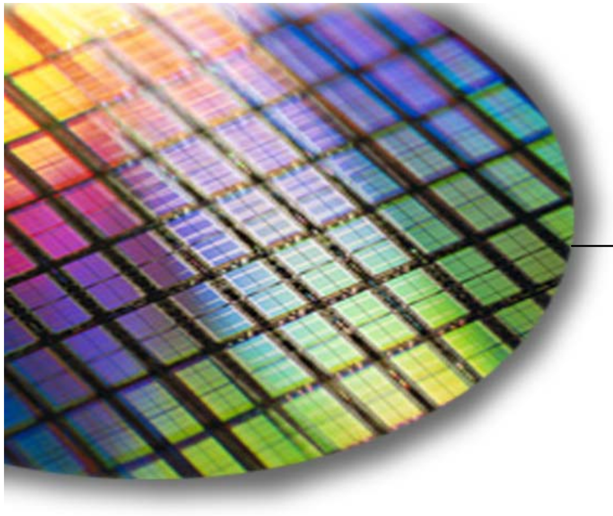


The World Leader in High-Performance Signal Processing Solutions

Calibrating the ADE7754 for Watt, RMS and VA measurements

Feb 17, 2003

ANALOG DEVICES

Agenda

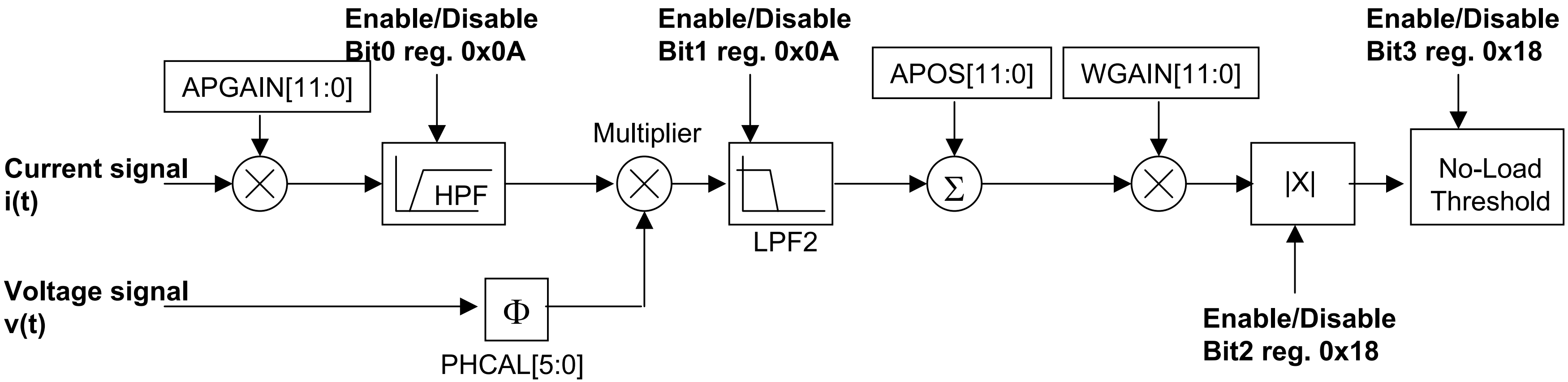
- Watt-hour Calibration
  - Signal path and functionality
  - Gain calibration
  - Offset Calibration
  - Phase calibration
- RMS Calibration
  - Signal path and functionality
  - Offset Calibration
- VA-hour Calibration
  - Signal path and functionality
  - Gain calibration
- Reactive Energy
  - Theory of Operation
  - ADE7754 implementation

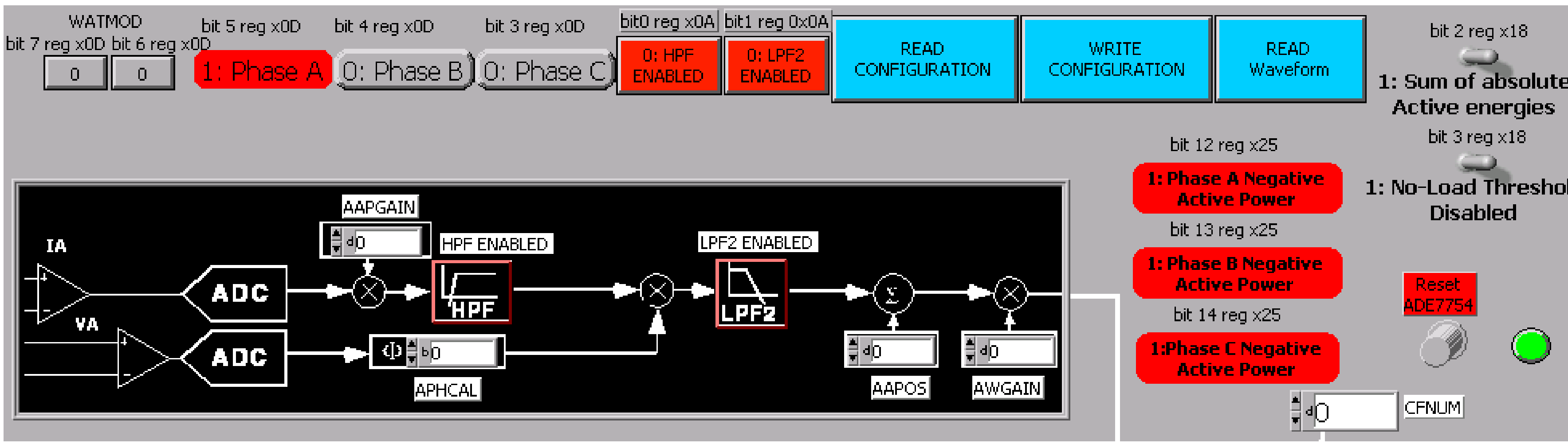
The World Leader in High-Performance Signal Processing Solutions

