ANALOG DEVICES

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APPLICATION NOTE

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A Power Meter Reference Design Based on the ADE7756

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INTRODUCTION

This application note describes a high-accuracy, low-cost power meter based on the ADE7756. The design is for use in the North American 3-wire/single-phase application. This meter may also be used in a single-phase, 2-wire distribution system with a minimal amount of changes. The reference design is comprised of the ADE7756, a microcontroller, LCD display, serial interface, and power supply.

The ADE7756 is designed to interface to a microcontroller through a serial interface (SPI). The SPI port allows the user to calibrate various components of the meter, including gain, offset, and phase errors. The purpose of the microcontroller is to send display data to the LCD and control the various functions of the meter. An EEPROM is used to store various calibration parameters of the meter and store the meter's data during a power-down. The entire meter is calibrated through an external calibration routine by a PC through an external SPI interface.

The ADE7756 is comprised of two ADCs, a reference circuit, and all the signal processing necessary for the calculation of real (active) power. Circuitry is provided to null out various system errors including gain, phase, and offset errors. Additional circuitry provides waveform sampling, programmable interrupts, and power line monitoring. All registers of the ADE7756 are available through the SPI port. (See the ADE7756 data sheet for their descriptions.) The data sheet provides detailed information on the functionality of the ADE7756 and will be referenced several times in this application note. This application note should be used in conjunction with the ADE7756 data sheet.

Design Goals

The goal for this meter is to comply with the ANSI C12.16 specifications. The reference design is for a single element, Class 100 meter in a form 2S designation. This designation complies with the wiring arrangements as defined in ANSI C12.16-1991. Although the design in this application is limited to the ANSI standard, the accuracies achieved are well within the accuracy requirements of the IEC1036 standards for a Class 1 meter. For reference, see the section at the end of this application note, comparing the IEC1036 and ANSI C12.16 standards. This section explains the key IEC1036 specifications in terms of their ANSI equivalents.

This design greatly exceeds the definition for many of the accuracy requirements, e.g., accuracy at unity power factor and at low (PF = ±0.5) power factor. In addition, the dynamic range performance of the meter has been extended to 500. The ANSI standard defines the maximum current of a Class 100 watt-hour meter as 100 amps with a reference current (I_{REF}) of 15 amps. The Accuracy Class is defined in Table I for both the Accuracy Class 0.5 and Class 0.2 static watt-hour meters. The current range (dynamic range) for accuracy is specified in terms of I_{REF}.

Table I. Accuracy Requirements

Current Value[1]	PF[2]	Percentage Error Limits[3] Accuracy Class 1	Class 0.5	Class 0.2
$0.1\ I_{REF} \le I < I_{MAX}$	1	±1.0%	±0.5%	±0.2%
1 Amp	1	±2.0%	±1.0%	±0.4%
3 Amps	0.5 lag	±2.0%	±1.0%	±0.5%
50 Amps	0.5 lag	±2.0%	±0.6%	±0.3%
100 Amps	0.5 lag	±2.0%	±0.6%	±0.3%

NOTES

[1] The current ranges for specified accuracy shown in Table I are expressed in accordance with Load Performance Test, ANSI C12.20-1998 Section 5.4.2.3, Table IV, in terms of the reference current.

[2] Power Factor (PF) in Table I relates the phase relationship between the fundamental (45 Hz to 65 Hz) voltage and current waveforms. PF in this case can be simply defined as *PF = cos(f)*, where *f* is the phase angle between pure sinusoidal current and voltage.

[3] Accuracy Class is defined as the limits of the permissible percentage error. The percentage error is defined as:

$$\text{Percentage Error} = \frac{\text{Energy Registered by Meter — True Energy}}{\text{True Energy}} \times 100\%$$

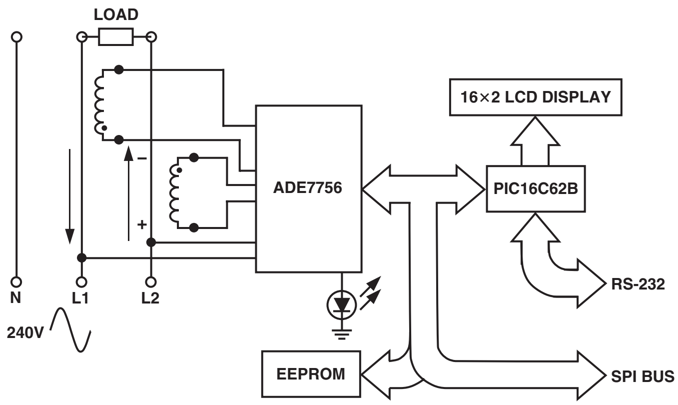

Figure 1. Simple Single Phase Watt-Hour Meter Block Diagram

OPERATION MODES

This section describes the operation of the reference meter. The meter itself is comprised of two boards, the meter board and the power supply board. The operation of the meter board is described in four parts; initialization, normal operation mode, calibration mode, and power-down.

The meter board is comprised of the ADE7756, a microprocessor or μC, an EEPROM, and an LCD display. The ADE7756 provides the measurement for the system. The μC provides control of the meter as well as communications. The EEPROM provides nonvolatile storage of various coefficients as well as the accumulated energy.

Although the data transfer/control of the meter is accomplished through the SPI port, an external RS-232 port is also provided. This provides the user with an additional method to communicate to the meter through a separate communication bus.

