

## Calibrating a Single-Phase Energy Meter Based on the [ADE7953](#)

by Aileen Ritchie

### INTRODUCTION

This application note describes how to calibrate the [ADE7953](#). It details the calibration procedure, including equations and examples of how to calculate each constant.

The [ADE7953](#) is a high accuracy single-phase metering IC that allows both the phase current and the neutral current to be

measurement simultaneously. It provides a variety of energy measurements including active, reactive, and apparent energy, along with current and voltage rms readings. A variety of power quality features, including no load, reverse power, and a direct power factor measurement, are also provided. The [ADE7953](#) can be accessed via an SPI, I<sup>2</sup>C, or UART interface.

TABLE OF CONTENTS

Introduction .....	1	Apparent Energy Calibration Using the CF Output.....	9
Revision History .....	2	Designing a Tamper-Proof Meter Using the CF Output.....	10
Calibrating the ADE7953 .....	3	Calibrating the Internal Energy Registers.....	11
Calibration Steps.....	3	Active Energy Calibration Using the Energy Registers.....	11
Calibration Method (CF Output or Registers).....	3	Current Channel B Gain Matching Using the Energy	
Calibration Setups .....	4	Registers.....	11
Calibrating the CF Pulse Output.....	5	Reactive Energy Calibration Using the Energy Registers .....	13
Active Energy Calibration Using the CF Output .....	5	Current and Voltage RMS Using the Energy Registers.....	14
Current Channel B Gain Matching Using the CF Output .....	5	Apparent Energy Calibration Using the Energy Registers ...	14
Reactive Energy Calibration Using the CF Output.....	7		
Current and Voltage RMS Using the CF Output.....	8		

REVISION HISTORY

6/11—Revision 0: Initial Version

## CALIBRATING THE ADE7953

To obtain accurate readings that do not reflect meter-to-meter variations in external components or the internal voltage reference, the [ADE7953](#) requires calibration. Calibration is required on every meter; however, it is a simple process that can be performed quickly.

### CALIBRATION STEPS

When designing a meter using the [ADE7953](#), a maximum of three calibration stages is required; gain, phase, and offset. Depending on the external configuration and meter class, one or more of these stages can be omitted.

Table 1 provides guidance on which calibration steps are typically required for a particular configuration. Because the requirements and performance can differ on a design-by-design basis, only use this table as a general guideline. The performance of the meter should be evaluated to determine whether any additional calibration steps are required.

### CALIBRATION METHOD (CF OUTPUT OR REGISTERS)

The [ADE7953](#) can be calibrated by either reading the internal energy registers or measuring the external CF output pulse. The relationship between these two measurements is shown in Figure 1.

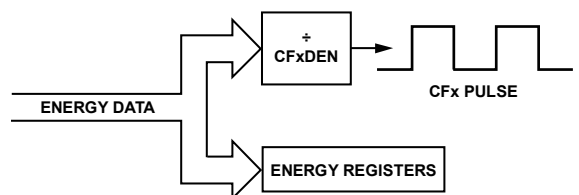


Figure 1. Accessing Energy Data

As shown in Figure 1, the energy register data and CFx output data are related by a factor of the CFxDEN register.

$$CFxOutput \text{ (Hz)} = 1/CFxDEN \times \text{Energy Register (Update Rate)}$$

The decision of whether to calibrate using the CF or energy register depends on both the application and available calibration equipment (see the Calibration Setups section). If the meter specification requires calibration to a particular meter constant, the CF output pin is typically used. If the CF output pin is not being used and no meter constant is specified by design, the register may be a more convenient method. Calibrating the energy registers results in accurate readings on the CF output pin and vice versa. Both methods result in the same level of accuracy.

Table 1. Typical Calibration Steps

Calibration Stage	Typical Requirement
Gain Calibration	It is always required
Phase Calibration	When using a CT, it is often required. When using a shunt, it is not always required.
Offset Calibration	When looking for high accuracy over a large dynamic range, it is often required. It is not usually required for all other meter designs.

## CALIBRATION SETUPS

Two calibration setups can be used to calibrate the [ADE7953](#): a reference meter and an accurate source. When using a reference meter, the CF output method of calibrating must be used. When using an accurate source, either the CF output or energy register can be used. Additional information on the two calibration setups are in the Reference Meter section and the Accurate Source section.

### Reference Meter

The most popular method of calibration uses an external reference meter to determine the required compensation. If using reference metering, the CF output must be used because the reference meter determines the error based on the CF pulse (see Figure 2). The reference meter should be more accurate than the desired specifications of the resulting meter.

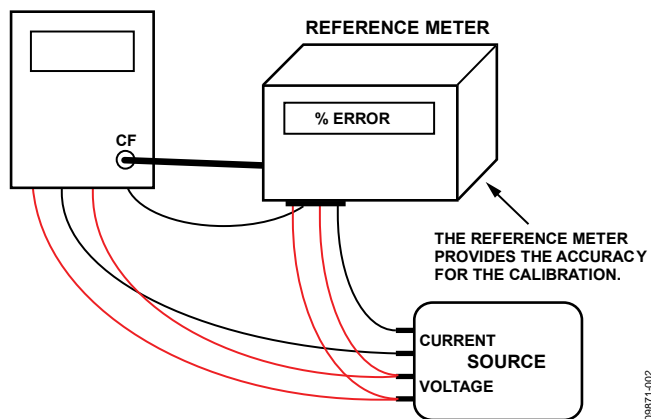


Figure 2. Reference Meter Configuration

When using a reference meter, a source is required to provide the required inputs to the meter; however, the accuracy of the source is not as critical because the reference meter determines the calibration result. Typically, reference meters are more cost effective than accurate sources; therefore, this is the most popular calibration method.

### Accurate Source

The second calibration method is to use an accurate source to perform the calibration. If using an accurate source, either the CF output or the energy registers can be used to access the energy data. The accurate source must be able to provide a controllable voltage and current input with higher accuracy than that required in the resulting meter. Figure 3 shows a typical setup using an accurate source.

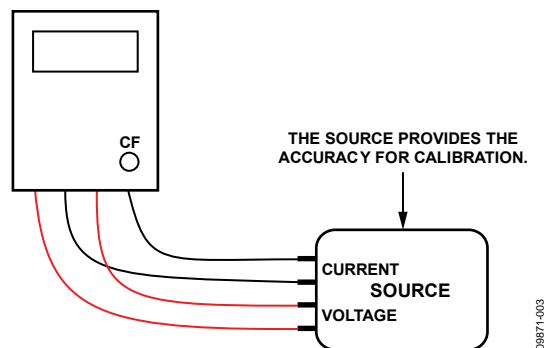


Figure 3. Accurate Source

An accurate source is typically more expensive than a reference meter and is therefore a less popular method of calibration.