Watt-Hour Calibration

ANALOG DEVICES

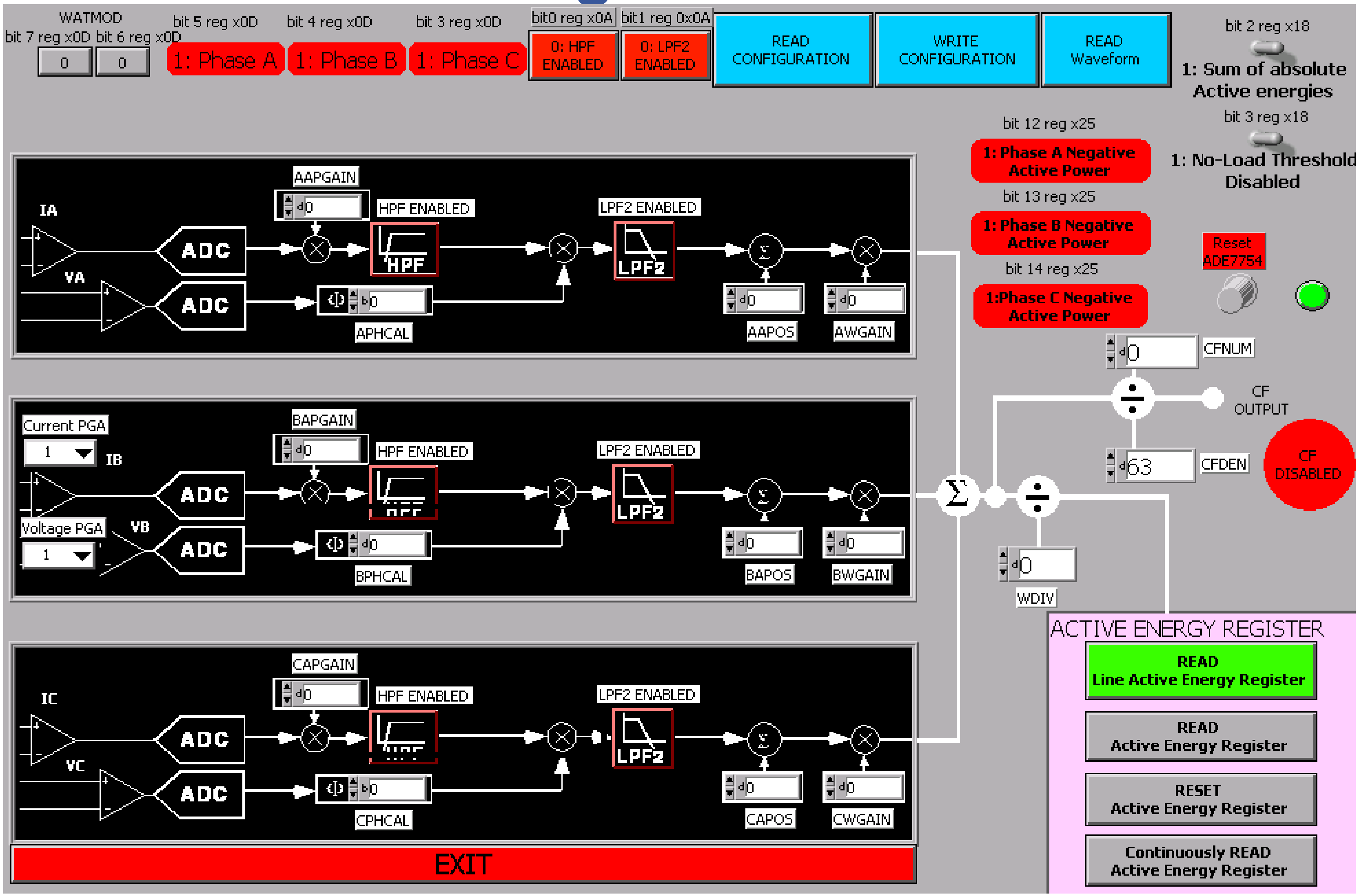
ADE7754 Watt-hour signal path



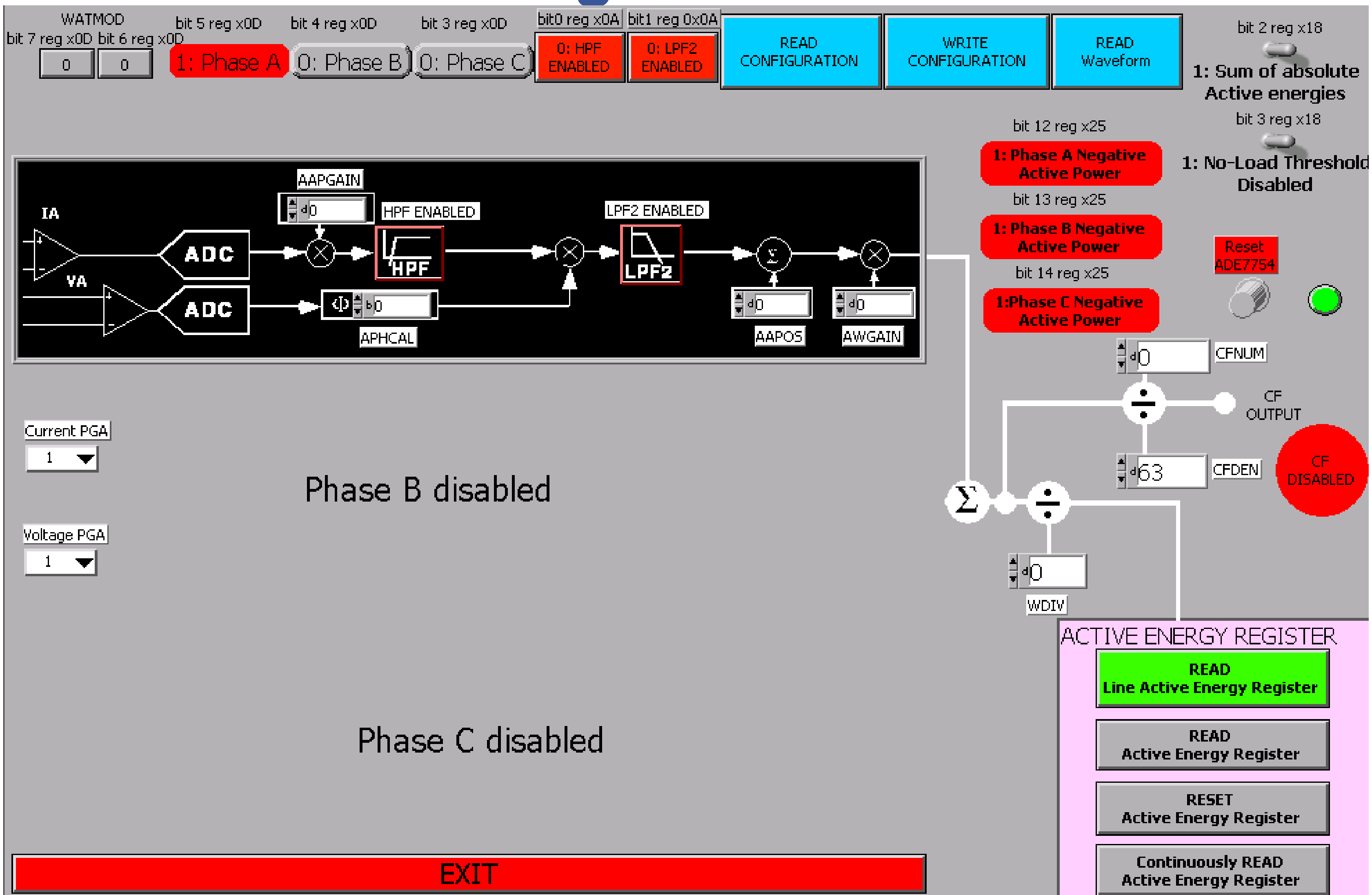


ANALOG DEVICES

Total Watt-hour Signal Path



Total Watt-hour Signal Path

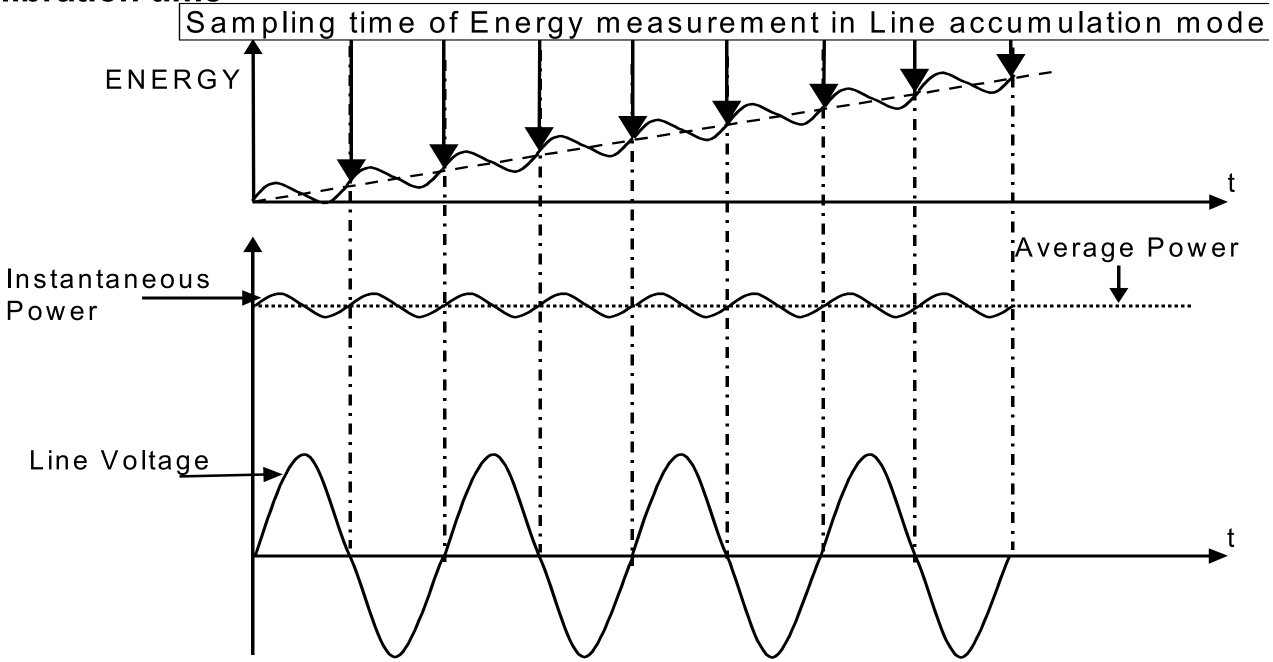


Total Watt-hour Signal Path

- 2 independent Total Watt-Hour signal paths:
  - AENERGY
  - LAENERGY (accurate if only one phase is selected)
- Bit3-5 of WATMODE register (0x0D) select input phases for AENERGY register and CF pulse output
- Bit0-2 of WATMODE register (0x0D) select input phases for LAENERGY register
- Frequency output CF generated based on AENERGY configuration
  - Bit2 of OPMODE register (0x0A) enable/disable CF output
- Under same conditions: AENERGY = LAENERGY/4
- Reverse active power information per phase available in bitC-E of CFNUM register (0x25)

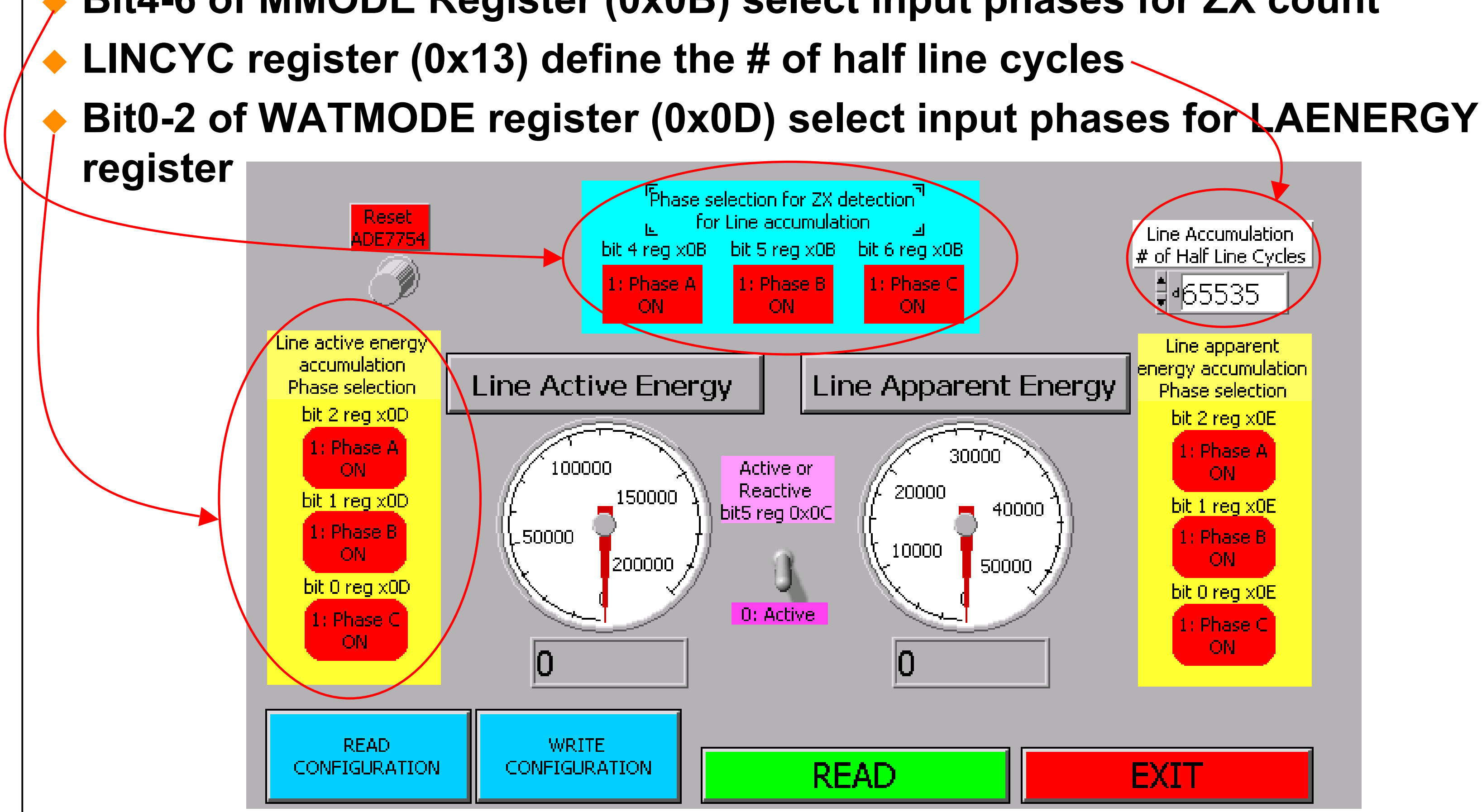
LAENERGY accumulation

- Principle: Accumulation of the Active Energy over N half line cycles (<65535)
  - If bit A of IRQMASK register (0x0F) is set => IRQ goes Low when finished
- Benefits:
  - Cancel the ripple frequency effect (2 x line freq) in Energy Measurement
  - Shorten calibration time



