \tag{6}$$

$$\text{IL\_min} = \frac{50\ \text{mV}}{22\ \text{m}\Omega} = 2.27\ \text{A} \tag{7}$$

With Inductor min and max currents the DC load current can be back calculated as follows:

$$\text{I\_DC} = \frac{(\text{IL\_max} + \text{IL\_min})}{2} = 2.69\ \text{A} \tag{8}$$

Calculated DC current is very close to the actual DC load current (2.6 A) at which device detected overcurrent threshold. Thus, the calculation correlates and the current is fairly constant across temperature.

5.3.2 Case 2, DCR Sensing Method

As shown in Figure 5, there is an approximately –10 mV offset, which must be accounted for while doing back calculation of peak inductor current based on measured sense voltage. Based on Figure 11, the measured peak voltage was 68 mV and 78 mV must be used for peak-inductor current (IL_max) calculation. Similarly for IL_min calculation, 56 mV was taken instead of measured value of around 46 mV. (In Figure 11, there is an undershoot due to measurement issue and hence cursor measured value (46mV) was taken for IL min calculation.)

$$IL\_max = \frac{78\ mV}{21.5\ m\Omega} = 3.36\ A \tag{9}$$

$$IL\_min = \frac{56\ mV}{21.5\ m\Omega} = 2.6\ A \tag{10}$$

With Inductor min and max currents the DC load current is calculated by:

$$I\_DC = \frac{(IL\_max + IL\_min)}{2} = 3.15\ A \tag{11}$$

Considering the tolerances, calculated DC current is close to the actual DC load current (3.2 A) and the calculation looks correlated.

Inductor resistance across temperature can be calculated according to Equation 5 and then used to calculate the peak inductor current at which OC is detected. This will be an approximation as there are additional tolerances due to actual inductor resistance, variation of sense capacitor (C_{DCR}) across temperature, measurement accuracy, and other variations.

Table 3. Calculation of Peak Inductor Current at OC Detection Point for DCR Sensing Method

Ambient Temperature	Case-2, DCR Sensing Method	
	Inductor Resistance (ohm) (RL) (Calculated Based on Equation Equation 5)	Calculated/Estimated peak Inductor Current at OC detection point (78 mV / R_L)
–40C	0.0160	4.87
–25C	0.0173	4.52
0C	0.0194	4.02
+25C	0.0215	3.63
+50C	0.0236	3.30
+75C	0.0257	3.03
+100C	0.0278	2.80
+125C	0.0299	2.60

5.3.3 Measurements Summary

Figure 13 provides the measurement plots (based on Table 2 and Table 3) for both methods across temperature. It is evident from the results that the sense resistor method has less variation across temperature and the DCR current sense method has considerable variation across temperature. Also, estimated peak current (assuming that peak current is proportional to average DC current) is correlating with the measured DC current between 0°C to 50°C and beyond this temperature range there is a wider difference between calculated and the measured values.

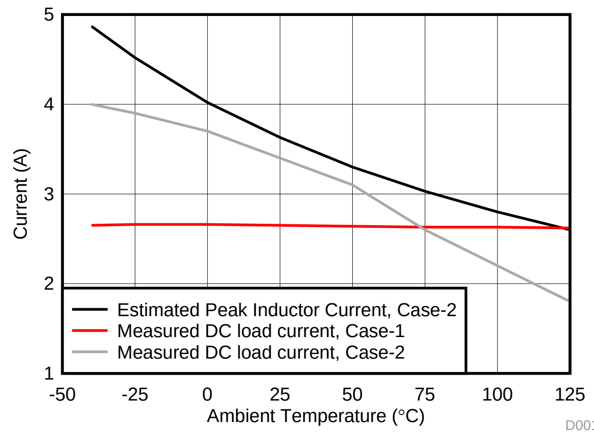


Figure 13. Comparison of Case-1 and Case-2 Measurement Results Across Temperature

6 Conclusion

- As expected, DCR Sensing Method has a wide variation across temperature. To accommodate for these variations, an inductor with large current rating and tighter DCR tolerance must be used. Since it needs an additional two components (R_{DCR}, C_{DCR}), accuracy of current sense also depends on accuracy of these two components.
- With DCR current-sensing method, BUCK1 controller efficiency can be improved as it eliminates the drop across the external sense resistor. This method will also help to save PCB space, as sense resistor is usually bulky.
- As DCR current sensing requires an inductor with a larger current rating and better tolerance along with additional two components, it may offset the cost of an additional sense resistor. A cost comparison between these two current sensing methods should be performed to determine the correct level of cost and performance optimization.
- Current sensing with external sense resistor, R_S, is very stable across temperature.
- With DCR Sensing Method, larger inductor-current ripple was observed at high temperature and might affect the EMC performance.
- Electrical and EMC performance of DCR Sensing Method must be studied by the customer in their application to ensure the applicability to use this method in the specific application use case.

Revision History

DATE	REVISION	NOTES
September 2016	*	Initial Release

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		**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