

Design considerations for resolver-to-digital converters in electric vehicles

By Ankur Verma, *Applications Engineer*

Anand Chellamuthu, *Design Engineer, Mixed Signal Automotive*

Introduction

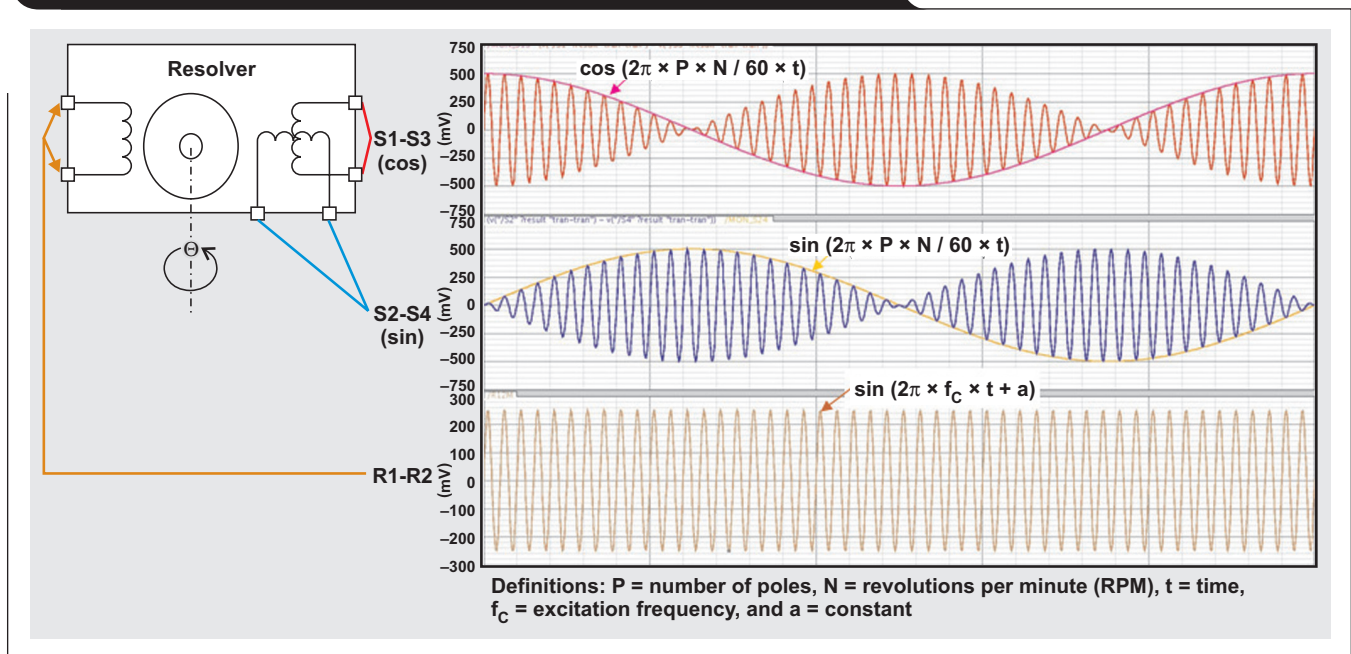
A resolver is an angular position sensor that is commonly used in harsh, rugged environments. A fully electric vehicle (EV) may use multiple resolvers for a variety of control systems that perform rotary motion and additional resolvers may be required to create system redundancy for safety.^[1] A resolver-to-digital converter (RDC) interface processes the analog output of the resolver sensor and communicates it in digital format to the engine control unit (ECU) in an EV. When designing an RDC interface, it is important to select the right RDC architecture to ensure that the circuit operates consistently under stringent conditions (such as vehicle acceleration). This article presents an overview for the architecture of a RDC interface circuit. The PGA411-Q1 is an example of the RDC interface circuit described.^[2] Included is a review of the basic principles involved in designing an RDC interface, a discussion of RDC architecture that is based on a digital

tracking loop, and special design considerations are covered for an EV application. Also included is a performance comparison of the PGA411-Q1 with RDC architecture versus a 19-bit optical encoder.