LAENERGY configuration

- Bit4-6 of MMODE Register (0x0B) select input phases for ZX count
- LINCYC register (0x13) define the # of half line cycles
- Bit0-2 of WATMODE register (0x0D) select input phases for LAENERGY register



Watt-Hour GAIN Calibration

- **Gain calibration:**
  - **Meter to meter gain adjustment**
  - **Phase to phase input gain matching**
  - **Pulse output rate**
  - **Wh/LSB constant**

- **CF gain adjustment:**

$$CF = CF_{initial} \times \frac{CFNUM[11:0]}{CFDEN[11:0]} \times \left(1 + \frac{WGAIN[11:0]}{2^{12}}\right)$$

- **AENERGY/LAENERGY Gain adjustment:**

$$AENERGY = AENERGY_{initial} \times \frac{1}{WDIV[11:0]} \times \left(1 + \frac{WGAIN[11:0]}{2^{12}}\right)$$

Relationship between CF and LAENERGY

$$CF(Hz) = \frac{LAENERGY}{4 \times \text{Accumulation } Time(s)} \times \frac{CFNUM}{CFDEN} \times WDIV \times \left(1 + \frac{WG}{2^{12}}\right)$$ Eq. 1

With

$$Accumulation\ time(s) = \frac{LINCYC[15:0] \times Line\ Period}{2 \times \#\ of\ \ phase\ selected}$$ Eq. 2

- **Line Period can be read from the ADE7754: Period register (0x07)**

  Phase input selected with Bit0-1 and 4-6 of MMODE register (0x0B)

  Bit weight: 2.4µs/LSB at CLKIN=10MHz (T_{CLKIN}/24)

$$Line\ Period(s) = Period\ \text{Register} \times 2.4 \cdot 10^{-6}$$

Conversion of AENERGY value to Wh

- AENERGY is an Energy register
  - One constant is sufficient to convert it to Wh

$$Wh = AENERGY \times Wh/LSB \text{ constant}$$

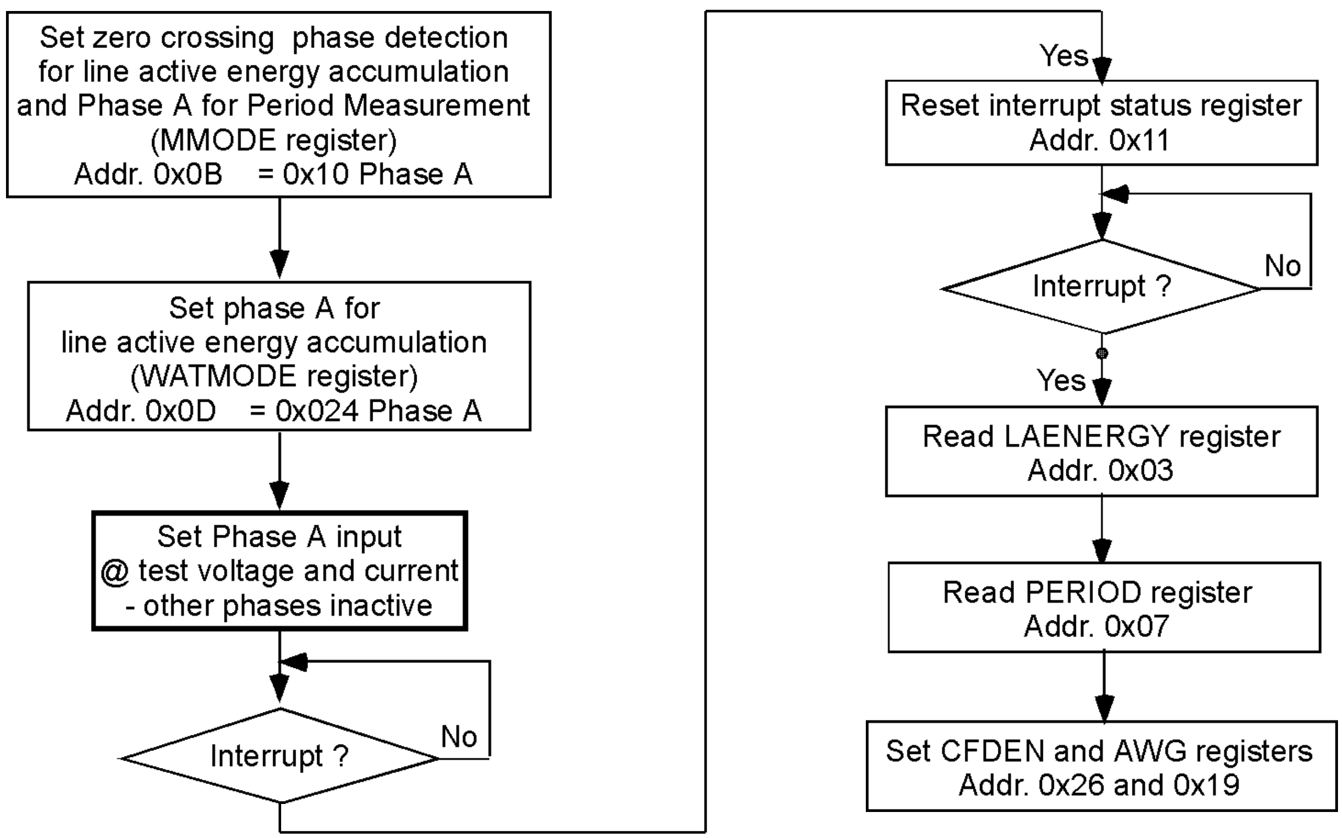
  - To calibrate Wh/LSB constant:
    - Known integration time
    - Known Load (W = V x I)
  - Wh/LSB constant can be determined with LAENERGY test:

$$\frac{Wh}{LSB}\text{constant} = \frac{W \times \frac{Accumulation\ time(s)}{3600}}{LAENERGY/4} \qquad \text{Eq. 3}$$

Where Accumulation time is given by Eq. 2

ANALOG DEVICES

Watt-Hour GAIN calibration example: Procedure



Watt-Hour GAIN calibration example: Configuration

	Phase A	Phase B	Phase C
MMODE (0x0B)	0x10	0x21	0x42
WATMODE (0x0D)	0x24	0x12	0x09
LINCYC (0x13)	0d200		
MASK (0x0F)	0x0400		

Watt-Hour GAIN calibration example: CF calibration

- **Gain adjustment by comparison with expected CF frequency**
  - **With 3200 imp/kWh ; Itest = 10A ; Vtest = 240V ; Line freq = 50Hz**

$$CF_{\text{expected}} = \frac{3200 \times 10 \times 240}{1000 \times 3600} = 2.1333\,Hz$$

- **ADE7754 CF frequency:**
  - **LAENERGY = 38760 with LINCYC = 200**
  - **Period register = 8336 => Accumulation time = 2.0006s**

$$CF(Hz) = \frac{38760 \times 2}{4 \times 8336 \times 2.4 \cdot 10^{-6} \times 200} = 4843.45\,Hz$$

From Eq. 1

- **Gain adjustment: CFDEN, WGAIN**

$$CFDEN = INT\left(\frac{4843.45}{2.1333}\right) = 2270$$

$$WGAIN = \left(\frac{2.1333}{\frac{4843.45}{2270}} - 1\right) \times 2^{12} = -1$$

Watt-Hour GAIN calibration example: Wh/LSB calibration

- **When CF is calibrated, AENERGY and LAENERGY registers will give the same value from design to design**

$$LAENERGY = 38760 \times \left(1 - \frac{1}{2^{12}}\right) = 38751$$

With Itest = 10A ; Vtest = 240V and accumulation time = 2s

- **Wh/LSB constant from previous test:**

$$Wh/LSB = \frac{240 \times 10 \times 8336 \times 2.4 \cdot 10^{-6} \times 200}{3600 \times {}^{38751}\!/_{4}} = 0.2753 \cdot 10^{-3}\,Wh/LSB$$

From Eq. 3

Watt-Hour OFFSET Calibration

- Offset calibration for:
  - Outstanding performances over wide dynamic range (10,000:1)
- 2 measurements at PF=1 needed:
  - Nominal current for reference: I_1
  - Lowest current specified for correction: I_2

$$Energy\ Offset = \frac{LAENERGY_2 \times I_1 - LAENERGY_1 \times I_2}{I_1 - I_2} \qquad \text{Eq. 4}$$

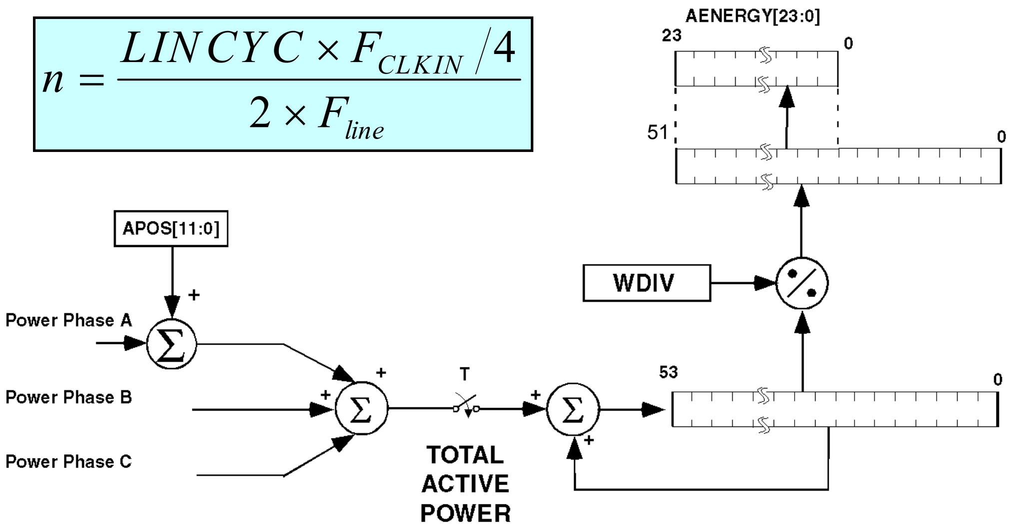
Watt-Hour OFFSET Calibration

- ADE7754 provides Active Power offset correction per phase
  - APOS is added each time the Total active power is accumulated in AENERGY (every CLKIN/4)

$$LAENERGY\ \ Offset = \frac{n \times APOS}{2^{28}} \qquad \text{Eq. 5}$$

Where n is the number of times APOS is added within a period of time

$$n = \frac{LINCYC \times F_{CLKIN}/4}{2 \times F_{line}}$$



Watt-Hour OFFSET calibration: Example

- **At 10A, with LINCYC=200: LAENERGY=38751**
- **At 10mA, with LINCYC=200 => LANERGY≅39**
  - **1 LSB variation at this level => 2.5% error**
  - **LINCYC is too small to make an accurate offset compensation**