Initialization

Upon power-up, the μC senses the voltage at Pin 28 (RB7) to determine the selected mode of operation. If the voltage sensed is low, the μC goes into the calibration mode. If the level sensed is high, the meter goes into the initialization routine prior to the normal mode of operation. The initialization routine loads the coefficients from the EEPROM into the various registers of the ADE7756. This data is transferred through the μC. See the EEPROM memory mapping (Table II) for addresses of the various registers. In addition, two parameters are read into the μC. This includes previously stored energy and the conversion coefficient. A detailed description of the calibration routine is discussed in a later section. The previously stored energy is read from the EEPROM and placed in an 11-byte register in the μC. The conversion coefficient in the μC converts the AENERGY reading from the ADE7756 into kWh. Upon completion of this routine, the system begins to measure power.

Normal Mode

The μC continually reads the data from the ADE7756. (See the ADE7756 data sheet for a detailed description of the power measurement and register descriptions.) The energy read from the AENERGY register of the ADE7756 is multiplied by the conversion constant in the μC and accumulated with the previously stored data. The result is the total kWh measured by the meter, which is then displayed on the LCD. In addition, the μC monitors both the $\overline{\text{IRQ}}$ and $\overline{\text{SAG}}$ pin from the ADE7756. If during the normal operation, a power-out or $\overline{\text{SAG}}$ is detected, the ADE7756 will send an interrupt to the μC. This puts the μC into the power-down mode.

Calibration Mode

In calibration mode, the output pins of the μC go into three-state. An external interface to the SPI port provides communication to a PC, the ADE7756, and the EEPROM. Calibration coefficients are calculated in the PC based on the ADE7756 measurements and transferred to the EEPROM through the SPI port.

During calibration, the PC controls all signal sources and provides the calculations necessary to calibrate the meter. This minimizes the size of the μC's program. Upon completion of the meter calibration, the PC writes all the necessary coefficients to the EEPROM (see EEPROM memory mapping, Table II, for memory addresses). At the completion of the meter calibration, the meter is powered off. Upon power-up, with Pin 28 (of the μC) high, the meter goes into the initialization routine, loads the coefficients and begins to operate in normal mode.

Power-Down Mode

The μC continually monitors the interrupt pin as well as the $\overline{\text{SAG}}$ pin of the ADE7756. The ADE7756 provides an interrupt under several conditions. If a power loss is detected by the ADE7756, an interrupt occurs. This interrupt now places the μC into the power-down mode of operation. The power-down mode takes 1.4 ms to store all data prior to the loss of power. Data includes the energy stored in the μC's accumulated energy register as well as the energy in the ADE7756's register. Upon power-up, the initialization sequence restores the data in the ADE7756 registers along with the accumulated energy reading from the previous data. All calibration coefficients are restored in the system; the system returns to normal mode.

Brownout Mode

A function in the ADE7756 allows the system to monitor for a sag or brownout in the line voltage. The interrupt has two parameters that determine the brownout condition. The first parameter (SAGLVL) is a threshold that the line voltage must exceed each cycle to ensure there is no sag in the line voltage. The second parameter (SAGCYC) counts the number of half cycles so that the line voltage does not exceed the threshold as set by the SAGLVL register. If these conditions are met, an interrupt will occur. The meter will continue to measure accumulated energy during a brownout provided the 5 volt supply (for the system) does not decay.

DETAILED DESCRIPTION

This section describes the meter's hardware and purpose of each section in the overall design.

The front end of the meter is comprised of the voltage and current input networks. The line voltage is attenuated and filtered through an antialiasing filter. This filter is described in the section Channel 2 Input Network. The current channels are converted from a current to a voltage through a current transformer (See Item 24, BOM, Meter Board) and a burden resistor. The output of this network is filtered before being applied to the inputs V1P and V1N. The ADE7756 multiplies the two current signals with the voltage signal and accumulates the results in the AENERGY register. An LED is used to display the energy measured in IMP/kWh. See the ADE7756 for a detailed description of this operation.

The μC is used to read the AENERGY register of the ADE7756 through the SPI communication port. A data transfer occurs when $\overline{CS}$ becomes active. The μC sends the READ AENERGY command and reads the data back from the register. This data is then multiplied within the μC and converted to BCD. Results are sent to the LCD display. Additional data from the ADE7756 can be read through the SPI port including waveform samples, temperature and various interrupts.

DESIGN EQUATIONS

The ADE7756 contains a register that is proportional to the total accumulated energy. In addition, the ADE7756 has an output pin with a frequency proportional to the product of the voltages. This section describes the equations necessary to calibrate the meter. Results from these calculations are used to set the coefficients in the ADE7756 and μC registers.

Calibrating CF

The meter is calibrated by setting V1 and V2 to the calibration signal and reading the accumulated energy register (in the calibration mode). This measurement is used to calculate total power over an integral number of half-line cycles. The results are used to calibrate both the output frequency at CF and the accumulated energy. The detailed functionality of the ADE7756 is explained in the ADE7756 data sheet. Equation 1 is used to calculate the average word from the multiplication of V1 and V2.

$$Avg\ Word = \frac{Line\ Freq \times Energy \times 8}{\#\ of\ Power\ Line\ Cycles \times CLKIN} \quad (1)$$

The *Avg word* of LPF2 (see Figure 23, ADE7756 data sheet) is used to calibrate the front end of the ADE7756. The output frequency of CF is set by adjusting various registers within the ADE7756. A coefficient is then calculated to determine the accumulated energy register values. Equation 2 calculates the CF output frequency for the given inputs.