The Calibrating the CF Pulse Output section deals with calibrating using the CF pulse, and the Calibrating the Internal Energy Registers section deals with calibrating using the energy registers.

## CALIBRATING THE CF PULSE OUTPUT

The active, reactive, and apparent energies, along with current and voltage rms, must be calibrated for accurate readings to be acquired. All signal paths are independent and, therefore, perform the calibration on the measurements that are required in the completed meter.

When calibrating using the pulse output, the CFx pin must be configured to output the correct measurement and channel for that particular calibration. For example, when calibrating active energy on Channel A, configure CF1 or CF2 to be proportional to the active power on Channel A. This is achieved by setting Bit 0 through Bit 7 of the ADE7953 CFMODE register (Address 0x107). Either CF1 or CF2 can be used. For faster calibration, two different measurements or channels can be output on CF1 and CF2, simultaneously, and two calibrations performed in parallel.

### ACTIVE ENERGY CALIBRATION USING THE CF OUTPUT

Figure 4 shows the calibration flow for the active energy measurement. Use this flow to determine a calibration routine.

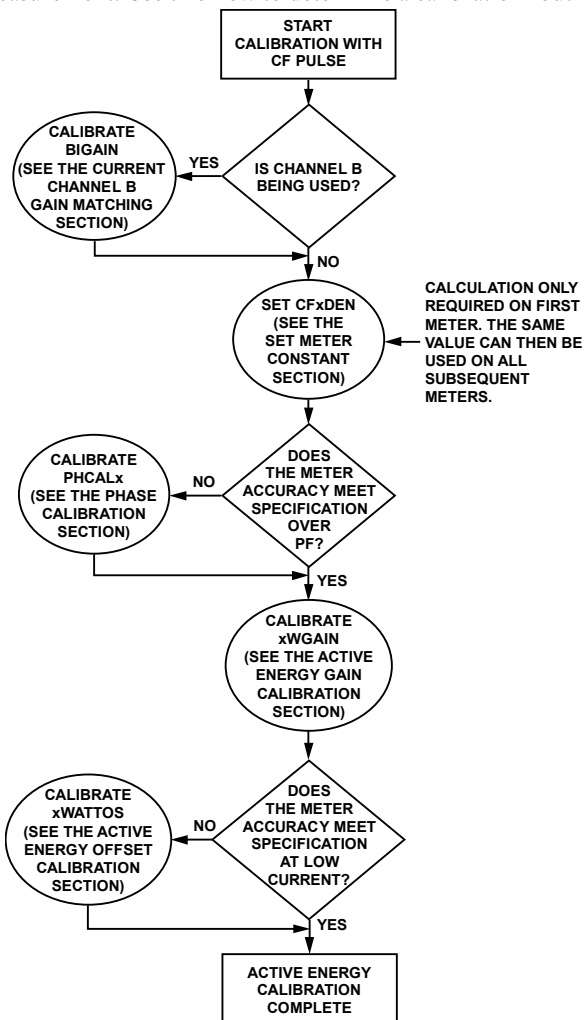


Figure 4. Active Energy Calibration Flow

### CURRENT CHANNEL B GAIN MATCHING USING THE CF OUTPUT

When using the second current input channel, Channel B, it is convenient to match the output to Channel A. Matching these channels results in easier computations because one bit in the energy register and one pulse on the CF output has the same weight on each channel. It is recommended that channel matching be performed as the first calibration step.

To match current Channel B to Channel A, apply the same fixed input current to both channels. Because the meter has not yet been calibrated, it is recommended that the amplitude of the applied signal be between full scale and 100:1. The current rms reading can then be used to determine if there is any error between the two channels. This error can then be corrected using the ADE7953 BIGAIN register (Address 0x28C and Address 0x38C). The following equation describes how to adjust the IRMSB reading to match that in IRMSA using the BIGAIN register:

$$BIGAIN = \left\lceil 0x400000 \times \frac{IRMSA}{IRMSB} \right\rceil$$

If significant reading-to-reading variation is obtained on the rms measurements, additional filtering can be enabled to improve the accuracy of the calibration. This filtering is enabled by setting the PWR\_LPF\_SEL bits in the CONFIG register (Address 0x102) to 11b.

### Set Meter Constant

Using the internal registers of the ADE7953, the CFx pulse output can be configured so that each pulse represents a fraction of a kWh. This relationship is known as the meter constant. Typically, design specifications require a particular meter constant to allow the utility to verify the accuracy of meters from multiple manufacturers. Typical meter constants are 1600 imp/kWh, 3200 imp/kWh, and 6400 imp/kWh. If designing a meter that does not require a specific meter constant, an arbitrary value can be chosen.

The CFx output is configured using the divider, CFxDEN. This divider is calculated based on the meter constant and the nominal scaling on the current and voltage channels.

Assuming that a meter constant of 3200 imp/kWh is required, the expected CFx can be determined under a given load. With a load of 220 V and 10 A at a power factor of 1, the CFx output frequency is calculated as follows:

$$CF_{EXPECTED} = \frac{Meter\ Constant [imp/kWh] \times Load [kW]}{3600 s/h}$$

$$CF_{EXPECTED} = \frac{3200\ imp/kWh \times 220\ V \times 10\ A / 1000 \times \cos(0)}{3600 s/h}$$

$$= 1.95556\ Hz$$

09871-004

Select the CFxDEN to obtain a frequency of 1.9556 Hz under the given load conditions. This can be done by determining the scale on the input pins.

Figure 5 shows a standard voltage channel input network.

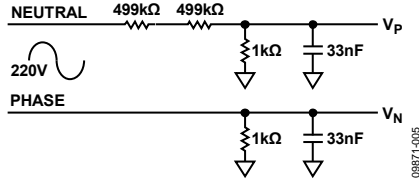


Figure 5. Voltage Channel Inputs

$$V_P = V_{INPUT\_MAX} \times \frac{1 \text{ k}\Omega}{(2 \times 499 + 1) \text{ k}\Omega} =$$

$$(220 \text{ V} \times \sqrt{2}) \times \frac{1}{(2 \times 499 + 1)} = 0.311 \text{ mV}$$

$$V_{AS \% \text{ OF FULL SCALE}} = \frac{0.311}{0.5} \times 100 = 62.29\%$$

With a voltage channel amplitude of 220 V rms, the input is operating at 62.29% of full scale.