  - **With LINCYC=10320 at 10mA => LANERGY=2041=$LAENERGY_2$**
    - **1 LSB variation represents .05% error**
    - **At 10A: LAENERGY=1999528=$LAENERGY_1$**

$$Energy\ Offset = \frac{2041 \times 10 - 1999528 \times 0.01}{10 - 0.01} = 41$$

From Eq. 4

    - **n=10320*Line Period/2/(CLKIN/4)=258082560**

$$APOS = -\frac{Energy\ Offset \times 2^{28}}{n} = -\frac{41 \times 2^{28}}{258082560} = -43$$

From Eq. 5

Watt-Hour PHASE Calibration

- Phase calibration for:
  - Compensation of phase shift from CT to CT
- 2 Measurements needed:
  - Nominal current @ PF=1: W1
  - Nominal current @ PF=0.5 Inductive Load: W2

$$Error = \frac{W_2 - W_1/2}{W_1/2}$$

$$Phase\ Error(°) = -\mathrm{Arcsin}\left(\frac{Error}{\sqrt{3}}\right)$$

Eq. 6

Watt-Hour PHASE Calibration

- **ADE7754 provides phase calibration per phase:**
  - **ADE7754's phase calibration is a time delay:**

$$Delay = PHCAL\ \ register \times 1.2\mu s$$

$$Phase\ Correction\left(°\right) = Delay \times 360° \times \frac{1}{Period\left(s\right)}$$

Dynamic range: +/-0.34° at 50Hz

  - **Period can be measured with ADE7754's Period register**

Period (s) = PERIOD register x 2.4μs

$$Phase\ Correction\left(°\right) = -Phase\,Error$$

$$\Rightarrow PHCAL\ \ \text{Register} = \text{Arcsin}\left(\frac{Error}{\sqrt{3}}\right) \times \frac{PERIOD\ \text{Register} \times 2}{360°}$$

Eq. 7

Watt-Hour PHASE Calibration: Example

- At 10A, PF=1 ; 50Hz with LINCYC=200
  - PF=1: LAENERGY=38751
  - PF=0.5 Inductive: LAENERGY = 19442

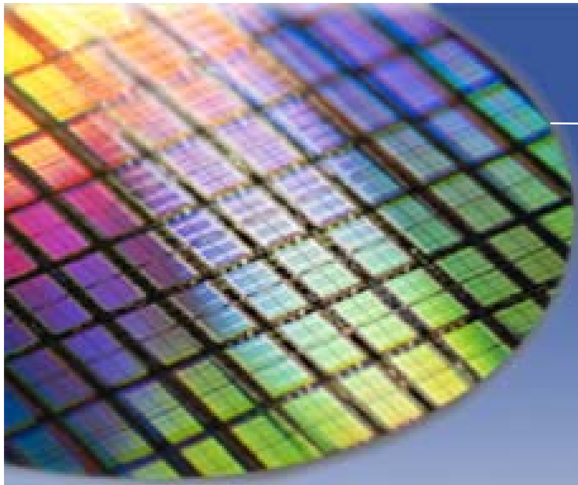
$$Error = \frac{19442 - {}^{38751}\!/_{2}}{{}^{38751}\!/_{2}} = 0.344\%$$

$$Phase\ Error(^\circ) = -\mathrm{Arcsin}\left(\frac{0.00344}{\sqrt{3}}\right) = -0.11^\circ$$

From Eq. 6

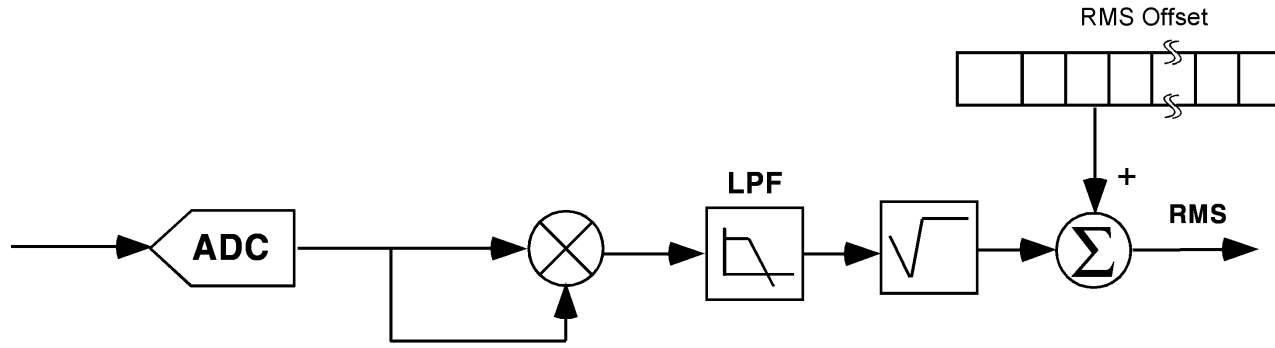
$$PHCAL\ \ \mathrm{Register} = 0.11 \times \frac{8336 \times 2}{360^\circ} = 5$$

From Eq. 7



RMS Calibration

ADE7754 RMS: Theory of operation



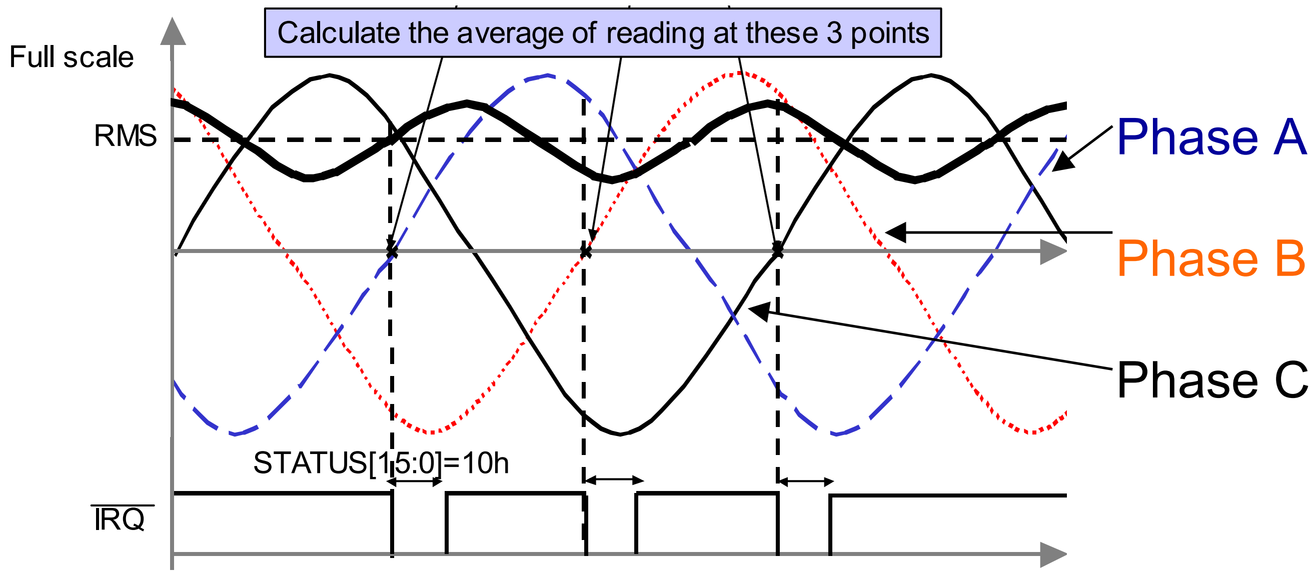
- The input is squared in a digital multiplier

$$v^2(t) = \sqrt{2}.V\sin(\omega t) \times \sqrt{2}.V\sin(\omega t) = V^2 - V^2 \cdot \cos(2\omega t)$$

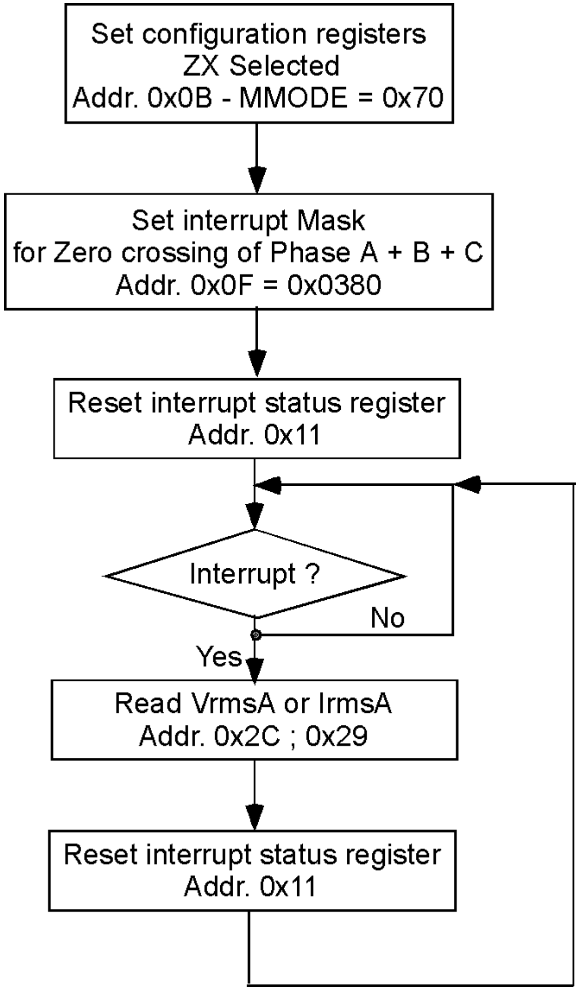
- The SQUARE of the RMS value is extracted from $V^2(t)$ by an LPF
- The square root of the output of the LPF gives the true RMS value
- An offset correction is provided to cancel noise and offset contributions from the input

ADE7754 RMS Register Reading

- Since the LPF is not perfect, ripple noise from 2ω term is present in the rms measurement
- Synchronize rms reading with zero crossings of voltage input from each phase to minimize this noise effect