$$CF\left(Hz\right) = \frac{Average\ LPF2\ Output \times CLKIN}{2^{25}} \quad (2)$$

The frequency of *CF* (from Equation 2) is used to calibrate the CFDIV register. This calibration is used to set the number of impulses per kilowatt-hour for the meter, the meter constant. Setting the frequency to the proper range is accomplished through Equation 3.

$$CFDIV = \frac{CF_{FREQUENCY}\left(CFDIV = 0\right)}{CF_{DESIRED\ FREQUENCY}} - 1 \quad (3)$$

An additional error still exists in the system and is calibrated out through the APGAIN register. The error is nulled out by adjusting the power gain in the APGAIN register. In order to adjust the APGAIN register, the error for the frequency at CF is calculated. This error is calculated from the ratio of CF at 00x and CF at the setting from Equation 3. Equation 4 calculates the CF Ratio.

$$CF\ OUT = \frac{CF}{CFDIV + 1} \quad (4)$$

Figure 2. Final Implementation of the ADE7756 Meter

The *CF* ratio is then used to calculate the error in the output frequency compared to the desired value. The desired value is defined as the meter constant (IMP/kWh) × calibration power. This result is used to adjust the APGAIN register. Error is calculated to be (CFdesired – CF OUT) / CF OUT. Equation 5 calculates the new setting for the APGAIN register.

$$APGAIN\ Setting = Error \times 2^{12} \quad (5)$$

Calibrating ECONST Coefficient

Upon calibrating the CF channel, the coefficient for the energy is now calculated. While in calibration mode, the meter is allowed to accumulate power for SAGCYC register number of line half cycles. The accumulated energy register is read once more. This new reading accounts for the adjustment made in the APGAIN register. The coefficient for accumulated energy is now calculated using Equation 6.

$$ECONST = \frac{\left(\frac{1}{Line\ Freq}\right) \times \left(\frac{SAGCYC}{2}\right) \times \left(\frac{Cal\ Pwr}{3600}\right)}{Accumulated\ Energy} \times 2^{40} \times 1000 \quad (6)$$

The resulting number is rounded off to the nearest whole number and stored in the ECONST register (see Table II, Memory Map).

Additional calibration coefficients may be calculated for current and voltage. These coefficients are used in the waveform sampling mode to calibrate the waveform samples. This design does not use this mode; however, the information concerning these coefficients is included.

Phase Calibration

In order to correct for phase error, the ADE7756 has a phase adjust register PHCAL. Calibrating the phase error is accomplished by setting the meter to a current and voltage reference value then adjusting the PF to 0.5. Using Equation 7, the meter error is calculated in measured power versus the calculated power.

$$Error = \frac{Measured\ Power - Calculated\ Power}{Calculated\ Power} \quad (7)$$

Since calculated power is the calibration power times the power factor, the error is a result of the phase difference between the two quantities. The phase error is then calculated by Equation 8.

$$Phase\ Error = -\arcsin\left(\frac{Error}{\sqrt{3}}\right) \quad (8)$$

The phase calibration register introduces a time delay in Channel 2 at the rate of 4.47 µs/LSB. At 50 Hz, the resolution of the system is 0.08 degrees/LSB; at 60 Hz it is 0.096 degrees/LSB. The phase error (in degrees) is divided by the degrees/LSB for the associated line frequency. The results of the calculation are written into the PHCAL register to null out the phase error.

Offset Calibration

Channel Offset from the ADC introduces a dc error into the system. The ADE7756 has a high-pass filter in the current channel that prevents any dc term from entering the power calculation. Offsets can be calibrated out to maintain the dynamic range of the two ADCs in the ADE7756. (See ADE7756 data sheet, Analog Inputs section.) The offset is nulled by grounding the inputs to the ADCs through Bits 8 and 9 of the mode register. The waveform register is read and the offset is calculated using the equation:

$$Channel\ Offset = \frac{CODE(ADC) \times VREF}{396{,}392} \quad (9)$$

The results of the calculation are entered into the channel offset register as sign magnitude. See Table II in the ADE7756 data sheet for the offset correction range and LSB size.

Temperature Calibration

Temperature measurement is also available through the ADE7756. Calibration of the measurement is made at room temperature. The offset of the device is measured and stored. The µC subtracts the temperature offset from all subsequent measurements to correct for the offset error. The temperature coefficient is approximately 1°C/LSB.

LCD DISPLAY

The LCD will display a minimum of four digits to display energy billing quantities as per ANSI C12.16-1991 sec 4.8.3. The IEC1036 section 4.2.11 specifies that the display shall register and display, starting at zero, for a minimum of 1500 hours, the energy corresponding to maximum current at reference voltage and unity power factor. A value of 1500 hours at maximum current is 33,000 kWh. A display with a five plus one digits is used, i.e., 10,000s, 1,000s, 100s, 10s, 1s, 1/10s. In addition, the display must indicate negative current. The display character "*" is used to display negative energy. In addition, the ANSI specification requires that all billing quantities be displayed for four seconds.

ADE7756 Reference

This design does not include an optional reference circuit. The on-chip reference circuit of the ADE7756 has a typical temperature coefficient of 20 ppm/°C. However, on A grade parts this specification is not guaranteed and may be as high as 80 ppm/°C. At 80 ppm/°C the ADE7756 error at –20°C/+60°C could be as high as +0.65%, assuming a calibration at 25°C.