Figure 6 shows a typical ADE7953 current channel configuration. With a current channel amplitude of 10 A rms and an internal gain of 16, the input operates at 15.84% of full scale.

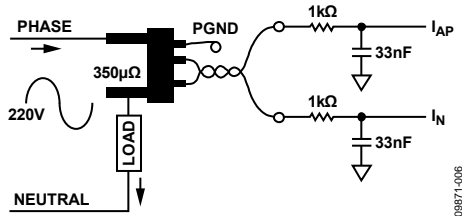


Figure 6. Current Channel Inputs

$$\begin{aligned} V_{ACROSS \text{ SHUNT}} &= I \times R \\ &= (10 \times \sqrt{2}) \times (350 \times 10^{-6}) = 0.0495 \text{ V} \\ &= X \text{ Gain } 16 = 0.0495 \times 16 = 0.079 \text{ V} \end{aligned}$$

$$I_{AS \% \text{ OF FULL SCALE}} = \frac{0.079}{0.5} \times 100 = 15.84\%$$

From the ADE7953 data sheet, the expected CFx pin output frequency with full-scale inputs is 210 kHz.

To obtain 1.9556 Hz with the given 220 V, 10 A input, the CF denominator should be set to 0x2963, as follows:

$$\begin{aligned} CFxDEN &= \\ \frac{\text{Output Freq}_{FULLSCALE} \times V_{OPERATING\%} \times I_{OPERATING\%}}{CF_{EXPECTED}} \\ CFxDEN &= \frac{210 \text{ kHz} \times 62.29\% \times 15.84\%}{1.9556 \text{ Hz}} = 0x2963 \end{aligned}$$

As previously shown, writing 0x2963 to the CFxDEN register sets the CF output to around 1.9556 Hz for the conditions previously described. This CFxDEN setting can now be used on every meter. The active energy gain calibration method provides a finer resolution calibration that should be performed on every meter to ensure that the 1.9556 Hz is precisely met.

### Phase Calibration (Optional)

Phase calibration is required when using a current transformer (CT) to remove any phase shift introduced by the sensor. CTs can add significant phase shift that introduce large errors at low power factors. If using a different type of sensor, such as a low resistance shunt, phase calibration is not always necessary.

The phase calibration is ideally performed with an inductive or capacitive load at a power factor of 0.5. If this load is not available, another power factor can be chosen. For best results, the power factor should be as close to 0.5 as possible. The following equation outlines how the phase compensation is determined:

$$PHCALA = - \left( \frac{\cos^{-1} \left( \frac{CF_{ACTUAL} \cos(\phi)}{CF_{EXPECTED}} \right) - \phi}{360^\circ \times f} \right) \times 893.85 \text{ kHz}$$

where:

$f$  refers to the line frequency.

$\phi$  refers to the angle between the voltage and the current (in degrees).

At 220 V and 10 A at a power factor of 0.5, the expected CFx pin output frequency is exactly half of that previously calculated.

$$\begin{aligned} CF_{EXPECTED} &= \\ \frac{3200 \text{ imp/kWh} \times 220 \text{ V} \times 10 \text{ A} / 1000 \times \cos(60)}{3600 \text{ s/h}} &= 0.9778 \text{ Hz} \end{aligned}$$

Assuming that the measured CF is 0.98 Hz and the line frequency is 50 Hz, the PHCALA compensation can be determined as

$$\begin{aligned} PHCALA &= \\ \left( \frac{\cos^{-1} \left( \frac{0.98 \cos(60)}{0.9778} \right) - 60}{360 \times 50} \right) \times 893.85 \text{ kHz} &= 0xFFFFFC \end{aligned}$$

Note that the PHCALx registers have a 10-bit sign magnitude format, and therefore, the hexadecimal number 0xFFFFFC should be entered as 0x203 into the PHCALx register.

Depending on the current sensors being used on current Channel A and Channel B, different phase calibration values may be required in PHCALA and PHCALB.

### Active Energy Gain Calibration

The purpose of the active energy gain calibration is to compensate for small gain errors due to part-to-part variation in the internal reference voltage and external components such as the time error introduced by the crystal. Gain calibration is required on every meter and is performed with nominal voltage and current inputs at a power factor of 1. As discussed in the Set Meter Constant section, the expected CF output is determined from the meter constant. The actual CF output is measured and the AWGAIN register used to adjust any error. The following formula described this relationship:

$$AWGAIN = \left[ 0x400000 \times \frac{CF_{EXPECTED}}{CF_{ACTUAL}} \right]$$

Using the previous example, at 220 V and 10 A, the expected CF is 1.9556 Hz. Assuming that the actually measured CF is 2.2238 Hz, the AWGAIN is calculated as

$$AWGAIN = \left[ 0x400000 \times \frac{1.9556}{2.2238} \right] = 0x384804$$

The BWGAIN register controls the gain calibration for Channel B. Assuming that the channels are correctly matched, as described in the Current Channel B Gain Matching section, the previous procedure does not need to be repeated for Channel B. Write the value calculated for AWGAIN to BWGAIN for accurate results.

### Active Energy Offset Calibration (Optional)

Active energy offset calibration is only required if accuracy at low loads is outside the required specification prior to offset calibration.

To correct for any voltage-to-current channel crosstalk that may degrade the accuracy of the measurements at low current levels, perform an active energy offset calibration. Apply the minimum expected current signal to allow the offset magnitude to be measured and then removed. Do not perform offset calibration with grounded inputs because a low level signal is necessary to accurately measure the offset.