Resolver-to-digital conversion principle

As shown in Figure 1, a resolver sensor has one rotor winding (R1-R2) with the exciter sine wave that is AC-coupled to two stator windings. The stator windings, a sine coil (S2-S4) and a cosine coil (S1-S3), are mechanically positioned 90 degrees out-of-phase. As the rotor spins, the rotor position angle (Θ) changes with respect to the stator windings. The rotor and stator windings have a turns ratio in the order of 30%. The resulting amplitude-modulated signals shown in Figure 1 are typical resolver output signals. These signals must be gained, demodulated and post processed to extract angle and velocity information.

Figure 1. Representation of resolver signals: exciter, sine, and cosine



RDC architecture

Figure 2 shows an RDC architecture that converts analog resolver signals into digital angle and velocity outputs. The analog front end (AFE) consists of programmable gain amplifiers and a comparator. The AFE block conditions the output signals of the resolver by removing noise, sets correct input DC bias, and appropriately gains up the AC signal to be used by the subsequent blocks. A digital feedback loop is the main part of the RDC conversion. It starts by assuming a digital angle, ϕ . This angle is digitally processed using the sine and cosine lookup tables stored in memory. This in turn is fed to the corresponding sine and cosine digital-to-analog converters (DACs). The DAC outputs are multiplied with the amplitude-modulated resolver signals (Equations 1 and 2), which are the sine and cosine inputs to the RDC.

$$\text{Resolver sensor sine signal} = \sin \Theta \times \sin \omega t \quad (1)$$

$$\text{Resolver sensor cosine signal} = \cos \Theta \times \sin \omega t \quad (2)$$

where Θ = resolver shaft angle and ω = excitation frequency applied at R1-R2.

The main objective of the RDC architecture is to calculate the rotation angle (Θ) and the velocity of the resolver shaft. As shown in Figure 1, angular position information is extracted from the envelope or voltage peaks of the input sine and cosine signals. In order to calculate the angle, $\sin \Theta$ is multiplied by a feedback signal ($\cosine \phi$), where ϕ is the assumed angle resulting from the lookup table in the memory. Similarly, $\cosine \Theta$ is multiplied by the feedback signal ($\sin \phi$). The purpose of this multiplication is to solve the general formula: $(\sin A \times \cos B) - (\sin B \times \cos A)$ and create $\sin (A - B)$.

$$\begin{aligned} \epsilon_{\text{pulse}} &= \sin (A - B), \text{ or} \\ &= (K \times \sin \Theta \times \sin \omega t \times \cos \phi) \\ &\quad - (K \times \cos \Theta \times \sin \omega t \times \sin \phi) \end{aligned} \quad (3)$$

$$\begin{aligned} \epsilon_{\text{pulse}} &\equiv K \times \sin \omega t \times (\sin \Theta \times \cos \phi - \cos \Theta \times \sin \phi) \\ &= K \times \sin \omega t \times \sin (\Theta - \phi) \end{aligned}$$

where ϕ = approximation of the resolver angle and K = a constant.

The output of the differential comparator is in digital form and is directly fed into the digital blocks to eliminate the carrier wave or the $\sin \omega t$ component with a synchronous detection circuit. This synchronous detection block uses the exciter feedback signal as the reference. The resulting output, $V_{\phi\text{ERR}}$, goes into the digital tracking control loop to generate the desired angle output.