Current Transformer Selection

The current transformer is the device used in this design for measuring the load current. This sensor arrangement provides isolation as the line-to-line voltage differs by more than 300 V. Along with this required isolation, the CT affords an easy, reliable and cost-effective way of combining (adding) the currents in both phase wires. Figure 3 illustrates the application used in this design for a 2-wire single-phase meter. When selecting a current transformer, care should be taken when evaluating the linearity of the current transformer under light load.

Channel 1 Input Network

Figure 3 shows the input stage to Channel 1 of the meter. The current transformer with a turns ratio of 2500:1 is used for the design. The burden resistor is selected to give the proper input range for the ADE7756. The additional components in the input network provide filtering to the current signal. The filter corner is set to 4.8 kHz for the antialias filters.

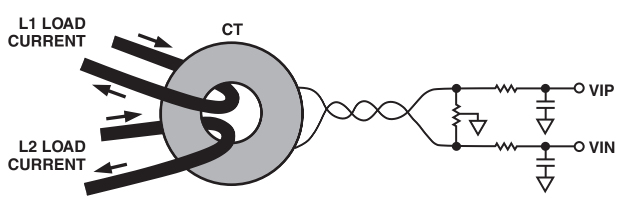

Figure 3. ADE7756 CT Wiring Diagrams

Channel 2 Input Network

From previous sections, it can be seen that the meter is simply calibrated by attenuating the line voltage down to 250 mV. The line voltage attenuation is carried out by a simple resistor divider as shown in Figure 4. The topology of the network is such that the phase matching between Channel 1 and Channel 2 is preserved. As can be seen from Figure 4, the –3 dB frequency of this network is determined by R8 and C8. This is due to R7 (255 kΩ) and R6 (255 kΩ) being much greater than R8 (1 kΩ).

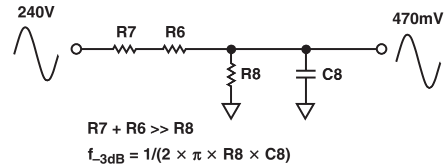

Figure 4. Attenuation Network

This meter can also be used in a 120 V application. The attenuation network need not be changed as the voltage channel can be gained up internally in the ADE7756. The PGA Gain adjust register of the ADE7756 is set to two to accommodate the 120 V input voltage. This allows the user to program the voltage channel gain through software to match the line voltage. This maintains the dynamic performance of the meter by maintaining the SNR. It should be noted that in switching the meter to 120 V operation, the power supply transformer must be set up to properly operate at that line voltage. See Power Supply Line Design section, Figure 12.

Since the ADE7756 transfer function is extremely linear, a one-point calibration (I_{REF}) at unity power factor, is all that is needed to calibrate the meter. If the correct precautions have been taken at the design stage, no calibration will be necessary at low power factor (PF = 0.5). A calibration routine for phase error is discussed earlier in this documentation in the Design Equations section. The next section discusses phase matching for the input networks at low power factor. Poor design of the input networks will cause the phase mismatch to be out range of the PHCAL adjustment.

CORRECT PHASE MATCHING BETWEEN CHANNELS

Phase matching of the system is another critical issue. The errors induced in the system at PF = 1 are minimal. A power factor of 0.5 with a phase error as little as 0.5 degrees will cause a 1.5% error in the power measurement. Some of the sources of the phase error are described later in this application note.

The ADE7756 has an internal phase compensation register to match the two input phases. The phase calibration register is a two's complement, 6-bit, signed register that can introduce a time delay in the Channel 2 signal path from +143 μs to –143 μs. This section describes some of the phase errors and how to compensate for them. Correct phase matching is important in energy metering applications since any phase mismatch between channels will translate into significant measurement error at low power factor. Proper matching reduces the amount of calibration needed for the overall accuracy of the system. This is easily illustrated with the following example. Figure 5 shows the voltage and current waveforms for an inductive load. In the example shown, the current lags the voltage by 60° (PF = –0.5). Assuming pure sinusoidal conditions, the power is easily calculated as V rms × I rms × cos(60°).

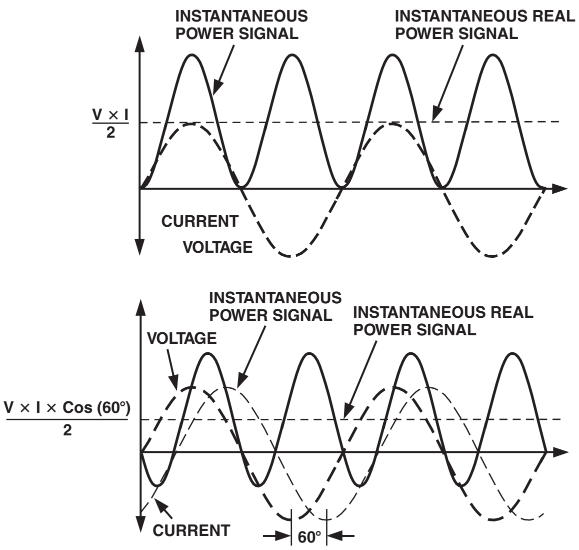

Figure 5. Voltage and Current (Inductive Load)

An additional phase error can be introduced into the overall system with the addition of antialiasing filters. Phase error (f_e) is introduced externally to the ADE7756, e.g., in the antialias filters, the error is calculated as

$$\left[\cos(\delta°) - \cos(\delta° + \phi_\varepsilon)\right] / \cos(\delta°) \times 100\% \qquad (10)$$

where δ is the phase angle between voltage and current and ϕ_e is the external phase error. See Note 3 in Table I. With a phase error of 0.2°, for example, the error at PF = 0.5 (60°) is calculated as 0.6%. As this example demonstrates, even a very small phase error will produce a large measurement error at low power factor.