In this example, an input current of 100 mA is applied to perform the offset calibration. With a voltage channel input of 220 V at a power factor of 1, the expected CFx output frequency is determine as

$$CF_{EXPECTED} = \frac{3200 \text{ imp/kWh} \times 220 \text{ V} \times 0.1 \text{ A} / 1000 \times \cos(0)}{3600 \text{ s/h}} = 0.0195556 \text{ Hz}$$

If the actual CF frequency is 0.020 Hz at 100 mA and 220 V, the percentage error due to offset is determined as

$$\%Error = \frac{0.02000 - 0.0195556}{0.0195556} = 2.273\%$$

The offset in the watt measurement is corrected according to the following equation:

$$\begin{aligned} AWATTOS &= \\ &= -\%Error \times CF_{EXPECTED} \times CFxDEN \times \frac{0x14000000}{128 \times 6.99 \text{ kHz}} \times 2^5 \\ AWATTOS &= \\ &= -0.02273 \times 0.0195556 \times 0x2963 \times \frac{0x14000000}{128 \times 6.99 \text{ kHz}} \times 2^5 \\ &= 0xFF233B \end{aligned}$$

Depending on the board layout and the crosstalk on the meter design, Channel B may need separate offset calibration from Channel A, which can be achieved through the BWATTOS register. BWATTOS corrects the Channel B active energy CF output in the same way because AWATTOS affects the Channel A active energy CF output.

### REACTIVE ENERGY CALIBRATION USING THE CF OUTPUT

#### VAR Gain

Because the ADE7953 active and reactive energy measurements are closely matched, separately reactive energy gain calibration is not always required. In most cases, the values calculated for AWGAIN described in the Active Energy Gain Calibration section can be written to the AVARGAIN register to retain the same meter constant.

If a different meter constant or further calibration is required, the reactive energy can be calibrated separately. Perform reactive energy calibration with nominal inputs at a power factor of 0 to maximize the energy output. Configure the CFx pulse output to output reactive energy. This is done by setting Bit 0 through Bit 7 of the ADE7953 CFMODE register (Address 0x107). The reactive energy calibration is performed in a similar manner to the active energy by first determining the expected CFx output.

$$\begin{aligned} VARCF_{EXPECTED} &= \\ &= \frac{\text{Meter Constant}[\text{imp/kVARh}] \times \text{Load}[\text{kVAR}]}{3600 \text{ s/h}} \end{aligned}$$

The compensation can then be determined by

$$AVARGAIN = \left[ 0x400000 \times \frac{VARCF_{EXPECTED}}{VARCF_{ACTUAL}} \right]$$

The reactive energy gain calibration for Channel B is controlled by the BVARGAIN register. Assuming that the channels are correctly matched, as described in the Current Channel B Gain Matching section, the same value can be written to the BVARGAIN register for accurate results.

## Advanced Reactive Calibration

### VAR Offset—Optional

Reactive energy offset calibration is only required if accuracy at low loads is outside the required specification prior to offset calibration.

To correct for any voltage-to-current channel crosstalk that may degrade the accuracy of the measurements at low current levels, perform a reactive energy offset calibration. A low level current signal at a power factor of 0 must be applied to allow the offset magnitude to be measured and then removed.

In this example, an input current of 100 A is applied to perform the offset calibration. With a nominal voltage channel input of 220 V, the expected CF output frequency is determined as

$$\begin{aligned} VARCF_{EXPECTED} &= \\ \frac{3200 \text{ imp/kWh} \times 220 \text{ V} \times 0.1 \text{ A} / 1000}{3600 \text{ s/h}} &= \\ = 0.0195556 \text{ Hz} \end{aligned}$$

If the actual CF frequency is 0.02050 Hz at 100 mA and 220 V, the percentage error due to offset is determined as

$$\%Error = \frac{0.020500 - 0.0195556}{0.0195556} = 4.829\%$$

The offset in the reactive measurement is corrected according to the following equation:

$$\begin{aligned} AVAROS &= -\%Error \times VARCF_{EXPECTED} \times \\ CFxDEN \times \frac{0x14000000}{128 \times 6.99 \text{ kHz}} \times 2^5 &= \\ AVAROS &= \\ -0.04829 \times 0.0195556 \times 0x2963 \times \frac{0x14000000}{128 \times 6.99 \text{ kHz}} \times 2^5 &= \\ = 0xFFEAF8 \end{aligned}$$

Depending on the board layout and the crosstalk on the meter design, Channel B may need separate offset calibration to Channel A, which can be achieved through the BVAROS register. BVAROS corrects the Channel B reactive energy CF output in the same way because the AVAROS affects the Channel A reactive energy CF output.

## CURRENT AND VOLTAGE RMS USING THE CF OUTPUT

Calibrating the voltage and current rms is only required if the instantaneous rms readings are required. RMS calibration does not affect the performance of the active or reactive energy.

Perform the rms calibration using the instantaneous rms register readings. The readings can be obtained from the IRMSA register, IRMSB register, and the VRMS register. The CFx pulse output is not used for this calibration. For increased stability, synchronize the rms register readings to the ZX measurement. This reduces the effects of ripple in the readings caused by the nonidealities of the internal filtering. See the [ADE7953](#) data sheet for details

on zero-crossing detection. For further stability, additional internal filtering can be enabled to improve the accuracy of the calibration. This filtering is enabled by setting the PWR\_LPF\_SEL bit in the CONFIG register (Address 0x102).

The current and voltage rms readings require gain calibration to compensate for any part-to-part variations. Offset calibration may also be required on every meter to remove crosstalk that may degrade the accuracy of the readings at low signal inputs. There is not an internal gain calibration register for the rms readings, and therefore, the gain adjustment is performed in the microcontroller firmware.

### RMS Gain

As mention previously, both the current and voltage rms gain constants are calculated and implemented in firmware. Along with compensating for part-to-part gain variations, the rms gain constant converts the rms reading in LSBs into a current or voltage value in amps or volts. The voltage and current rms constants are determined under fixed load conditions, by dividing the number of LSBs in the rms register by the amplitude of the input.

$$V \text{ Constant [V/LSB]} = \frac{\text{Voltage Input [V]}}{\text{VRMS[LSBs]}} \times k$$

$$I \text{ Constant [Amps/LSB]} = \frac{\text{Current Input [A]}}{\text{IRMS[LSBs]}} \times k$$

To maintain the full resolution when the conversion is taking place in the firmware, the voltage and current rms constants may be multiplied by a constant, k. The use of a multiplication factor, k, allows resolution to be maintained when converting and storing the rms readings as a hexadecimal number using fixed point multiplication. Converting the reading to the hexadecimal format is required prior to performing a hex-to-binary coded decimal conversion for display purposes.

An example of how the voltage rms register reading can be converted into a value in volts, maintaining resolution of one digit below the decimal point, is provided in the following equation. In this example, 220 V is applied, producing a VRMS register reading of 5400000d.

$$V \text{ Constant} = \frac{220 \text{ V}}{5400000} \times 100 \times 2^{16} = 0x10B$$

The volts/LSB constant is multiplied by a factor of  $100 \times 2^{16}$  to maintain accuracy when using fixed point multiplication. The V constant is 0x10B.