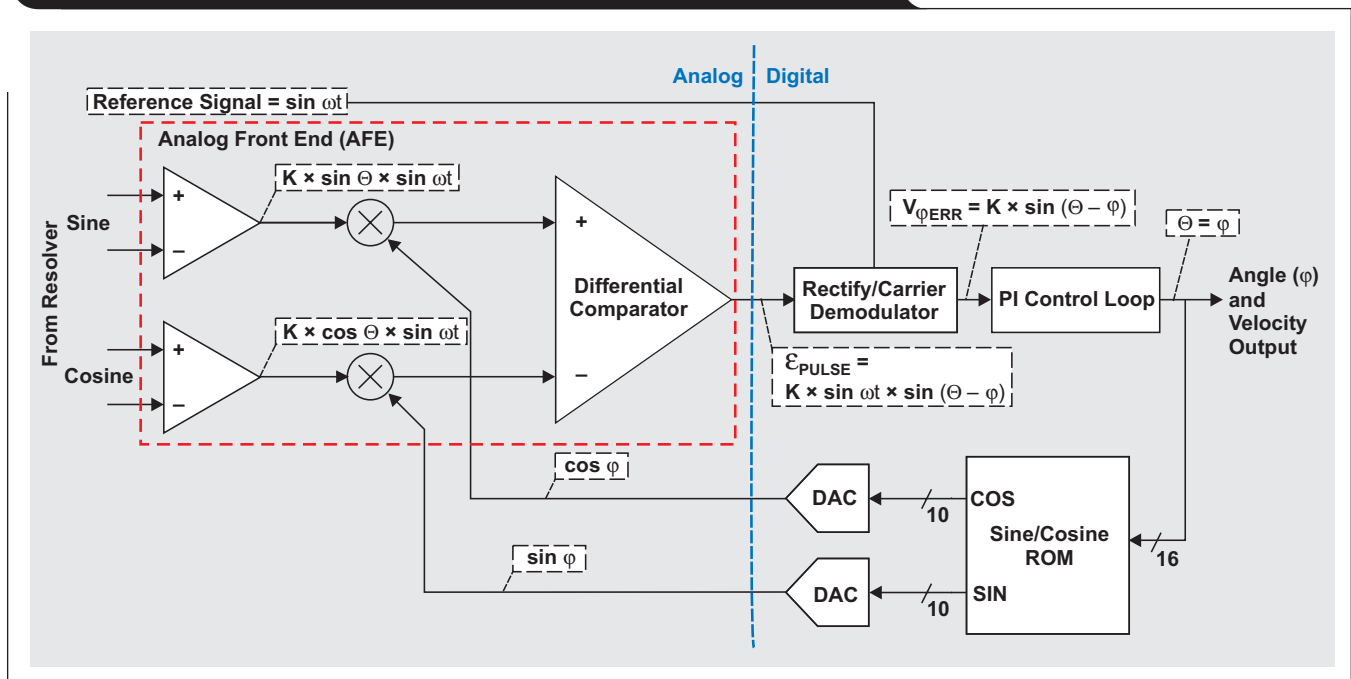
$$V_{\phi\text{ERR}} = K \times \sin (\Theta - \phi) \quad (4)$$

The negative feedback of the control-loop configuration employed in this RDC architecture helps to continuously reduce the $V_{\phi\text{ERR}}$ signal to be very close to zero. For small values of $\Theta - \phi$, $V_{\phi\text{ERR}}$ is very near zero. Thus, the digital feedback loop continuously corrects itself, making the error close to zero so that the assumed RDC output angle (ϕ) is equal to the resolver shaft angle (Θ).

As shown in Figure 2, the $V_{\phi\text{ERR}}$ signal is fed into a PI-control loop (Type II direct servo loop). Many control topologies for implementing loop tracking are possible.

One of the commonly used feedback control configurations is known as integral action.^[3, 4] The advantage of this control configuration is its ability to reduce the steady-state tracking error to nearly zero. However, precautions must be taken because slightly excessive integral gain can cause oscillations in the system or even instability. This

Figure 2. Simplified resolver-to-digital converter (RDC) architecture



issue is addressed by adding another widely used proportional control known as proportional plus integral control (PI).

PI control is typically implemented as shown in Figure 3.^[5] It helps bring steady-state error to zero and has improved transient response. Because of the added benefit of proportional control, it also does not cause any offset and leads to faster response than integral control alone.