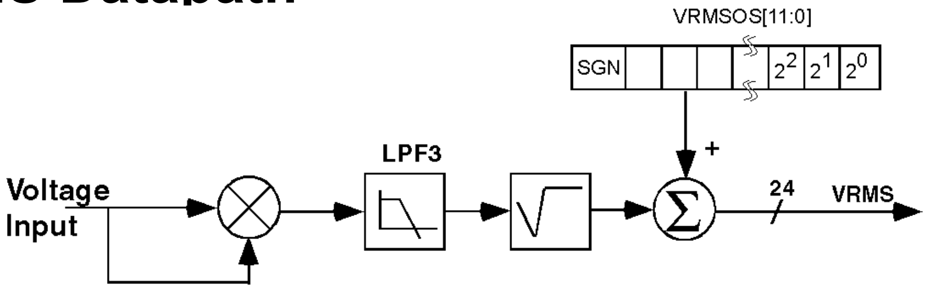


ADE7754 RMS Reading Micro Routine Flowchart

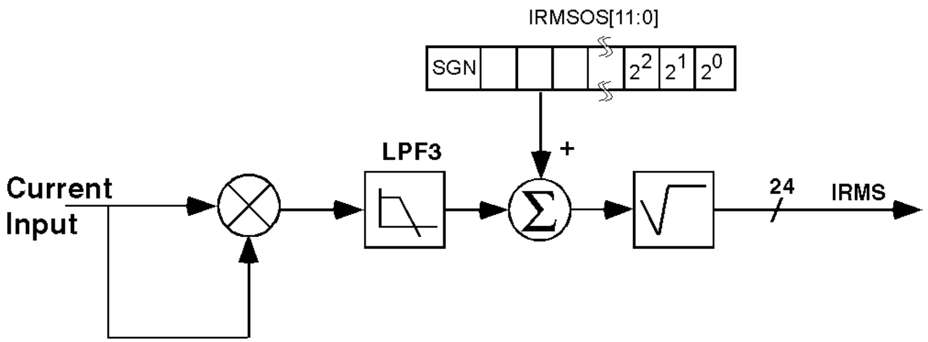


RMS Signal Processing Datapaths for Voltage and Current Channels

- **Voltage RMS Datapath**



- **Current RMS Datapath**



Voltage RMS Offset Compensation

- Voltage RMS compensation is performed after the square root:

$$V_{rms} = V_{rms0} + 64 \times VRMSOS$$

where V_{rms0} is the rms measurement without offset correction

- Voltage rms calculation is linear from FS to FS/20
- To measure the V_{RMS} offset (VRMSOS), measure rms values at two different voltage levels (e.g. $V_{nominal}$ and $V_{nominal}/10$)

$$VRMSOS = \frac{1}{64} \times \frac{V_1 \times V_{rms2} - V_2 \times V_{rms1}}{V_2 - V_1} \quad \text{Eq. 8}$$

where V_{rms1} and V_{rms2} are rms register values without offset correction for input V_1 and V_2 respectively

Note: To minimize noise, synchronize each reading with zero crossing of voltage input in each phase and take the average of these readings

Current RMS Offset Compensation

- Current RMS compensation is performed before the square root:

$$I_{rms}{}^2 = I_{rms0}{}^2 + 32768 \times IRMSOS$$

where I_{rms0} is the rms measurement without offset correction

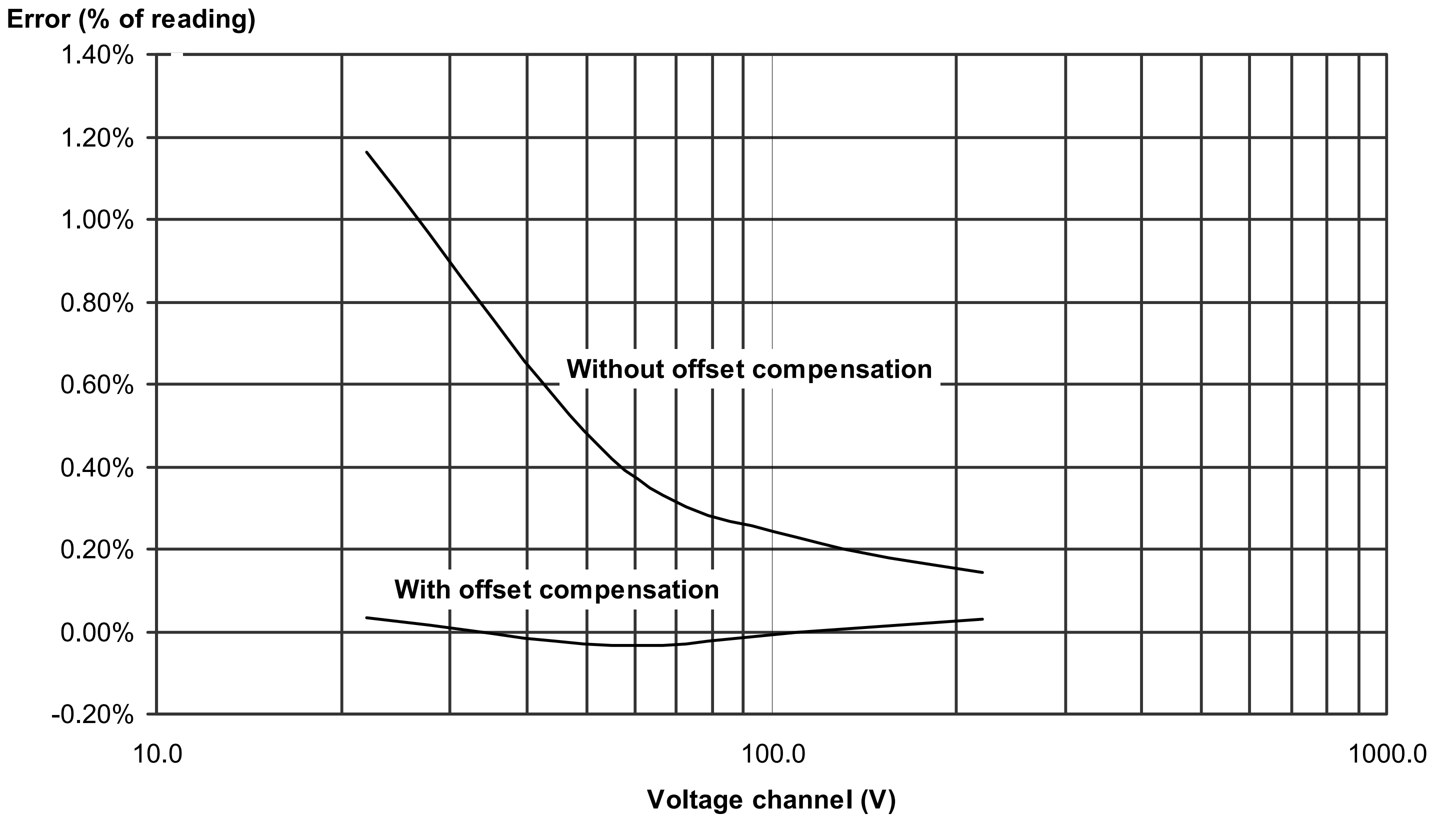
- Current rms calculation is linear from FS to FS/100
- To measure the I_{RMS} offset (IRMSOS), measure rms values at two different current levels (e.g. I_{test} and I_{max}/100)

$$IRMSOS = \frac{1}{32768} \times \frac{I_1{}^2 \times I_{rms2}{}^2 - I_2{}^2 \times I_{rms1}{}^2}{I_2{}^2 - I_1{}^2} \qquad \text{Eq. 9}$$

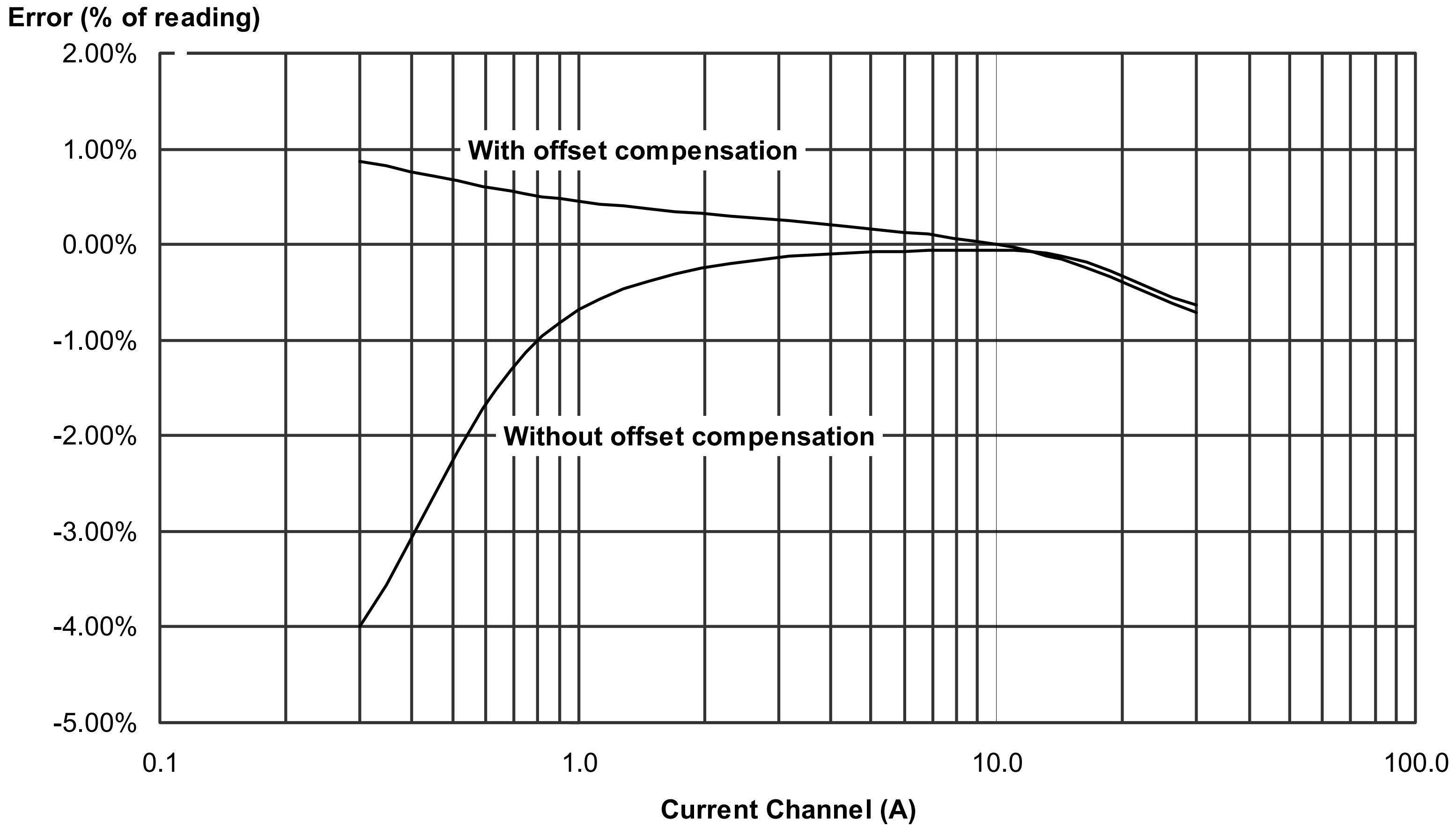
where I_{ms1} and I_{rms2} are rms register values without offset correction for input I_1 and I_2 respectively