ANTIALIAS FILTERS

As mentioned in the previous section, one possible source of external phase errors is the antialias filter on Channel 1 and Channel 2. The antialias filters are low-pass filters that are placed before the analog inputs of any ADC. They are required to prevent a possible distortion due to sampling called aliasing. Figure 6 illustrates the effects of aliasing.

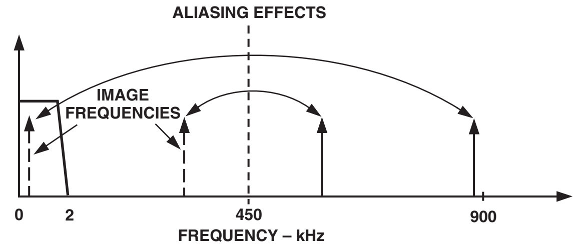

Figure 6. Aliasing Effects

Figure 6 shows how aliasing effects could introduce inaccuracies in an ADE7756 based meter design. The ADE7756 uses two Σ-Δ ADCs to digitize the voltage and current signals. These ADCs have a very high sampling rate, i.e., 900 kHz. Figure 6 shows how frequency components (arrows shown in black) above half the sampling frequency (also know as the Nyquist frequency), i.e., 450 kHz, are imaged or folded back down below 450 kHz (arrows shown in dashed lines). This will happen with all ADCs no matter what the architecture. In the example shown it can be seen that only frequencies near the sampling frequency, i.e., 900 kHz, will move into the band of interest for metering, i.e., 0 kHz–2 kHz. This fact will allow us to use a very simple LPF (Low-Pass Filter) to attenuate these high frequencies (near 900 kHz) and so prevent distortion in the band of interest.

The simplest form of LPF is the simple RC filter. This is a single-pole filter with a roll-off or attenuation of –20 dBs/dec.

Choosing the Filter –3 dB Frequency

As well as having a magnitude response, all filters also have a phase response. The magnitude and phase response of a simple RC filter (R = 1 kΩ, C = 33 nF) are shown in Figures 7 and 8. From Figure 7, it is seen that the attenuation at 900 kHz for this simple LPF is greater than 40 dB. This is enough attenuation to ensure no ill effects due to aliasing.

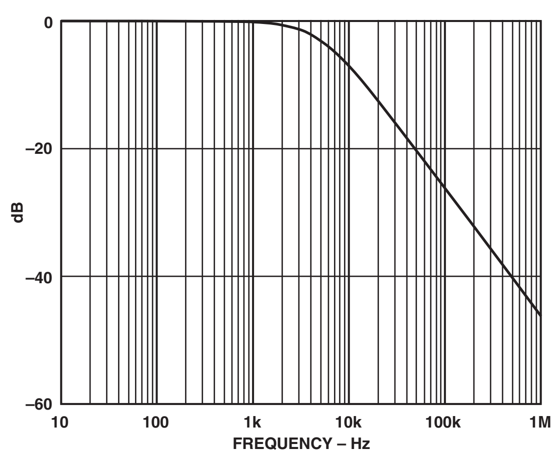

Figure 7. RC Filter Magnitude Response

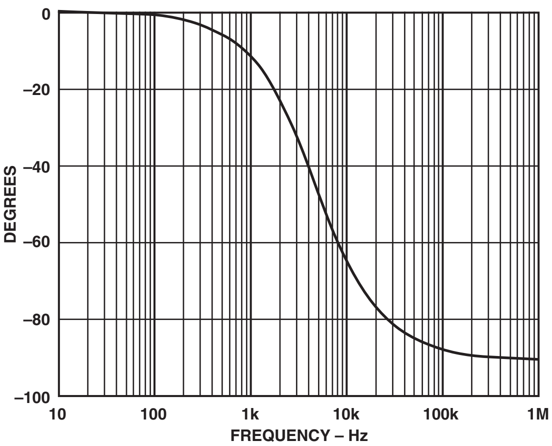

Figure 8. RC Filter Phase Response

As explained in the last section, the phase response can introduce significant errors if the phase responses of the LPFs on both Channel 1 and Channel 2 are not matched. Phase mismatch can easily occur due to poor component tolerances in the LPF. The lower the –3 dB frequency in the LPF (antialias filter), the more pronounced these errors will be at the fundamental frequency component or the line frequency. Even with the corner frequency set at 4.8 kHz (R = 1 kΩ, C = 33 nF), the phase errors due to poor component tolerances can be significant. Figure 7 illustrates the point. In Figure 9, the phase response for the simple LPF is shown at 50 Hz for R = 1 kΩ ± 10%, C = 33 nF ± 10%. Remember, a phase shift of 0.2° can cause measurement errors of 0.6% at low power factor. This design uses resistors of 1% tolerance and capacitors of 10% tolerance for the antialias filters to reduce the possible problems due to phase mismatch. Alternatively, the corner frequency of the antialias filter could be pushed out to 10 kHz–15 Hz. However, the corner frequency should not be made too high, as this could allow enough high-frequency components to be aliased and so cause accuracy problems in a noisy environment.