A further example showing the generation of the current rms gain constant is provided in the following equation. In this example, the resulting LCD display measurement is accurate to two digits below the decimal point. A current input of 10 A is applied, resulting in an IRMS reading of 1700000.

$$I \text{ Constant} = \frac{10 \text{ A}}{1700000} \times 1000 \times 2^{16} = 0x181$$

The amps/LSB constant is multiplied by a factor of  $1000 \times 2^{16}$  to maintain the required accuracy during conversion. The resulting I constant is 0x181.

### RMS Offset

To obtain accurate readings at low signal levels, the current and voltage rms offset may have to be calibrated. This calibration is done using the internal VRMSOS and IRMSOS registers that apply an offset prior to the square root function. The compensation factor is determined by applying the following equations:

$$VRMSOS = \frac{VRMS_{EXPECTED}^2 - VRMS_{ACTUAL}^2}{2^{12}}$$

$$IRMSOS = \frac{IRMS_{EXPECTED}^2 - IRMS_{ACTUAL}^2}{2^{12}}$$

As illustrated in Figure 7, the rms offset calibration is based on two points, where the expected reading is derived from the rms measurement with nominal inputs.

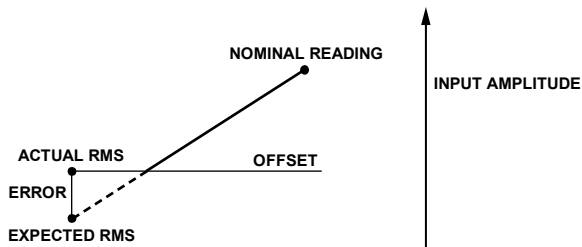


Figure 7. RMS Reading

The Current Channel A rms measurements are specified over a dynamic range of 1000:1. Current Channel B rms and the voltage channel rms measurements are specified over a dynamic range of 500:1. This is the minimum input level at which the measurement is accurate and, hence, the minimum point at which the offset calibration should take place. In this example, the voltage rms offset is calibrated at 175 V, and the current rms offset calibrated at 100 mA. To determine the expected rms reading, take a measurement at the nominal current and the nominal voltage. This reading should then be scaled down to obtain the expected value at the calibration point.

For example:

Reading at  $I_{NOMINAL}$  (10 A) = 1700000

Expected reading at  $I_{CAL}$  (100 mA) =  $(0.1/10) \times 1700000 = 17000$

Actual reading obtained at  $I_{CAL}$  (100 mA) = 17250

Therefore,

$$IRMSOS = \frac{17000^2 - 17250^2}{4096} = 0xF7D6$$

The voltage rms offset is calibrated in a similar manner.

For example:

Reading at  $V_{NOMINAL}$  (220 V) = 5400000

Expected reading at  $V_{CAL}$  (175 V) =  $(175/220) \times 5700000 = 4295454$

Actual reading obtained at  $V_{CAL}$  (175 V) = 4295400

Therefore,

$$VRMSOS = \frac{4295454^2 - 4295400^2}{4096} = 0x113258$$

## APPARENT ENERGY CALIBRATION USING THE CF OUTPUT

### VA Gain

Because the ADE7953 active and apparent energy measurements are closely matched, separate apparent energy gain calibration is not always required. In most cases, the values calculated for AWGAIN in the Active Energy Gain Calibration section can be written to the AVAGAIN register to retain the same meter constant.

If a different meter constant or further calibration is required, the apparent energy can be calibrated separately. Perform apparent energy calibration with nominal inputs at a power factor of 1. Configure the CFx pulse output-to-output apparent energy, which is achieved by setting Bit 0 through Bit 7 of the CFMODE register (Address 0x107). The apparent energy calibration is performed in a similar manner to the active energy calibration by first determining the expected CF output by

$$VACF_{EXPECTED} = \frac{\text{Meter Constant [imp/kVAh]} \times \text{Load [kVA]}}{3600 \text{ s/h}}$$

The compensation can then be determined by

$$AVAGAIN = \left[ 0x400000 \times \frac{VACF_{EXPECTED}}{VACF_{ACTUAL}} \right]$$

Note that the apparent energy gain calibration for Channel B is controlled by the BVAGAIN register. Assuming that the channels are correctly matched, as described in the Current Channel B Gain Matching section, write the same value to the BVAGAIN register for accurate results.

## Advanced Apparent Calibration

### VA Offset—Optional

VA offset calibration is only required if accuracy at low loads is outside the required specification.

Because the apparent energy is derived from the product of the instantaneous voltage and current rms readings, the apparent energy offset through calibration of the IRMS and VRMS offset compensation must be removed. If additional calibration is required or the IRMS and VRMS are not being used, the AVAOS register can be used. The apparent energy offset compensation performs in a similar way to the active and reactive offset compensation and should be performed with a low level current signal at a power factor of 1. The following formula describes how the AVAOS register compensates for errors in the Channel A apparent energy measurement.

AVAOS =

$$-\%Error \times CF_{EXPECTED} \times CFxDEN \times \frac{0x14000000}{128 \times 6.99 \text{ k}\Omega} \times 2^5$$

Note that depending on the board layout and the crosstalk on the meter design, Channel B may need separate offset calibration to Channel A. This can be achieved through the BVAOS register. BVAOS corrects the Channel B apparent energy CF output in the same way as the AVAOS affects the Channel A apparent energy CF output.

## DESIGNING A TAMPER-PROOF METER USING THE CF OUTPUT

### Missing Neutral Calibration

This calibration step is only required when designing an anti-tamper meter, which is required to perform in the absence of a neutral connection. Perform missing neutral calibration after the current rms measurement has been calibrated.

The missing neutral condition is entered when the voltage channel drops below a certain threshold. SAG detection and the zero-crossing timeout can be enabled to detect this event (see the [ADE7953](#) data sheet). Because there is no voltage going to the meter, no current should be consumed at this time. If current is consumed, there is a tamper attack. In this condition, the [ADE7953](#) can measure energy based on the current rms reading, allowing billing to continue. There are two ways to configure

the [ADE7953](#) to operate under this condition. The first is to output the IRMS on the CF output. This can be done using the CFMODE register. The second option is to redirect the IRMS signal to the apparent energy path. This allows the IRMS to be accumulated internally in the APENERGYx register along with providing a CF output. This option is enable by setting Bit 8 and Bit 9 of the ACCMODE register.

