

# **THD Reduction of DCM PFC With UCD3138**

Yunsheng Qu

## **ABSTRACT**

An active PFC stage is an indispensable part to reduce the harmonic content of input currents. In order to reduce the total cost, the inductance of the PFC choke is made extremely small in more and more practical designs. However, in existing UCD3138 single-phase PFC solutions, the input current distortion in DCM (discontinuous conduction mode) is greater than that measured in large choke-inductance PFC designs. Thus, in small choke-inductance PFC designs, it is difficult to meet the THD (Total Harmonic Distortion) specification at light load levels. This paper analyzes the root cause of the significant input current distortion in DCM and proposes a simple method to reduce THD at light load levels.

## **Contents**

1	Existing Solution, Introduction.....	2
2	Proposed Solution .....	4
3	Implementation of Proposed Solution .....	4
4	Test Results With Different Current Sample Methods .....	6
5	Conclusions .....	7
6	References .....	7

## **List of Figures**

1	UCD3138-Controlled Single Phase PFC Block Diagram.....	2
2	Current Loop Diagram of UCD3138 PFC Solution .....	2
3	Oversampling Mechanism for Average Input-Current Measurement .....	3
4	Current-Error Sensor Saturation Analysis in CCM Operation.....	3
5	Typical Input Signals of DCM PFC Current Loop .....	4
6	Diagram for Triangular Mode.....	4
7	Proposed Sample Trigger Point in DCM PFC .....	5

## **List of Tables**

1	Test Results With Different Current Sample Methods .....	6
---	--	---

## 1 Existing Solution, Introduction

The existing single-phase PFC solution based on UCD3138 is shown in Figure 1.

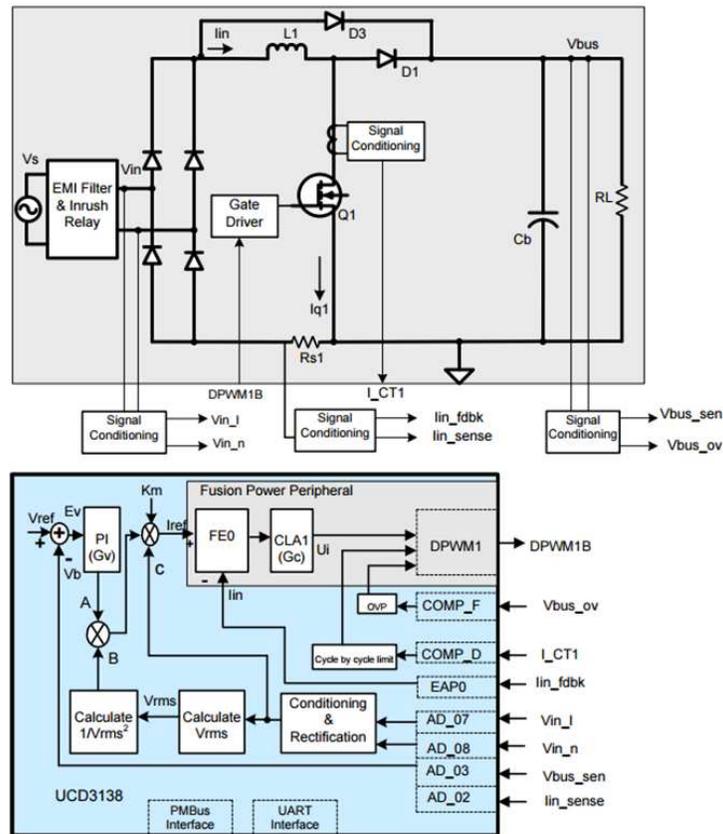


Figure 1. UCD3138-Controlled Single Phase PFC Block Diagram

Average-current mode control is employed to force the input current to track the input voltage. Figure 2 shows the block diagram of the current loop. I\_reference is calculated by firmware and follows the product of input voltage and the output of the outer voltage loop.