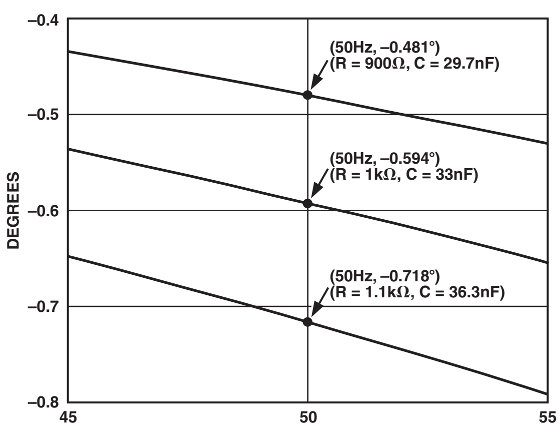

Figure 9. Phase Shift at 50 Hz Due to Component Tolerances

Note this is also why precautions were taken with the design of the calibration network on Channel 2 (voltage channel).

CALIBRATING THE METER

The meter is calibrated through the SPI port using an external calibration routine. This program calculates the various coefficients needed by the meter. These parameters are then stored in the EEPROM.

Design Calculations

Design parameters:
Line voltage = 240 V (phase-to-phase nominal)
Class 100 meter with I_{MAX} = 100 A
Meter constant = 3200 imp/kWh
CT Turns ratio = 2500:1
Meter calibrated at I_{REF} = 15 A
Power dissipation at Ib = 240 V × 15 A = 3.6 kW
V1 = 354 mV_{rms} max

The current transformer has two primaries; therefore, the output of the transformer is the combined load currents.

$$P_{TOTAL} = \frac{V_{LINE}}{2} \times \left(I_{L1} + I_{L2}\right) \tag{11}$$

When $I_{L1} = I_{L2}$, the total power is the line voltage times the load current. For this reason, the maximum voltage per burden resistor must be one-half of the maximum allowable input voltage or 177 mV.

$$R_{BURDEN} = 177\ mV/(100\ A/2500) = 4.4\ \Omega$$

The current channel should be approximately 1/6th of full scale at I_{REF}. At test current (I_{REF} = 15 A)

$$15\ A \times 2 \times 4.4\ \Omega/2500 = 52.8\ mV\ Referred\ to\ Input$$

As seen above, the input level to the current channel is set to approximately 1/6th of full scale with the current through both lines equal to 15 amps.

The input level to the voltage channel should be set to approximately half-scale. The voltage channel (V2) is attenuated through a resistor divider network to approximately 250 mV rms. This configuration is for the 240 line voltage. In order to run the meter at 120 V, the GAIN for Channel 2 is increased to a gain of 2 through the GAIN register.

Calibration mode bit set with SAGCYC = 80x, the average of LPF2, is calculated by reading the multiplier output of the waveform sampling register. The result for this measurement is 3138.6. Equation 2 is used to calculate the output frequency at CFDIV = 00x. The output frequency is found to be 334 Hz. The IMP/kWh is set at 3200 IMP/kWh or

$$\frac{IMP}{sec} = \frac{3200\ IMP}{kWh} \times \frac{1\ h}{3600\ sec} \tag{12}$$

The meter constant is 0.8888 Hz/kW from Equation 12. The calibration power (3.6 kW) is multiplied by the meter constant to determine the desired output frequency. CF is calculated to be 3.2 Hz. Using Equation 3, the CFDIV register is calculated. The results (104d) are written into the CFDIV register.

CF is now calculated to be 334 Hz/(104 + 1) or 3.189 Hz from Equation 4. The result is used to calculate the error for Equation 5. The APGAIN register is set to 14d (0Ex).

Once the gain for the meter is calibrated, a phase of 60 degrees (PF = 0.5) is introduced. CF should be 50% of CF at a 0.5 power factor. Using Equation 8, the phase error is calculated. CF is measured to be 1.57 for desired value of 1.6 Hz (3.2 Hz × 0.5). Error is then calculated to be = 0.62 degrees. The specification for the PHCAL register is 0.08 per LSB, therefore the register is set to –8d (38×).

EEPROM DATA TABLE

The EEPROM is used to store all the data of the meter. The addresses and their contents are listed in Table II.

Table II. EEPROM Memory Map

Add.	Page 1	Page 2	Page 3
0	Energy (0–7)	CFDIV (0–7)	Econst (0–7)
1	Energy (8–15)	CFDIV (8–15)	Econst (8–15)
2	Energy (16–23)	APGAIN (0–7)	Econst (16–23)
3	Energy (24–31)	APGAIN (8–15)	Resolution
4	Energy (32–39)	NA	Temp Offset
5	Energy (40–47)	CH1OS (0–7)	APOS (0–7)
6	Energy (48–55)	CH2OS (0–7)	APOS (8–14)
7	Energy (56–63)	GAIN (0–7)	NA
8	Energy (64–71)	PHCAL (0–7)	NA
9	Energy (72–79)	SAGCYC (0–7)	NA
A	Energy (80–87)	SAGLVL (0–7)	NA
B	NA	IRQEN (0–7)	NA
C	NA	MODE (0–7)	NA
D	NA	MODE (8–15)	NA
E	NA	ZXTOUT (0–7)	NA
F	NA	ZXTOUT (8–15)	NA

Page 1 of the EEPROM contains the accumulated energy in bytes 0–Ax. Page 2 of the EEPROM contains the settings for the various registers of the ADE7756. Page 3 is used to store the calibration coefficient used to translate the AENERGY register into kWh. Address 4, page 3 is used for temperature offset.