To ensure that the CFx pulse weight is maintained under these conditions, CFxDEN is modified to provide the correct meter constant.

When operating in missing neutral mode, the voltage amplitude and phase angle are unknown and therefore have to be assumed. The expected CFx output frequency should once again be based on the meter constant determine in the previous calibration steps, in this case 3200 imp/kWh. For this example, an assumed voltage of 240 V with a phase angle of 30° was used. The expected CF output frequency is determined as before.

$$CF_{EXPECTED} = \frac{\text{Meter Constant [imp/kWh]} \times \text{Load [kW]}}{3600 \text{ s/h}}$$

$$\begin{aligned} CF_{EXPECTED} &= \\ \frac{3200 \text{ imp/kWh} \times 240 \text{ V} \times 10 \text{ A} / 1000 \times \cos(30)}{3600 \text{ s/h}} \\ &= 1.84752 \text{ Hz} \end{aligned}$$

To adjust the CFx output frequency to obtain the missing neutral operating conditions, the CFxDEN has to be scaled according to the new expected CFx frequency.

$$\frac{1}{CFxDEN_{MN}} = \frac{CF_{EXPECTED}}{CF_{ACTUAL}} \times \frac{1}{CFxDEN}$$

For example, assuming that the measured CFx in missing neutral mode is 1.954 Hz, and from previous calculations, the current CFxDEN = 0x2963.

$$\begin{aligned} \frac{1}{CFxDEN_{MN}} &= \frac{1.84752}{1.954} \times \frac{1}{10595} \\ CFxDEN_{MN} &= 0x2BC5 \end{aligned}$$

The missing neutral mode CFxDEN should only be programmed into the CFxDEN register when operating in missing neutral mode.

## CALIBRATING THE INTERNAL ENERGY REGISTERS

This section explains the calibration procedure and calculations when using the internal energy registers. The internal energy registers provide access energy metering measurements via the SPI/I<sup>2</sup>C or UART interface (see the [ADE7953](#) data sheet for more details).

If calibrating using the internal energy registers, use an accurate source. Calibration via the internal registers is typically performed when the CF pulse is not required in the final meter design. Figure 1 shows the relationship between the CF output and energy registers.

### ACTIVE ENERGY CALIBRATION USING THE ENERGY REGISTERS

Figure 8 shows the calibration flow for the active energy measurement. Use this flow to determine a calibration routine.

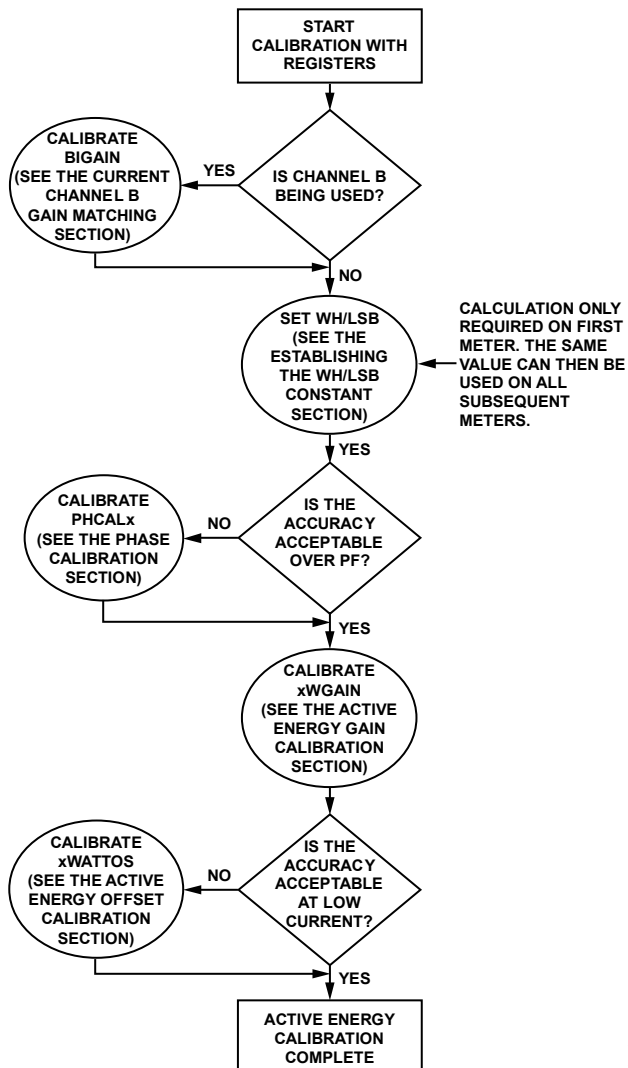


Figure 8. Active Energy Calibration Flow—Registers

### CURRENT CHANNEL B GAIN MATCHING USING THE ENERGY REGISTERS

When using the second current input channel, current Channel B, it is convenient to match the output to Channel A. Matching these channels result in easier computations because one bit in the energy register and one pulse on the CF output have the same weight on each channel. It is recommended that channel matching be performed as the first calibration step.

To match Channel B to Channel A, follow the procedure outlined in the Current Channel B Gain Matching section.

#### Establishing the Wh/LSB Constant—First Meter Only

When calibrating the first meter, determine the Wh/LSB. The Wh/LSB constant is used to set the weighting of each LSB in the active energy register. This constant allows the energy register readings to be converted into real-world values. Once established, the same Wh/LSB meter can be used for each subsequent meter. To determine the Wh/LSB constant, the following formula can be used:

$$Wh/LSB = \frac{Load(W) \times Accumulation Time(sec)}{AENERGYx \times 3600s/h}$$

where:

The *Accumulation Time* is the line-cycle accumulation time. The *AENERGYx* is the energy register reading after this time has elapsed.