Example application: Electric vehicle

Motor control action is an integral part of an EV. Communicating the motor position information accurately and quickly is essential. The resolver attached to a motor shaft tends to change its output very quickly. Hence, the RDC architecture must be designed to follow this change.

Typically, the most critical component of the RDC architecture that determines how fast this can happen is the digital tracking loop.

To determine the behavior of the tracking loop, it is important to understand a key term, settling time. When the resolver output signal changes rapidly, the converter's step response is determined by the phase margin and gain margin of the control loop.^[3] Settling time is a quick performance indicator of the RDC's control system. Figure 4 shows a settling-time example of an RDC feedback control system with a step-input change shown in black. The blue signal shows normal-mode response for the circuit in Figure 3 and the red signal shows response during acceleration mode (rapid change in angle), which is described on the following page.

Figure 3. Example of a PI control loop

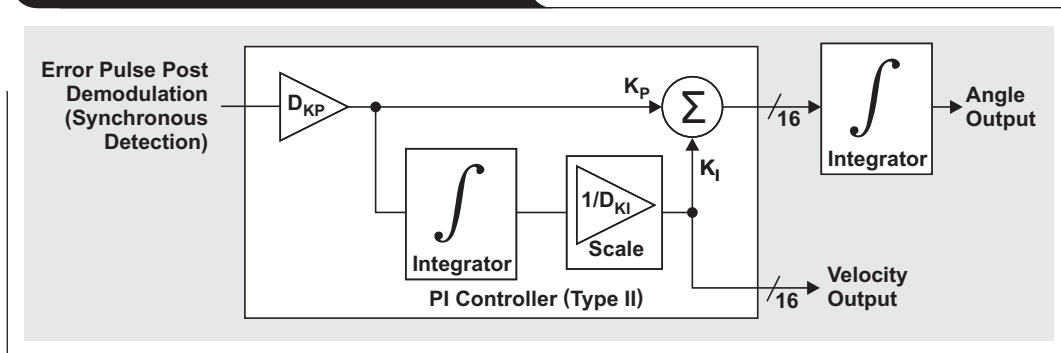
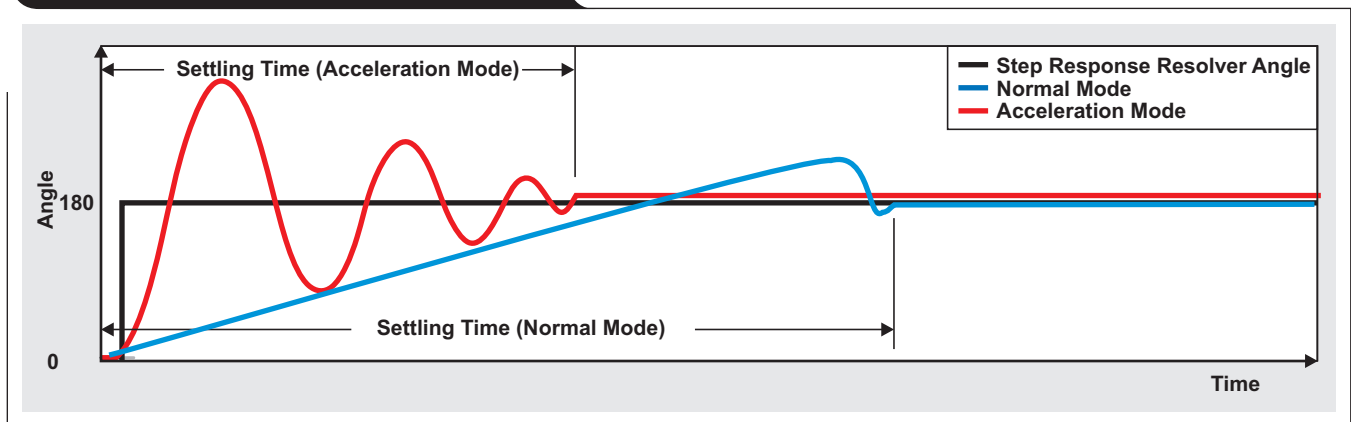


Figure 4. RDC step-response settling time



In order to follow the rotation angle under rapidly changing conditions, another loop-acceleration block is added in Figure 5 that can change the control-loop feedback gain. The higher-gain option helps the control loop to track a fast rotation angle much easier. In the acceleration mode (red signal in Figure 4), the proportional gain is increased by several times compared to the normal mode. Several diagnostic features are also added to alert the system if the signal integrity of the exciter and sine/cosine coils have been compromised.