Note: To minimize noise, synchronize each reading with zero crossing of voltage input in each phase and take the average of these readings

Voltage RMS offset correction: Example

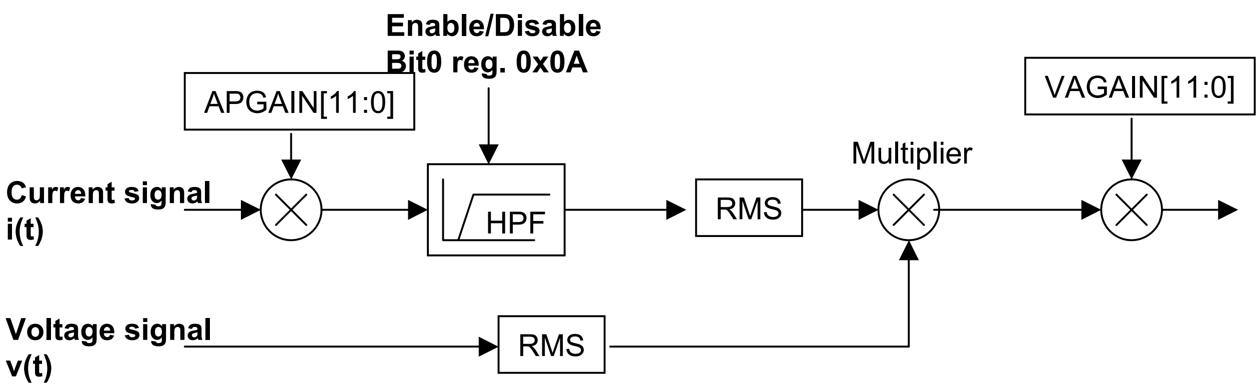


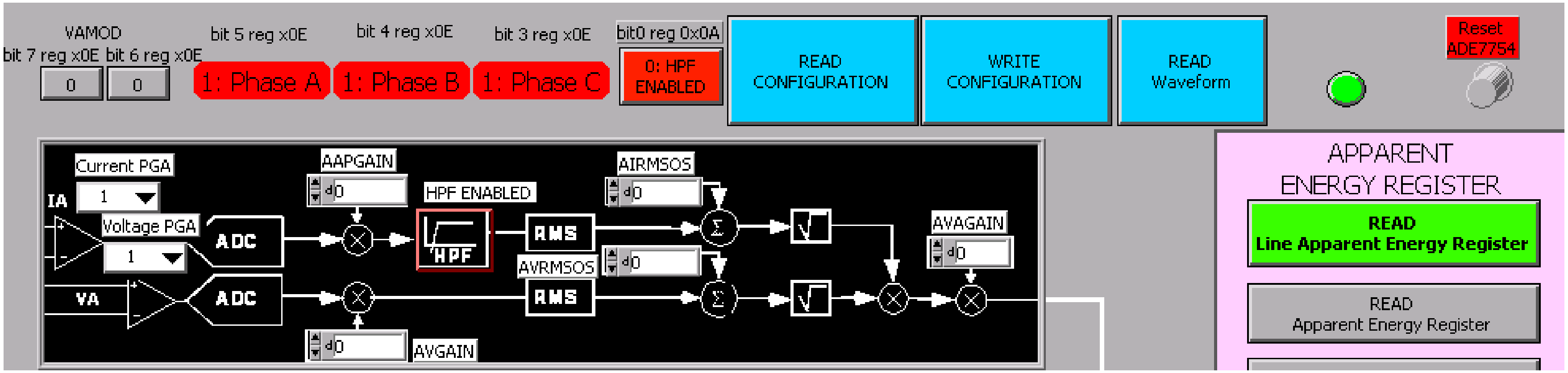
Current RMS offset correction: Example



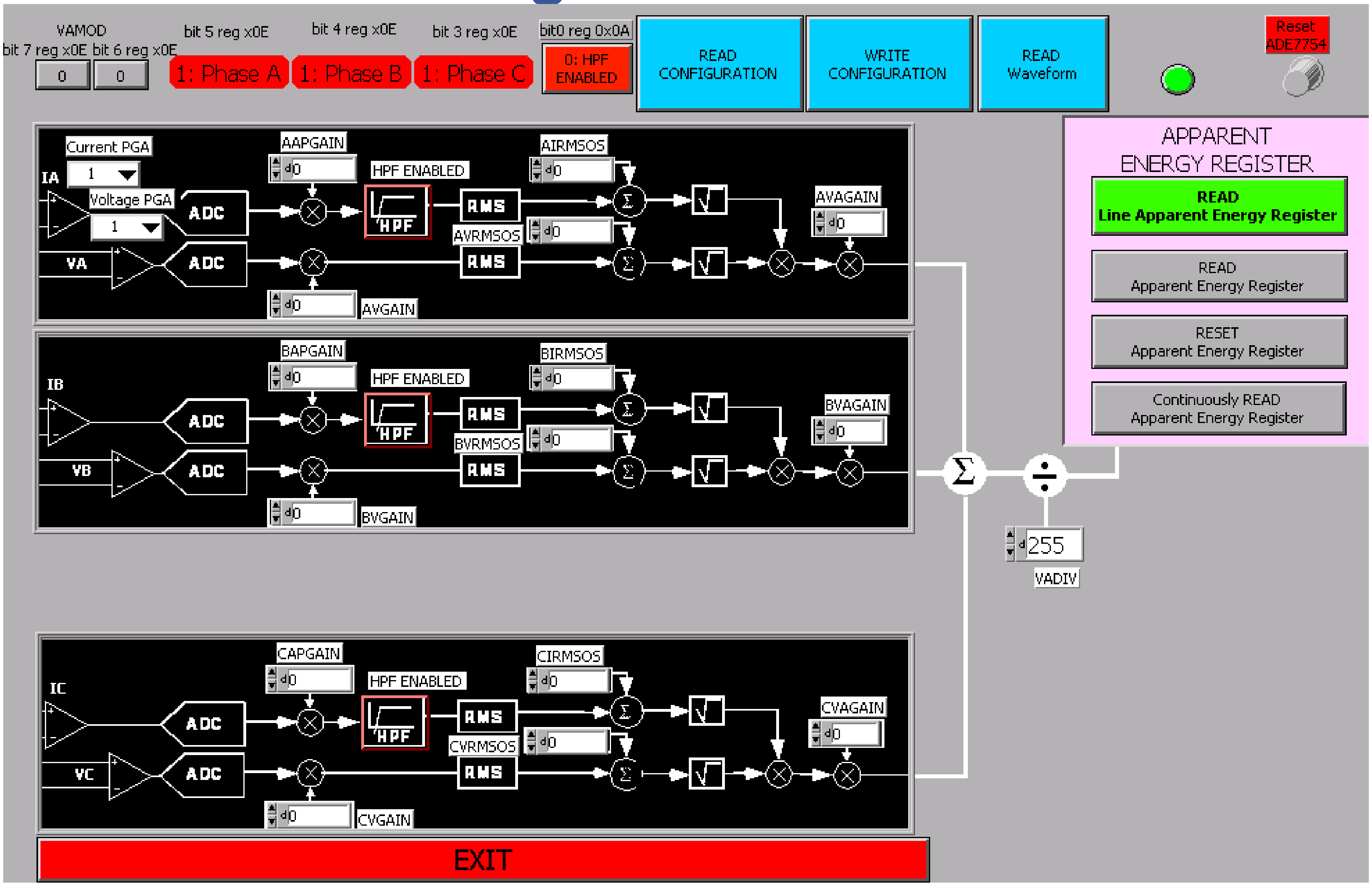
VA-Hour Calibration

ADE7754 VA-Hour Signal Path

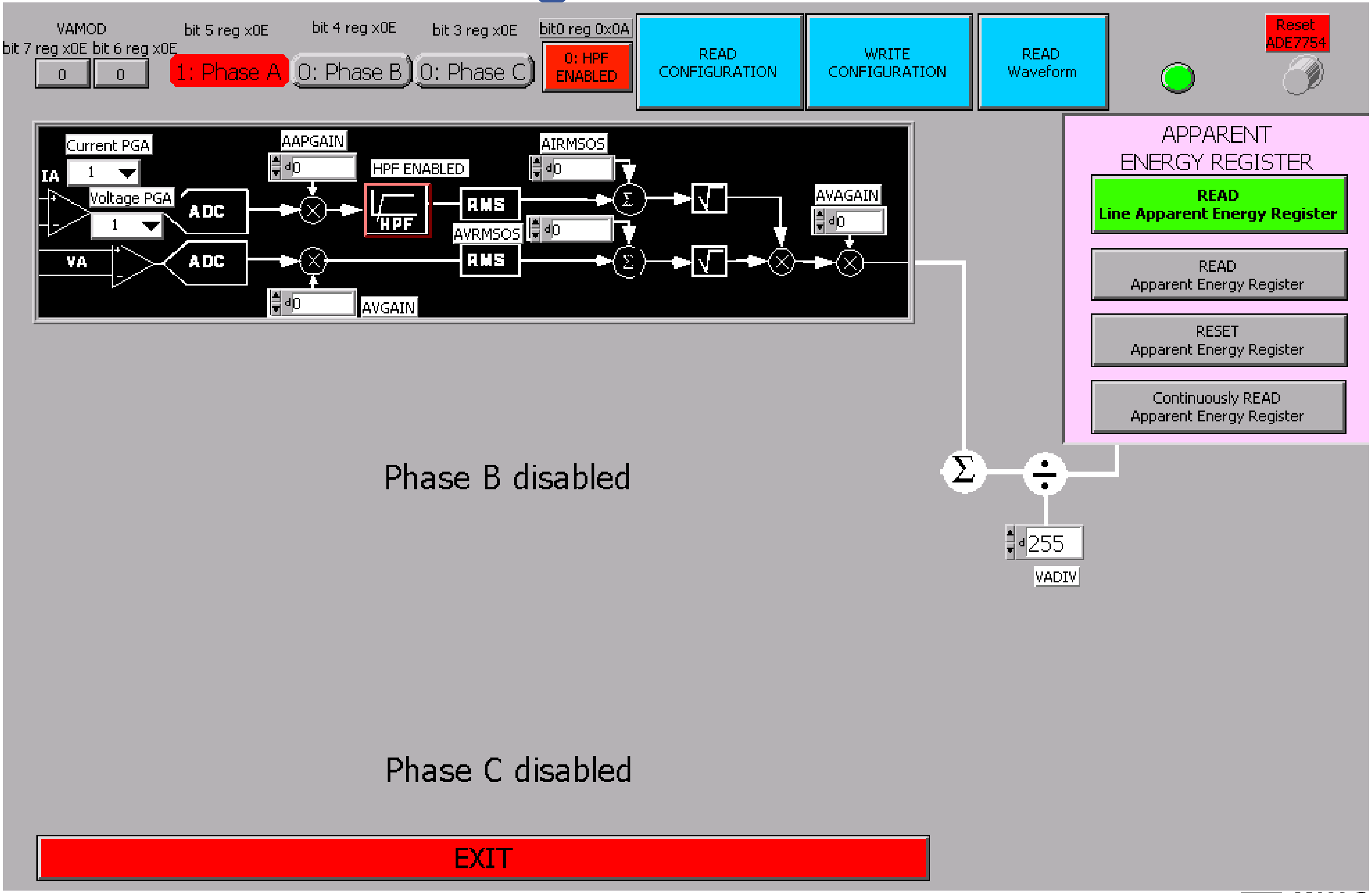




Total VA-Hour Signal Path



Total VA-Hour Signal Path

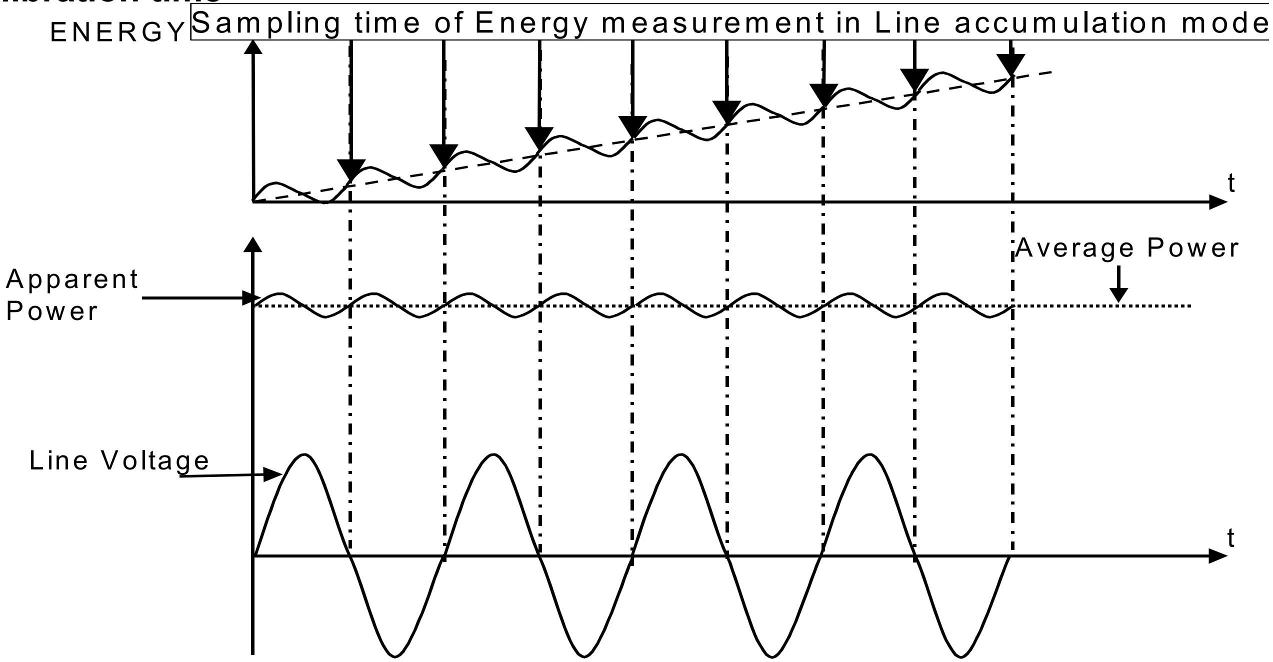


Total VA-Hour Signal Path

- 2 independent Total Apparent hour signal paths:
  - VAENERGY
  - LVAENERGY (see VAR)
- Bit3-5 of VAMODE register (0x0E) select input phases for VAENERGY register
- Bit0-2 of VAMODE register (0x0E) select input phases for LVAENERGY register

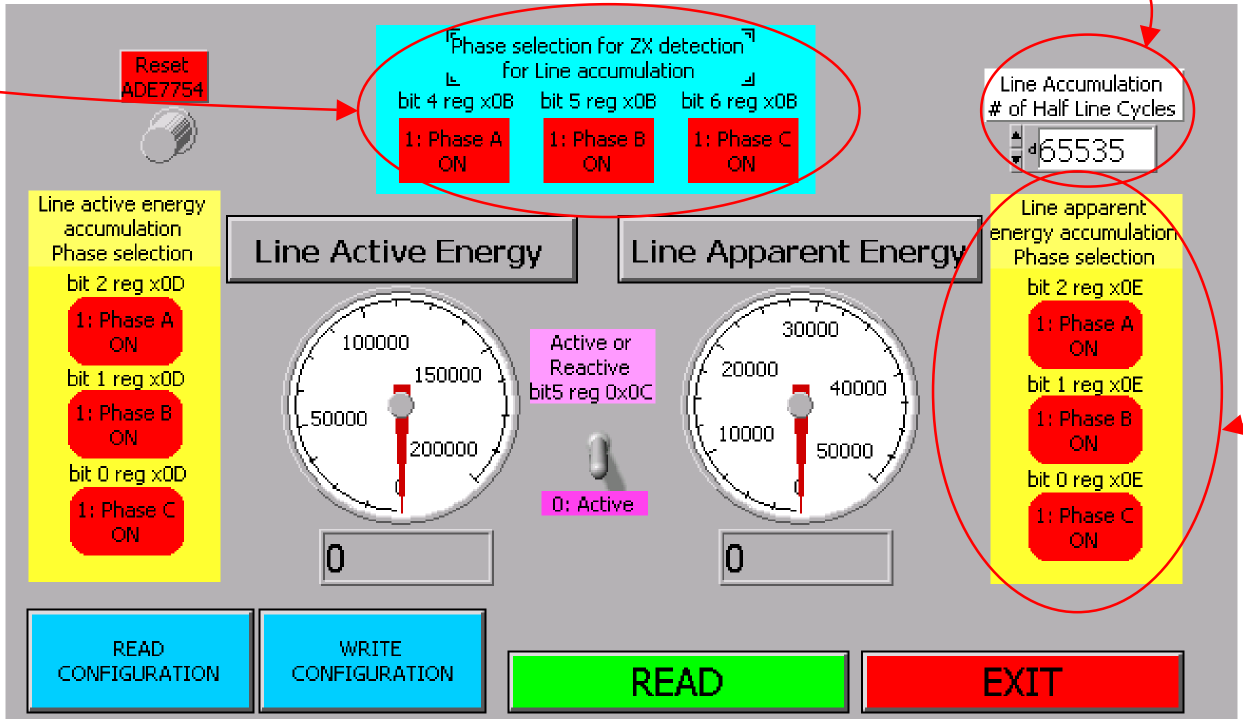
LVAENERGY accumulation

- Principle: Accumulation of the Apparent Energy over N half line cycles (<65535)
  - If bit A of IRQMASK register (0x0F) is set => IRQ goes Low when finished
- Benefits:
  - Cancel the ripple frequency effect (2 x line freq) in Energy Measurement
  - Shorten calibration time



LVAENERGY configuration

- Bit4-6 of MMODE Register (0x0B) select input phases for ZX count
- LINCYC register (0x13) define the # of half line cycles