For example, if a LINECYC value of 100 half line cycles is set and the frequency of the input signal is 50 Hz, the accumulation time is 1 second ( $0.5 \times (1/50) \times 100$ ). Assuming a load of 220 V and 10 A produces an AENERGYx reading of 20398, the Wh/LSB constant can be calculated as

$$Wh/LSB = \frac{220 V \times 10 A \times \cos(0) \times 1sec}{20398 \times 3600} = 2.9959 \times 10^{-5}$$

Should the user wish to adjust the constant to meet a particular specification or make the constant easier to store, the AWGAIN register can be used. The AWGAIN register can be used to modify the Wh/LSB constant by  $\pm 50\%$ . The AWGAIN register affects the AENERGYA register as shown in the following formula:

$$AWGAIN = \left[ 0x400000 \times \frac{AENERGYA_{EXPECTED}}{AENERGYA_{ACTUAL}} \right]$$

To achieve a different meter constant, alter the AENERGYA reading based on the desired Wh/LSB.

$$AENERGYA_{EXPECTED} = \frac{Load(W) \times Accumulation Time(sec)}{Wh/LSB \times 3600s/h}$$

For example, if it is desirable to alter the previously calculated Wh/LSB constant of  $2.99959 \times 10^{-5}$  to  $3 \times 10^{-5}$  for storing purposes, the desired AENERGYA reading is

$$AENERGYA_{EXPECTED} = \frac{220 \text{ V} \times 10 \text{ A} \times \cos(0) \times 1 \text{ sec}}{3 \times 10^{-5} \times 3600 \text{ s/h}} = 20370 \text{ d}$$

This adjustment can be made using the AWGAIN register as described in the Active Energy Gain Calibration section.

### Phase Calibration (Optional)

Phase calibration is required when using a current transformer, CT, to remove phase shift introduced by the sensor. CTs can add significant phase shift that introduces large errors at low power factors. If using a different type of sensor, such as a low resistance shunt, phase calibration is not always necessary.

The phase calibration is ideally performed with an inductive or capacitive load at a power factor of 0.5. If this load is not available, another power factor can be chosen. For best results, the power factor should be as close to 0.5 as possible. The following equation outlines how the phase compensation is determined, where  $f$  refers to the line frequency and  $\phi$  refers to the angle between the voltage and the current (in degrees).

$$PHCALX = - \left( \frac{\cos^{-1} \left( \frac{AENERGY_{ACTUAL} \cos(\phi)^0}{AENERGY_{EXPECTED}} \right) - \phi^0}{360^0 \times f} \right) \times 893.85 \text{ kHz}$$

For example, at 220 V and 10 A at a power factor of 0.5, the expected AENERGYx reading is exactly half of that previously calculated.

$$AENERGYx_{EXPECTED} = \frac{220 \text{ V} \times 10 \text{ Amps} \times \cos(60) \times 1 \text{ sec}}{3 \times 10^{-5} \times 3600 \text{ s/h}} = 10185 \text{ d}$$

Assuming that the AENERGYx register reading is 10141, and the line frequency is 50 Hz, the PHCALx compensation can be determined as follows:

$$PHCALx = \left( \frac{\cos^{-1} \left( \frac{10141 \times \cos(60)}{10185} \right) - 60}{360 \times 50} \right) \times 893.85 \text{ kHz} = 0x07$$

Note that the PHCALx registers are in 10-bit sign magnitude format.

Depending on the current sensors being used on Channel A and Channel B, different phase calibration values can be required in PHCALA and PHCALB.

### Active Energy Gain Calibration

The purpose of the active energy gain calibration is to compensate for small gain errors due to part-to-part variation in the internal reference voltage and external components such as the time error introduced by the crystal. Gain calibration is required on every meter and is performed with nominal voltage and current inputs at a power factor of 1. For simplicity, it is recommended that all meters be calibrated to use the same Wh/LSB value. Use the following formula to determine the expected reading in the AENERGYA register:

$$AENERGYA_{EXPECTED} = \frac{\text{Load (W)} \times \text{Accumulation Time (sec)}}{\text{Wh/LSB} \times 3600 \text{ s/h}}$$

The actual value can then be read from the AENERGYx register and the AWGAIN register can be used to correct any error. The following formula shows how AWGAIN can be used to adjust the AENERGYA reading:

$$AWGAIN = \left[ 0x400000 \times \frac{AENERGYA_{EXPECTED}}{AENERGYA_{ACTUAL}} \right]$$

Using the previous example, at 220 V and 10 A, the expected AENERGYA reading is 20370. Assuming that the actual AENERGYA reading is 20073, AWGAIN is calculated as

$$AWGAIN = \left[ 0x400000 \times \frac{20370}{20073} \right] = 0x40F26A$$

Note that the gain calibration for Channel B is controlled by the BWGAIN register. Assuming that the channels are correctly matched, as described in the Current Channel B Gain Matching section, the previous procedure does not need to be repeated for Channel B. Write the value calculated for AWGAIN to BWGAIN for accurate results.

### Active Energy Offset Calibration (Optional)

Active energy offset calibration is only required if accuracy at low loads is outside the required specification prior to offset calibration.

To correct for any voltage-to-current channel crosstalk that may degrade the accuracy of the measurements at low current levels, perform active energy offset calibration. A low level current signal must be applied to allow the offset magnitude to be measured and then removed.

When performing offset calibration, it is often required to increase the accumulation time to minimize the resolution error. Because the line-cycle accumulation mode accumulates energy over a fixed time, the result is accurate to  $\pm 1$  LSB. If the number of bits accumulated in the AENERGYx register is small after this time, the  $\pm 1$  LSB error can result in a large error in the output. For example, if only 10 bits are accumulated in the AENERGYx register, the resolution error is 10%. Increasing the number of accumulation bits to 1000 reduces the resolution error to 0.1%.

In the following example, a LINECYC of 1000 half line cycles is set, and an input current of 100 mA is applied. With a voltage channel input of 220 V at a power factor of 1, the expected AENERGYA reading is determined as

$$AENERGYA_{EXPECTED} = \frac{220 \text{ V} \times 0.1 \text{ Amps} \times \cos(0) \times 10 \text{ sec}}{3 \times 10^{-5} \times 3600} = 2037$$

If the actual AENERGYA register reading is 1987 at 100 mA, the percentage error due to offset is determined as

$$\%Error = \frac{1987 - 2037}{2037} = -2.454\%$$

The offset in the watt measurement is corrected according to

$$AWATTOS = -\%Error \times \frac{AENERGYA_{EXPECTED}}{\text{Accumulation Time (sec)}} \times \frac{0x14000000}{128 \times 6.99 \text{ kHz}} \times 2^5$$

$$AWATTOS = 0.02454 \times \frac{2037}{10} \times \frac{0x14000000}{128 \times 6.99 \text{ kHz}} \times 2^5 = 0x00E956$$

Note that, depending on the board layout and the crosstalk on the meter design, Channel B may need a separate offset calibration from Channel A. This can be achieved through the BWATTOS register. BWATTOS corrects the AENERGYB register reading in the same way that the AWATTOS affects the AENERGYA register reading.