Error sources that affect system accuracy

The errors can be categorized into three groups:

Group 1: Resolver sensor placement

- Sensor’s mechanical construction: Static error is generated by manufacturing variations.
- Coil imbalance: The output voltages of the sine and cosine coils could be imbalanced and result in an error.
- Misalignment of resolver sensor: The resolver may be incorrectly mounted and lead to static error in the system.

Group 2: RDC architecture

The RDC architecture can cause static and dynamic errors in the system. The time delay from the input of the resolver signal to the output of the angle data also can

cause errors in the system. For example, the input filter is used to decouple noise from the system. The delay caused by the filter circuit or the filter time constant may result in angular displacement during high-speed resolver operation. Therefore, be careful when selecting any common-mode capacitors that are added to the circuit to filter out noise. These common-mode capacitors can significantly affect phase relationship of the resolver signals and cause an imbalance between sine and cosine outputs, which can cause an error in the RDC output angle.

In addition, offset drifts in the AFE and linearity of the DACs can significantly affect the accuracy of the converted angle.

Group 3: Environmental factors

The external magnetic field from the motor-control circuit and high-voltage support in the EV can affect the resolver sensor’s magnetic-coupling action and cause an error. Cable shielding is commonly used to prevent resolver signals from becoming affected, along with filter design at the input of the resolver converter to cut off any unwanted signals. The ability of the RDC architecture to reject common-mode noise is critical. Otherwise, the noise shows up on the signal-to-noise floor of the RDC, affecting the signal-to-noise ratio (SNR) and total harmonic distortion (THD) performance.