- Bit0-2 of VAMODE register (0x0E) select input phases for LVAENERGY register



VA-Hour GAIN Calibration

- **Gain calibration for**
  - **Meter to meter gain adjustment**
  - **Phase to phase input gain matching**
  - **VAh/LSB constant**

- **VAENERGY/LVAENERGY Gain adjustment:**

$$VAENERGY = VAENERGY_{initial} \times \frac{1}{VADIV[11:0]} \times \left(1 + \frac{VAGAIN[11:0]}{2^{12}}\right) \quad \text{Eq. 10}$$

Conversion of VAENERGY value to VAh

- **VAENERGY is an Energy register**
  - **One constant is sufficient to convert it to VAh**

$$VAh = VAENERGY \times VAh/LSB \text{ constant}$$

  - **To calibrate VAh/LSB constant:**
    - **Known integration time**
    - **Known Load (VA = V_{rms} x I_{rms})**
  - **VAh/LSB constant can be determined with LVAENERGY test:**

$$VAh\!\!\diagup_{LSB}\text{ constant} = \frac{VA \times Accumulation\ time(s)\!\!\diagup_{3600}}{LVAENERGY} \qquad \text{Eq. 11}$$

Where $Line\ Period(s) = Period\ \text{Register} \times 2.4 \cdot 10^{-6}$

VA-Hour GAIN calibration example: Procedure

- Calibration of VA-Hour GAIN should be done after RMS offset corrections
- Calibration of VA-Hour GAIN can be done at the same time as Watt-Hour GAIN calibration
  - Program VAMODE and WATMODE to the same value
  - Read LAENERGY and LVAENERGY