POWER SUPPLY DESIGN

This design uses a simple low-cost power supply based on a power transformer. This scheme allows better isolation of the system. The secondary of the transformer is used to power the meter only. Although the secondary could be used as an attenuated input for Channel 2, load currents can affect the overall accuracy of the system. The filter capacitor (C18) should be chosen to ensure there is enough charge stored during a brownout to power the meter for the power-down mode.

The total power consumption in the voltage circuit including power supply is specified in ANSIC12.1-1995 section 4.7.2.8 Test No. 8 Meter Losses. It specifies that the total power consumption in each phase is 5 W and 20 VA under nominal conditions. Total power dissipation is approximately 2.5 W in the reference design. Figure 10 shows the power supply design.

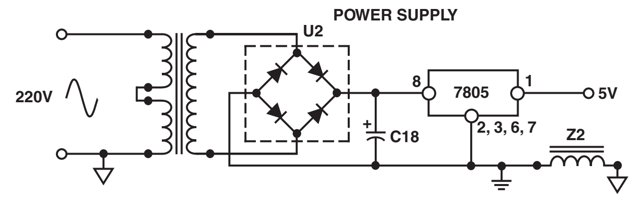

Figure 10. Power Supply

Figure 11 shows the power supply performance under heavy load (100 A) with the line voltage at 240 V. By far the biggest load on the power supply is the current required to drive the LED. The supply current measures 10.69 mA_{RMS} or 2.57 VA.

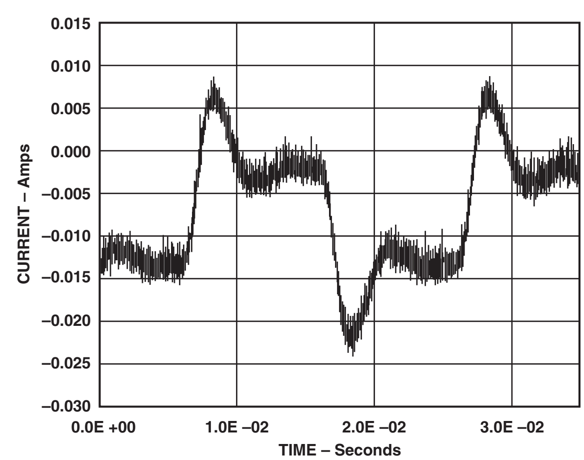

Figure 11. Power Supply Current

The power supply is designed to operate for both 240 V and 120 V. The power supply has three 0 Ω resistors that are used to set the line voltage input. See Figure 12.

COMPONENT	220V	120V
R2	OPEN	SHORT
R3	OPEN	SHORT
R4	SHORT	OPEN

Figure 12. Power Supply Line Select

The power supply as shown in Figure 10 does not show the MOV-Ferrite bead input. These components are used at the inputs to the power supply to minimize the effect of electrical fast transients. Large differential signals may be generated by the inductance of the PCB traces and signal ground. These large signals may effect the operation of the meter. The analog sections of the meter will filter the differential signal and its effect is minimized to the duration of the pulse. Digital components are at greater risk due to data corruption. A spike on a digital reset pin of the microprocessor can cause an undesirable reset to the digital system.

In order to minimize the effects of the EFT, two ferrite beads are used to increase the impedance of the meter during a fast transient. The MOV shorts the remaining signal thus minimizing the amount of fast transient seen by both the power supply and the meter board. For more information concerning this issue, see application note AN-559.

CREEP

The measured power of the meter with no load is defined as its creep. ANSI C12.16-1991 states the meter display shall not change by more than ±1 least significant digit with the voltage circuit energized and current circuit unenergized for 24 hours. Although current is not measured directly in the meter, it can be calculated. A threshold is set in the microcontroller so that any energy reading below the threshold is discarded.

In a class 100 meter, the starting current is defined to be 150 mA. At this current level, the meter must "operate continuously." The threshold for creep must be set to a level below 150 mA to satisfy both creep and starting current. The meter compares the accumulated energy for each sample period to a fixed threshold. If the results are below that threshold, the meter discards the results.

Calculating the threshold (for creep) is accomplished during meter calibration. Equation 6 calculates kWh/LSB for the accumulated energy register. Creep is set to a current of less than 150 mA, the starting current. Since the meter does not monitor current directly, calculating the energy for a current of 150 mA will result in a threshold that is proportional to the starting current. The meter must operate to a line voltage of 90% or 216 V (for 240 V nominal). The starting current is now converted to a starting power of 32.4 watts. The sampling rate is the rate at which the meter reads the accumulated energy register in the ADE7756. Multiplying the power by 1 Hr/3600 seconds times the sampling rate results in the threshold level of the accumulated energy register. Each time the microcontroller reads the accumulated energy register, the results are compared to the threshold. If the energy measured is less than the threshold, the results are not added to the total accumulated energy. This satisfies the condition that the display will not change by more than ±1 least significant digit with no load.

BROWNOUT

The ADE7756 contains circuitry to monitor the line voltages to the meter. This has a distinct advantage over other designs as it allows the meter additional time to store all necessary data before the power supplies decay. The decay is proportional to the current drawn by the meter board and the size of the storage capacitor on the supply board. Figure 13 illustrates the time between power loss and the 5 V supply decaying. By setting the ADE7756 brownout detect registers, the part can send an interrupt to the μC and save all the data prior to the decay of the power supply. (See Zero Cross Detection and Line Voltage Sag Detection sections in the ADE7756 data sheet.) Figure 14 shows the 5 V decay with a load current of 40 amps. The line voltage in Figure 13 was measured at the secondary of the power supply. The line-in voltage is 220 V_{RMS}, 50 Hz. The 50 Hz line frequency was used as the worst case for the power supply line frequency during a brownout.