Figure 5. PI control with acceleration block

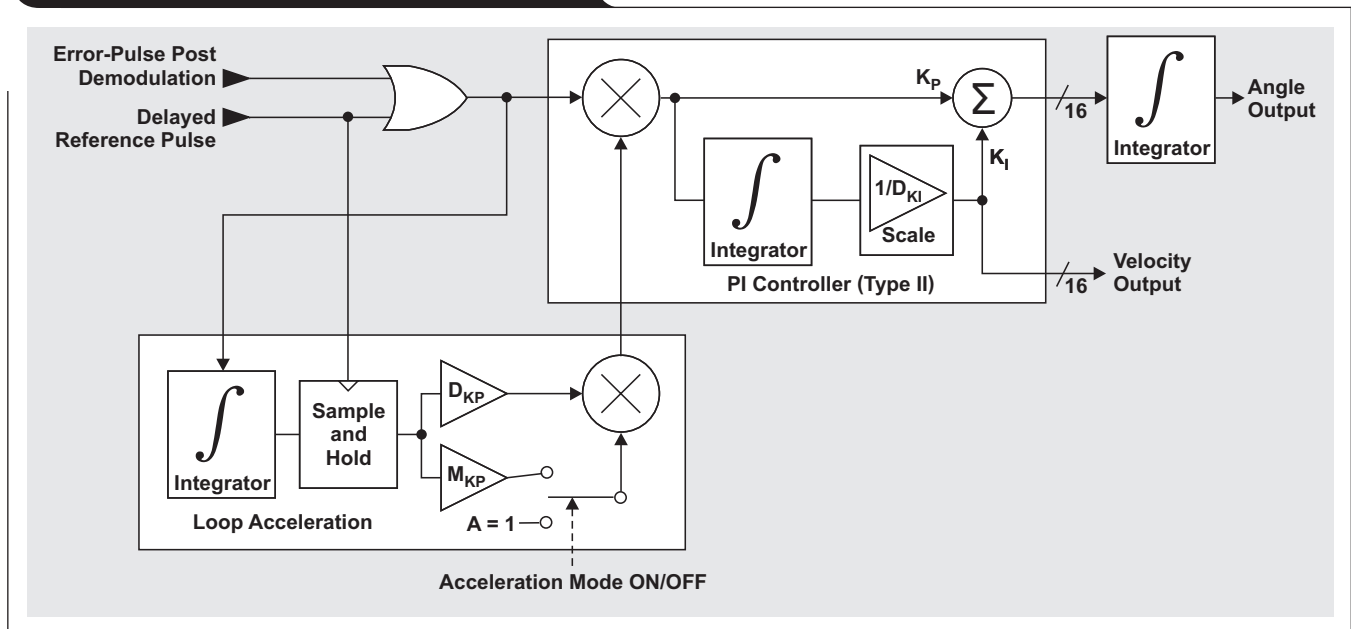
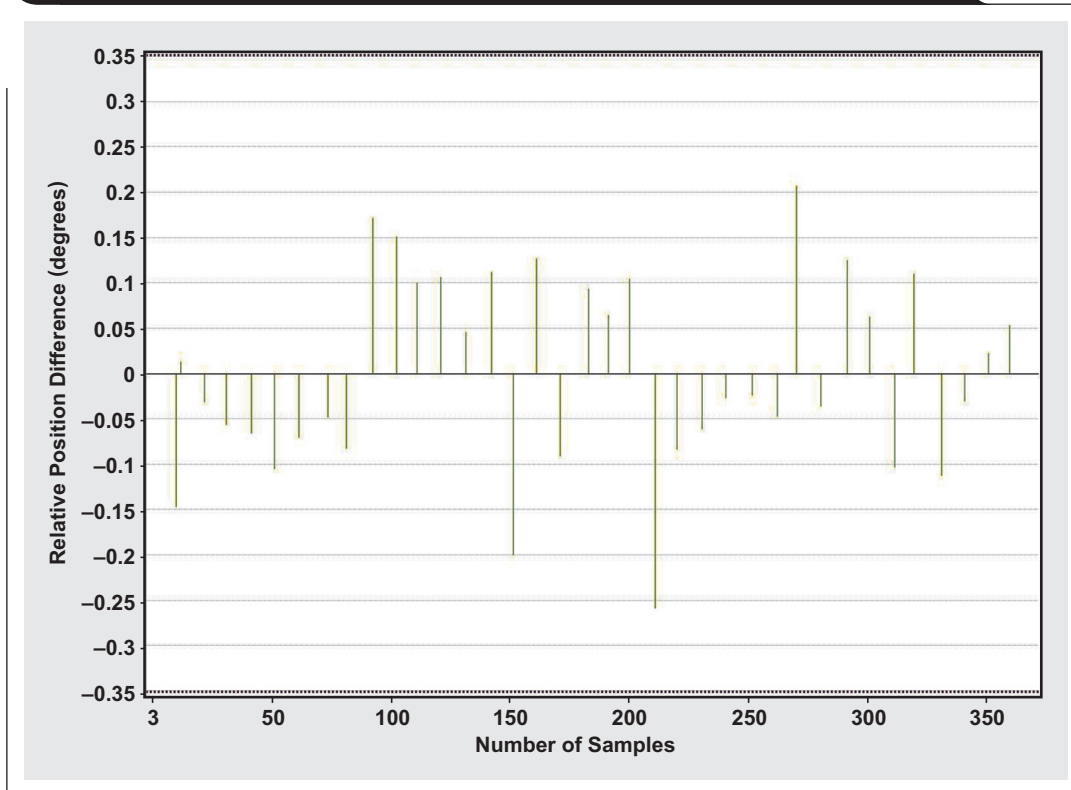


Figure 6. Measured RDC performance compared to a 19-bit optical encoder


RDC performance versus a 19-bit optical encoder

To better understand the performance of the resolver system, the results of a 12-bit RDC were compared to a 19-bit optical encoder. The mechanical set up included an example resolver and optical encoder mounted on the same shaft. Relative position difference was measured and plotted (Figure 6). The relative difference rules out any common-mode noise in the system that may cause the absolute values to misalign. The errors between the absolute angle deviation of the measured 16-bit RDC and the 19-bit optical encoder are less than ± 0.25 degrees.