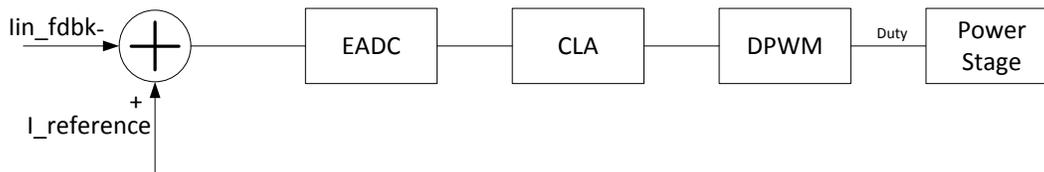
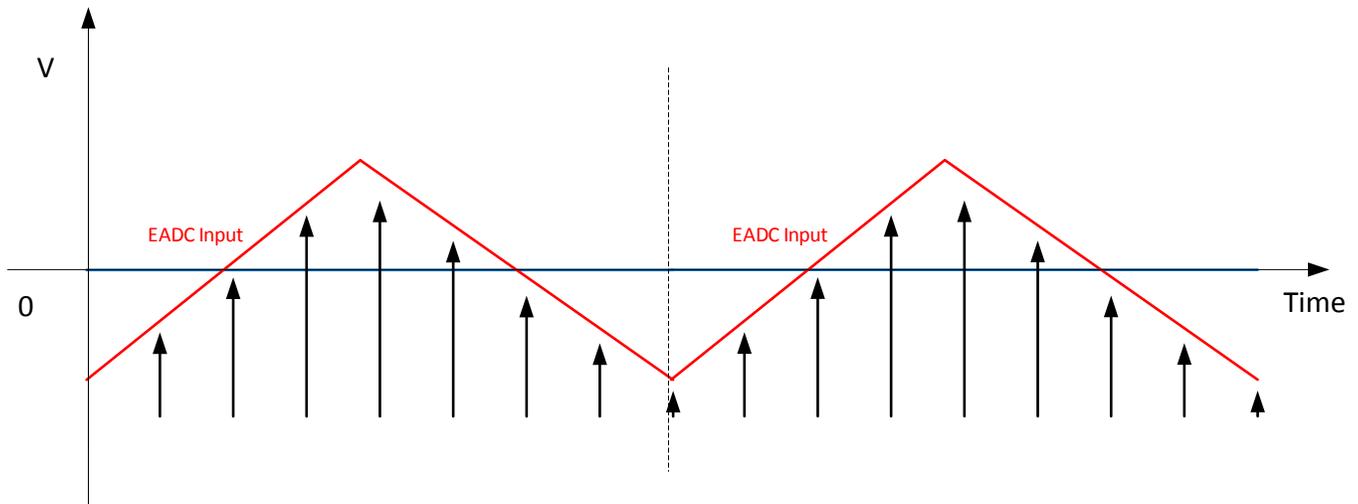


Figure 2. Current Loop Diagram of UCD3138 PFC Solution

The input current sensing result,  $lin\_fdbk$ , is from current shunt  $R_{s1}$  and the signal conditioning circuit which is formed by an operational amplifier used to amplify the current signal to a level suitable for the PFC control circuit. The error between  $I\_reference$  and  $lin\_fdbk$  is the analog input of EADC (Error ADC) which converts its analog error input into a digital form used for duty-cycle calculation by Control Law Accelerator (CLA). Since the current signal conditioning circuit does not provide sufficient attenuation of the input current ripple, the ripple still appears at the input of the EADC. The existing solution utilizes an oversampling mechanism (refer to SLUA709) to average out the ripple. In the oversampling mechanism, as shown in Figure 3, the instantaneous input current is sampled 8 times, distributed equally in time, per switching cycle. The average value of 8 samples is used for the duty cycle calculation.