## REACTIVE ENERGY CALIBRATION USING THE ENERGY REGISTERS

### VAR Gain

Because the ADE7953 active and reactive energy measurements are closely matched, separate reactive energy gain calibration is not always required. In most cases, the values calculated for AWGAIN in the Active Energy Gain Calibration section can be written to the AVARGAIN register to retain the same VARhr/LSB constant.

Should a different LSB weighting (that is, VARhr/LSB constant) or further calibration be required, the reactive energy can be calibrated separately. Reactive energy calibration should be performed with nominal inputs at a power factor of 0 to maximize the energy output. The reactive energy calibration is performed in a similar manner to the active energy calibration by first determining the expected RENERGYx output.

$$RENERGYx_{EXPECTED} = \frac{\text{Load (VAR)} \times \text{Accumulation Time (sec)}}{\text{VARhr / LSB} \times 3600 \text{ s/h}}$$

The compensation can then be determined by

$$AVARGAIN = \left[ 0x400000 \times \frac{RENERGYA_{EXPECTED}}{RENERGYA_{ACTUAL}} \right]$$

Note that the reactive energy gain calibration for Channel B is controlled by the BVARGAIN register. Assuming that the channels are correctly matched, as described in the Current Channel B Gain Matching section, the same value can be written to the BVARGAIN register for accurate results.

### Advanced Reactive Calibration

#### VAR Offset—Optional

Reactive energy offset calibration is only required if accuracy at low loads is outside the required specification prior to offset calibration.

To correct for any voltage-to-current channel crosstalk that may degrade the accuracy of the measurements at low current levels, reactive energy offset calibration is performed. A low level current signal at a power factor of 0 must be applied to allow the offset magnitude to be measured and then removed.

When performing offset calibration, it is often required to increase the accumulation time to minimize the resolution error. Because the line-cycle accumulation mode accumulates energy over a fixed time, the result is accurate to  $\pm 1$  LSB. If the number of bits accumulated in the RENERGYx register is small after this time, the  $\pm 1$  LSB error can result in a large error in the output. For example, if only 10 bits are accumulated in the RENERGYx register, the resolution error is 10%. Increasing the number of accumulation bits to 1000 reduces the resolution error to 0.1%. In this example, a LINECYC of 1000 half line cycles is set, and an input current of 100 mA is applied. With a voltage channel input of 220 V at a power factor of 0, the expected RENERGYA reading is determine as

$$RENERGYA_{EXPECTED} = \frac{220 \text{ V} \times 0.1 \text{ Amps} \times \sin(90) \times 10 \text{ sec}}{3 \times 10^{-5} \times 3600} = 2037d$$

If the actual RENERGYA reading is 2044, the percentage error due to offset is determine as

$$\%Error = \frac{2044 - 2037}{2037} = 0.343\%$$

The offset in the reactive energy measurement is corrected according to the following equations:

$$AVAROS = -\%Error \times \frac{RENERGYA_{EXPECTED}}{\text{Accumulation Time (sec)}} \times \frac{0x14000000}{128 \times 6.99 \text{ kHz}} \times 2^5$$

$$AVAROS = -0.00343 \times \frac{2037}{10} \times \frac{0x14000000}{128 \times 6.99 \text{ kHz}} \times 2^5 = 0xFFDF3Fh$$

Note that, depending on the board layout and the crosstalk on the meter design, Channel B may need separate a offset calibration from Channel A. This can be achieved through the BVAROS register. BVAROS corrects the RENERGYB register reading in the same way that the AVAROS register affects the RENERGYA register reading.

## CURRENT AND VOLTAGE RMS USING THE ENERGY REGISTERS

See the Current and Voltage RMS section for details on how to calibrate the IRMSA, IRMSB, and VRMS measurements.

## APPARENT ENERGY CALIBRATION USING THE ENERGY REGISTERS

### VA Gain

Because the [ADE7953](#) active and apparent energy measurements are closely matched, separate apparent energy gain calibration is not always required. In most cases, the values calculated for AWGAIN in the Active Energy Gain Calibration section can be written to the AVAGAIN register to retain the same VAhr/LSB meter constant.

Should a different LSB weighting (that is, VAhr/LSB constant) or further calibration be required, the apparent energy can be calibrated separately. Perform apparent energy calibration with nominal inputs at a power factor of 1. The apparent energy calibration is performed in a similar manner to the active energy calibration by first determining the expected energy reading.

$$\frac{APENERGYA_{EXPECTED}}{Load (VA) \times Accumulation Time (sec)} = \frac{VAhr / LSB \times 3600s/h}{}$$

The compensation can then be determined by

$$AVAGAIN = \left[ 0x400000 \times \frac{VACF_{EXPECTED}}{VACF_{ACTUAL}} \right]$$

Note that the apparent energy gain calibration for Channel B is controlled by the BVAGAIN register. Assuming that the channels are correctly matched, as described in the Current Channel B Gain Matching section, the same value can be written to the BVAGAIN register for accurate results.

## Advanced Apparent Calibration

### VA Offset—Optional

VA offset calibration is only required if accuracy at low loads is outside the required specification.

Because the apparent energy is derived from the product of the instantaneous voltage and current rms readings, remove the apparent energy offset through calibration of the IRMS and VRMS offset compensation. If additional calibration is required or the IRMS and VRMS measurements are not used, the AVAOS register can be used. The apparent energy offset compensation is performed in a similar way to the active and reactive offset compensation and should be performed with a low level current signal at a power factor of 1. The following formula describes how the AVOS register compensates for errors in the Channel A apparent energy measurement.

$$AVAOS = -\%Error \times \frac{APENERGYA_{EXPECTED}}{Accumulation Time (sec)} \times \frac{0x14000000}{128 \times 6.99 \text{ kHz}} \times 2^5$$

Note that, depending on the board layout and the crosstalk on the meter design, Channel B may need a separate offset calibration from Channel A. This can be achieved through the BVAOS register. BVAOS corrects the APENERGYB register reading in the same way that the AVAOS register affects the APENERGYA register reading.

## NOTES

## NOTES

I<sup>2</sup>C refers to a communications protocol originally developed by Philips Semiconductors (now NXP Semiconductors).