Acknowledgement

The authors would like to acknowledge Toru Tanaka from Texas Instruments for his initial work on RDC system definition.

References

1. Ankur Verma and Amanda Weise, "Rotary position sensing for electric vehicles," Part I, EDN, October 02, 2015
2. PGA411-Q1 data sheet, Texas Instruments, 2015
3. Ron Mancini, "Feedback and Stability Theory," Texas Instruments literature, (SLOA077)
4. Irfan Ahmed, "Implementation of PID and Deadbeat Controllers with the TMS320™ Family," Application Report, Texas Instruments (SPRA083)
5. Dave Wilson, "Teaching Your PI Controller to Behave (Part 1)," Motor Drive & Control, E2E™ blog, Texas Instruments, July 20, 2015
6. Martin Staebler, "Designing an EMC-compliant interface to motor position encoders – Part 1," Motor Drive & Control, E2E blog, Texas Instruments, August 31, 2015

Related Web sites

Product information:

PGA411-Q1

PGA411-Q1 Troubleshooting Guide (SLAA687)

Subscribe to the AAJ:

www.ti.com/subscribe-aaaj

TI Worldwide Technical Support

Internet

TI Semiconductor Product Information Center Home Page

support.ti.com

TI E2E™ Community Home Page

e2e.ti.com

Product Information Centers

Americas	Phone	+1(512) 434-1560
Brazil	Phone	0800-891-2616
Mexico	Phone	0800-670-7544
	Fax	+1(972) 927-6377
	Internet/Email	support.ti.com/sc/pic/americas.htm

Europe, Middle East, and Africa

Phone		
European Free Call	00800-ASK-TEXAS (00800 275 83927)	
International	+49 (0) 8161 80 2121	
Russian Support	+7 (4) 95 98 10 701	

Note: The European Free Call (Toll Free) number is not active in all countries. If you have technical difficulty calling the free call number, please use the international number above.

Fax	+ (49) (0) 8161 80 2045
Internet	www.ti.com/asktexas
Direct Email	asktexas@ti.com

Japan

Fax	International	+81-3-3344-5317
	Domestic	0120-81-0036
Internet/Email	International	support.ti.com/sc/pic/japan.htm
	Domestic	www.tij.co.jp/pic

Asia

Phone	<u>Toll-Free Number</u>
Note: Toll-free numbers may not support mobile and IP phones.	
Australia	1-800-999-084
China	800-820-8682
Hong Kong	800-96-5941
India	000-800-100-8888
Indonesia	001-803-8861-1006
Korea	080-551-2804
Malaysia	1-800-80-3973
New Zealand	0800-446-934
Philippines	1-800-765-7404
Singapore	800-886-1028
Taiwan	0800-006800
Thailand	001-800-886-0010
International	+86-21-23073444
Fax	+86-21-23073686
Email	tiasia@ti.com or ti-china@ti.com
Internet	support.ti.com/sc/pic/asia.htm

Important Notice: The products and services of Texas Instruments Incorporated and its subsidiaries described herein are sold subject to TI's standard terms and conditions of sale. Customers are advised to obtain the most current and complete information about TI products and services before placing orders. TI assumes no liability for applications assistance, customer's applications or product designs, software performance, or infringement of patents. The publication of information regarding any other company's products or services does not constitute TI's approval, warranty or endorsement thereof.

A021014

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

Applications

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

TI E2E Community

e2e.ti.com