VA-Hour GAIN calibration example: VAh/LSB calibration

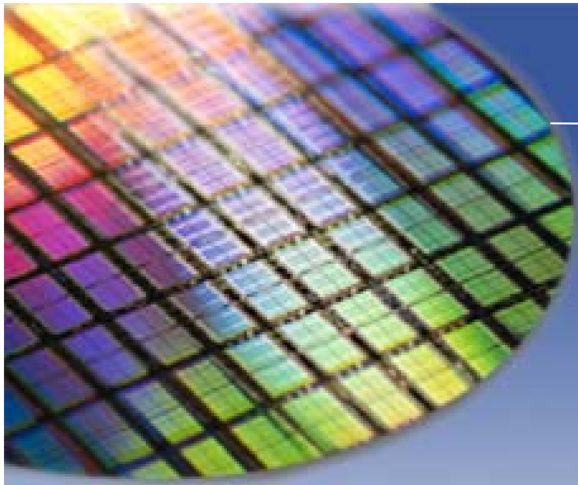
- Calibration of VA-hour GAIN to get a pre-determined value
  - V=240V ; I=10A ; 50Hz ; LINCYC = 200
  - $LVAENERGY_{reference} = LVAENERGY_{phase\ A} = 10582$
  - PERIOD register = 8336 => Accumulation time = 2.0006s

$$VAh/_{LSB}\ \text{constant} = \frac{240 \times 10 \times 2.0006}{3600 \times 10582} = 1.26 \cdot 10^{-4}$$

From Eq. 11

- Calibration of BVAGAIN to get to this value:
  - $LVAENERGY_{phase\ B\ initial} = 10558$
  - With BVAGAIN=9 => $LVAENERGY_{phase\ B} = 10581$

From Eq. 10



The World Leader in High-Performance Signal Processing Solutions

Reactive Energy Measurement

ANALOG DEVICES

Reactive Power calculation (VAR)

- **The reactive power is defined in the IEEE Standard Dictionary 100-1996 under the energy "magner" as:**

$$\text{Reactive } power = \sum_{n=1}^{\infty} V_n \cdot I_n \cdot \sin(\varphi_n)$$

where V_n and I_n are respectively the voltage and current rms values of the n^th harmonics of the line frequency, and φ_n is the phase difference between the voltage and the current n^th harmonics.

Note:

$$\text{Active } power = \sum_{n=1}^{\infty} V_n \cdot I_n \cdot \cos(\varphi_n)$$

Reactive Power calculation

- **The implementation of the reactive power definition can be done by introducing a 90° phase shift on one channel at any frequency – Hilbert Transform**

$$v(t) = \sqrt{2}.V.\sin(\omega t)$$

$$i(t) = \sqrt{2}.I.\sin(\omega t + \theta) \Longrightarrow i'(t) = -\sqrt{2}.I.\cos(\omega t + \theta)$$

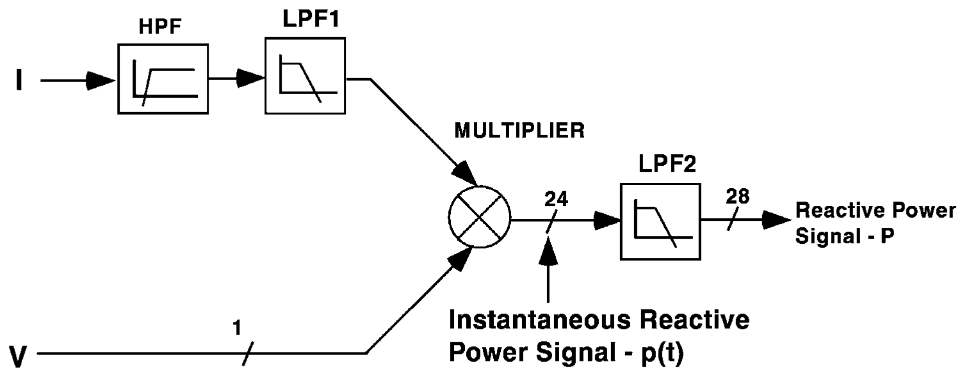
Hilbert transform

$$VAR(t) = v(t) \cdot i'(t) = V \cdot I \cdot \sin(\theta) - V \cdot I \cdot \sin(2\omega t + \theta)$$

Reactive Power is the DC part of the instantaneous reactive power: V.I.sin(θ)

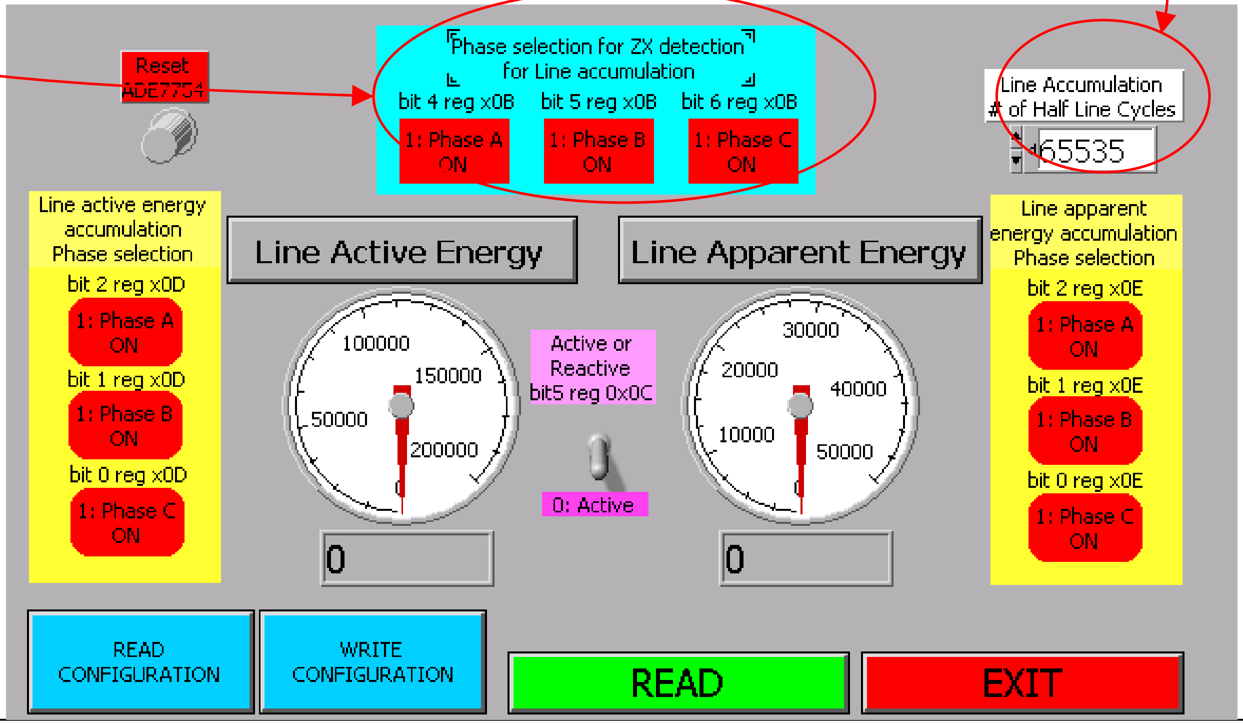
ADE7754 Reactive Power: Theory of operation

- A low frequency low pass filter introduces a 89° phase shift at any frequency
  - In the ADE7754, the Reactive Power calculation is processed by using a frequency Low-pass filter @ 2Hz (LPF1)



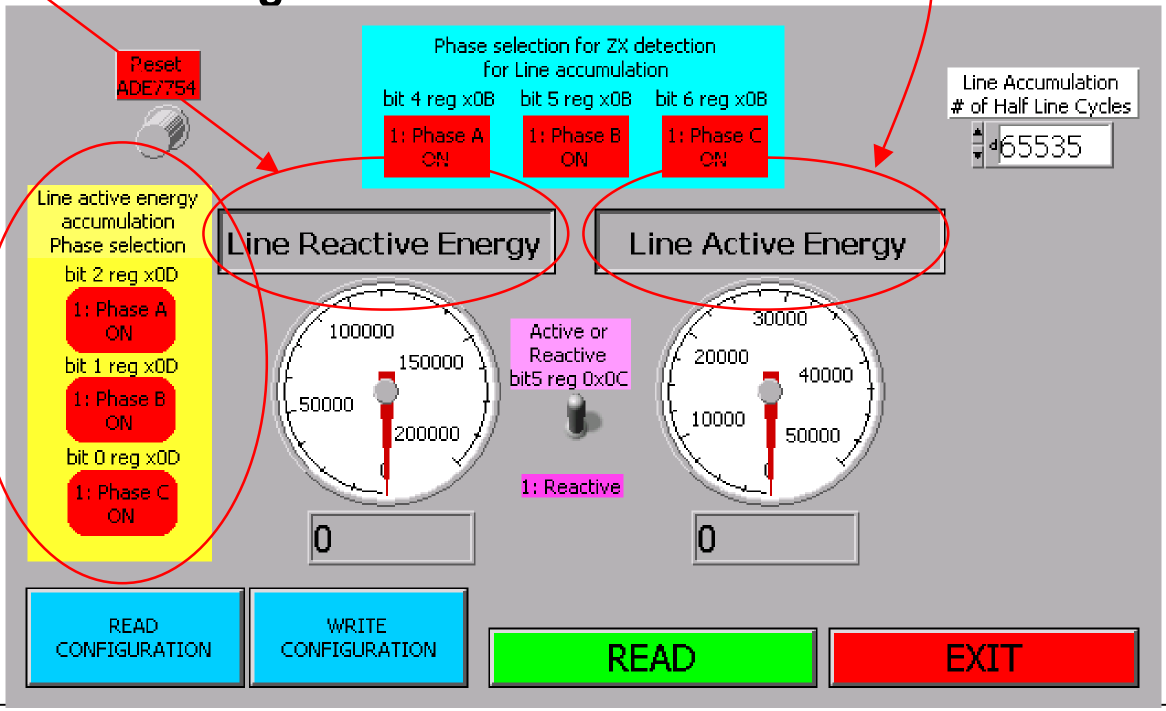
Bit5 Register 0x0C = 0 LVAENERGY configuration

- Bit4-6 of MMODE Register (0x0B) select input phases for ZX count
- LINCYC register (0x13) define the # of half line cycles



Bit5 Register 0x0C = 1 LVARENERGY configuration

- Reactive energy accumulated in LAENERGY
- Active energy accumulated in LVAENERGY
- Bit0-2 of WATMODE register (0x0D) select input phases for LAENERGY and LVAENERGY registers



Reactive Energy Measurement

- Sign of Reactive Energy can be directly read from the LVARENERGY[23:0]
- The sign of LVARENERGY indicates inductive or capacitive loading
- Proposed Method to measure Reactive Energy and Power Factor including harmonics:

  Using synchronous VAh and Wh data

$$Varh = \sqrt{(VAh^2 - Wh^2)} = \sqrt{(LVAENERGY^2 - LAENERGY^2)}$$

$$PF = sign(LVARENERGY) * LAENERGY / LVAENERGY$$