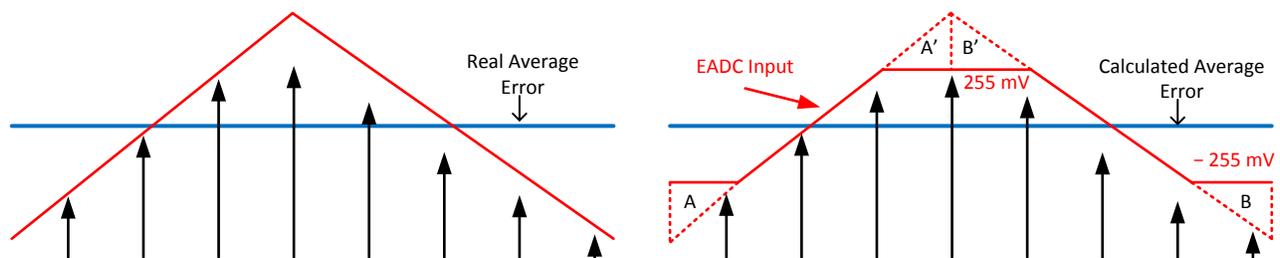


**Figure 3. Oversampling Mechanism for Average Input-Current Measurement**

In order to avoid EADC saturation, the EADC input at the sample instant which is indicated by an arrow must be within the EADC measurement range,  $-255\text{ mV}$  to  $+255\text{ mV}$ . Otherwise, the conversion result is clamped to either the maximum or minimum value. When the inductance of the PFC choke is so small as to cause the pk-pk magnitude of  $lin\_fdbk$  to exceed  $512\text{ mV}$ , then EADC saturation is unavoidable. But the correlation between EADC saturation and input current distortion depends on the convertor's operation mode, CCM or DCM.

### 1.1 EADC Saturation Does not Cause Input Current Distortion in CCM Operation

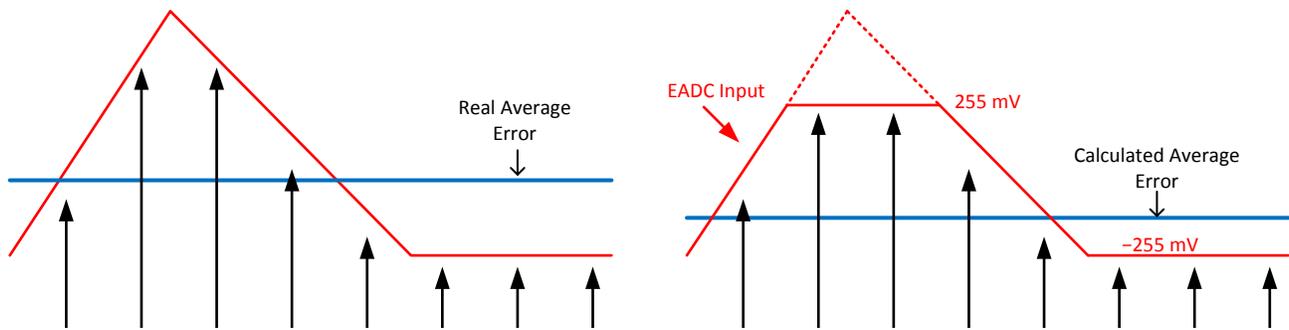
In steady-state CCM operation, the average error between  $I\_reference$  and  $lin\_fdbk$  per switching cycle, is very close to 0 due to the closed-loop control of the current loop. The analog input of EADC is shown in the left side of Figure 4. The positive and negative peak values are equal. The solid line in the right picture represents the EADC conversion result and the zones A, A', B, and B' represent truncation error due to EADC saturation. It is obvious that the area of A and B is equal to that of A' and B', so it is clear from a mathematic perspective that the truncation error makes no difference between the actual average EADC input in one switching cycle and its digital conversion result which is important for the calculation of duty cycle. That is why there is no input current distortion in CCM operation even though the small inductance of the PFC Choke causes EADC saturation.



**Figure 4. Current-Error Sensor Saturation Analysis in CCM Operation**

### 1.2 EADC saturation does cause input current distortion in DCM operation

As in CCM control, the average error between the scaled input current ( $lin\_fdbk$ ) and  $I\_reference$  per switching cycle is also close to 0. However, the peak value of the positive error is much higher than that of the negative error in the same switching cycle as shown in Figure 5. Hence, the truncation of positive and negative in one switching cycle is unbalanced and the conversion result of the average error per switching cycle is not equal to the actual average error, which causes input current distortion in DCM operation and large THD at light-load levels.


**Figure 5. Typical Input Signals of DCM PFC Current Loop**

## 2 Proposed Solution

As previously discussed, EADC saturation must be avoided in order to eliminate the input current distortion in DCM operation. Oversampling is not suitable for the current loop error sensing in small choke-inductance PFC applications. A single-sample-per-switching cycle is the best way to address the EADC saturation problem. At the same time, in order to get good THD, the instantaneous current at the single sample instant must represent the average current of the whole switching cycle. Refer to [SLUA712](#), the best sample location is at the middle of the PWM on time. Since the closed-loop control is able to force its input error to be 0 at steady state operation, the input of EADC at sample instant is always close to 0 for both CCM and DCM operation.

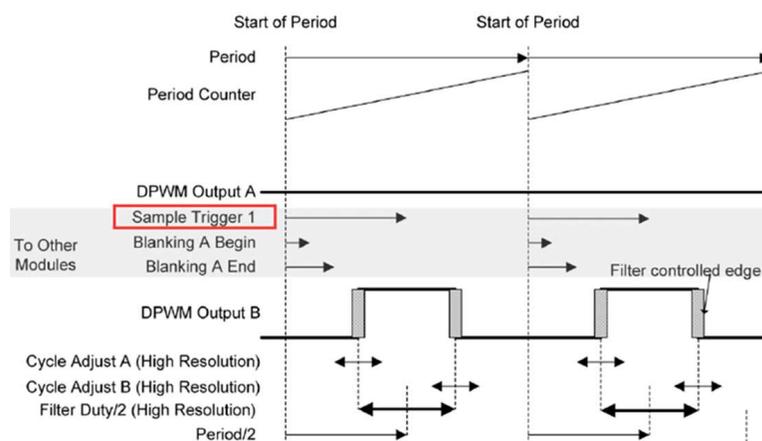
## 3 Implementation of Proposed Solution

This section describes in detail the method to reduce THD in DCM PFC. THD in DCM PFC is reduced significantly by following the method step by step.

### 3.1 Configure DPWM Mode to Triangle Mode

#### 3.1.1 Introduction of Triangle Mode of DPWM

There are many DPWM modes in the UCD3138 DPWM module. In triangular mode, the PWM pulse is centered in the middle of the period, rather than starting at one end or the other. In triangular mode, only the DPWMB output is available. [Figure 6](#) is a diagram for triangular mode.


**Figure 6. Diagram for Triangular Mode**

### 3.1.2 Firmware Configuration of DPWM Mode

Configure the PWM mode to triangular mode as in the following:

```
Dpwm1Regs.DPWMCTRL0.bit.PWM_MODE = 3;
```

### 3.2 Disable Oversampling

The EADC converts the analog error signal only once per DPWM period if oversampling is disabled. In this application note, oversampling must be disabled, the configuration of oversampling in firmware follows:

```
Dpwm1Regs.DPWMCTRL2.bit.SAMPLE_TRIG1_OVERSAMPLE = 0;
```

### 3.3 Configure Sample Trigger Point to ½ Period

#### 3.3.1 Introduction of ½ Period

Since DPWM mode is configured to triangular mode, the PWM pulse is centered in the middle of the period. If the sample trigger point is set to ½ of the period, then the sample trigger point is just at ½ PWM on time, as shown in Figure 7. Since the input signal is not saturated at this time, the calculated error used for the duty cycle calculation is accurate enough for good THD.

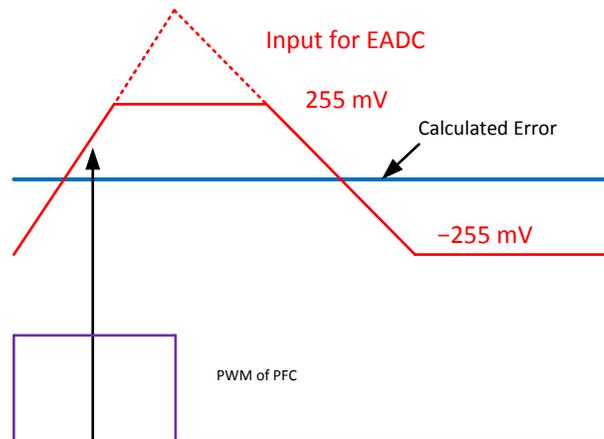


Figure 7. Proposed Sample Trigger Point in DCM PFC

#### 3.3.2 Firmware Configuration of Sample Trigger Point

The current sample trigger point is configured for the middle of the period, the configuration of the sample trigger point in firmware follows:

```
Dpwm1Regs.DPWMSAMPTRIG1.all = (iv.switching_period >> 1) + (iv.sample_trigger_offset * 4);
```

iv.switching\_period is the value of the switching period register, the resolution is 4 ns

iv.sample\_trigger\_offset is the delay compensation of driver circuit, the resolution is 250 ns

### 3.4 Configure the Calculation of Current Reference to CT Method

The current target calculation for the current loop for DCM PFC without oversampling, shown in the following image, is the same as the CT method used on the UCD3138PFCEVM. For the principle used by the CT method to calculate current target of current loop, please refer to [SLUA712](#).

Firmware for calculation of the current reference follows:

```
int32 pointer;

//for EMI CAP compensation
iv.cir_buff[iv.cir_buff_ptr] = iv.vin_filtered;
pointer = (iv.cir_buff_ptr - iv.cir_buff_delay) & 0x3f; //get pointer to delayed signal
iv.cir_buff_ptr = (iv.cir_buff_ptr + 1) & 0x3f;

iv.vbus_scaled = (iv.adc_avg[VBUS_CHANNEL] * VBUS_TO_VAC_SCALING) >> 15;
//scale vbus to match scale of vrect Q12 * Q15 >> 15 = Q12

if(iv.vbus_scaled > iv.vin_filtered)
{
    iv.numerator_1 = iv.vbus_scaled - iv.vin_filtered; //Q12
}
else
{
    iv.numerator_1 = 0; //if vrect greater than vout, don't need any boost. shouldn't happen often
}

iv.numerator_2 = (iv.i_target_average * iv.numerator_1) >> 8; //Q14 * Q12 >> 8 = Q18
iv.numerator_3 = (iv.cir_buff[pointer] * iv.numerator_2); //Q12 * Q18 = Q30

iv.clai_output_filtered = (Uint32)Filter1Regs.FILTERYNREAD.bit.YN + iv.clai_output_filtered -
    (iv.clai_output_filtered >> 2); //Q25

iv.denominator = ((iv.clai_output_filtered >> 6) * iv.vbus_scaled) >> 11; //Q19 * Q12 >> 11 = Q20
iv.i_target_sensed = (iv.numerator_3 / iv.denominator) + iv.i_target_offset; //Q30/Q20 = Q10

if(iv.i_target_sensed > 0x3fff) //saturate current target at maximum current
{
    iv.i_target_sensed = 0x3fff;
}

FeCtrl0Regs.EADC_DAC.bit.DAC_VALUE = iv.i_target_sensed << 4; //1211
```

## 4 Test Results With Different Current Sample Methods

Change the PFC inductance to 180  $\mu\text{H}$  from 330  $\mu\text{H}$  on UCD3138PFCEVM to make the PFC work in DCM. By using the middle current sample PWM method and disabling oversampling of the EADC, the THD is significantly reduced, as shown in [Table 1](#).

**Table 1. Test Results With Different Current Sample Methods**

Shunt+ Oversampling		Shunt+ Middle Point Sample	
UCD3138PFCEVM With 180 $\mu\text{H}$ PFC inductor			
115/60 Hz		115/60 Hz	
Load	THD	Load	THD
390 V $\times$ 0.1 A	10.47	390 V $\times$ 0.1 A	2.83
390 V $\times$ 0.2 A	7.62	390 V $\times$ 0.2 A	1.82
390 V $\times$ 0.3 A	6.93	390 V $\times$ 0.3 A	1.28
390 V $\times$ 0.4 A	5.43	390 V $\times$ 0.4 A	1.26

## 5 Conclusions

This application note shows a simple method to reduce THD in DCM PFC. It only needs a modification of the firmware, hardware modification is not needed. This document also shows that THD in DCM PFC is significantly reduced with this new method.

## 6 References

1. *Design a UCD3138 Controlled Interleaved PFC* ([SLUA712](#)) — Bosheng Sun
2. *UCD3138 Digital Power Peripherals Programmer's Manual* ([SLUU995A](#))

## 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)