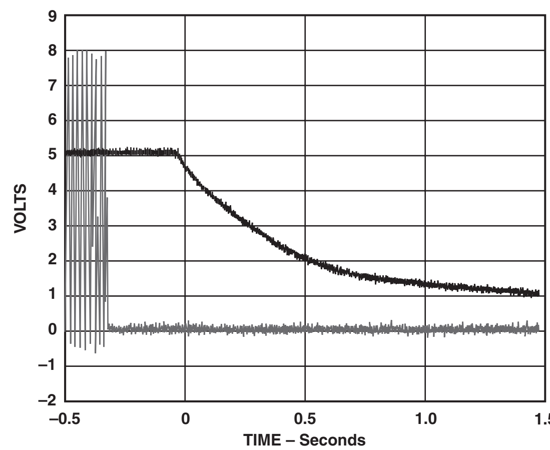

Figure 13. Power Supply Droop

MICROCONTROLLER PROGRAM FLOW

This section briefly describes the program used with the ADE7756 and microcontroller. The routines in the program provide the initialization sequence for the system, interrupt service routines, power-down routines, communication routines, and LCD display driver routines. The block diagram of the program is shown in Figure 14.

The program is interrupt-driven. Upon completion of the initialization sequence, the program goes into an idle mode. An interrupt must occur for the microcontroller to leave the idle loop. If the microcontroller receives an interrupt, the program goes into an interrupt service routine, services the interrupt, and goes back into the idle loop.

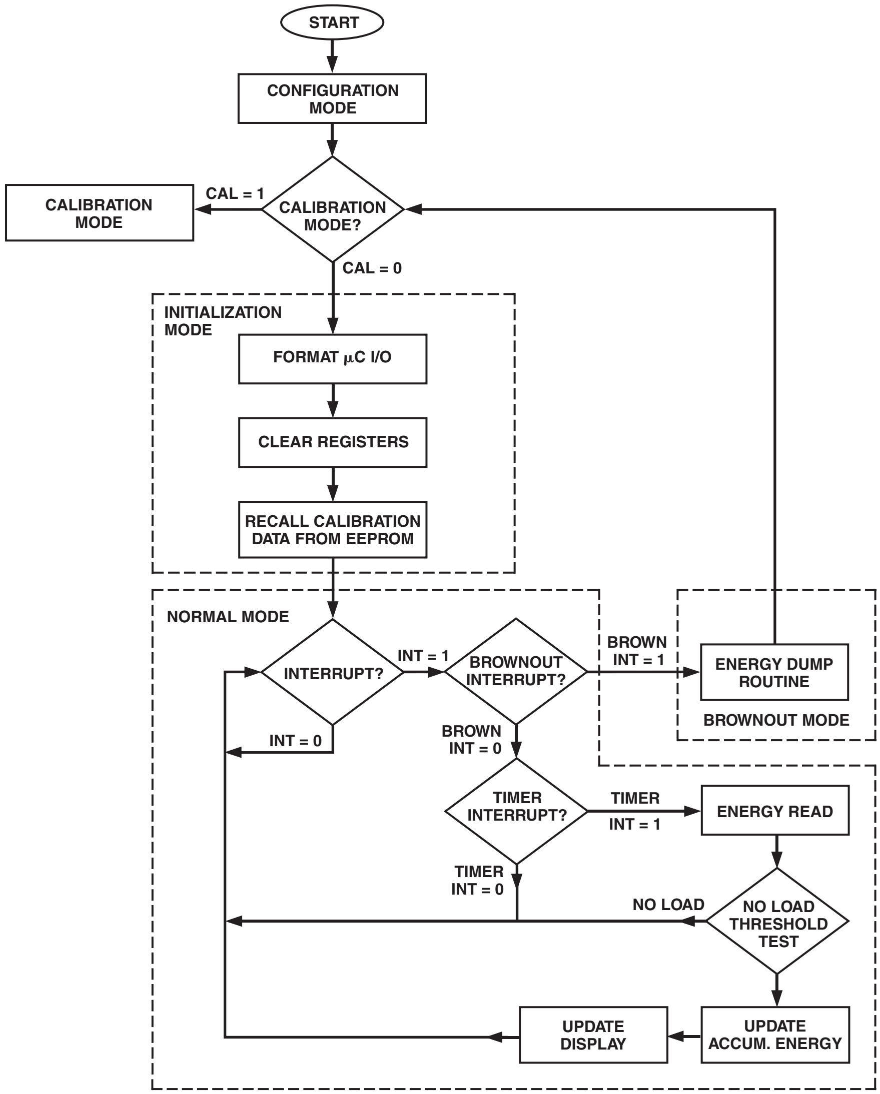

Figure 14. Program Flow Chart

Initialization of the meter begins with assigning various registers to be used by the system. This includes various coefficient registers, as well as storage registers for accumulated energy in the microcontroller.

The assign ports routine is next in the program. Within this routine, the microcontroller maps the various I/Os. This includes the LCD display port, system SPI port, and the serial port.

Once the ports have been assigned, the microcontroller determines which mode to go into, either normal or calibration mode. Port B of the microcontroller has a 10 kΩ pull-up resistor connected to it. A calibration cable, when connected, grounds the pin. This CALMODE signal forces the microcontroller I/O to go into three-state. External control allows the user to access the ADE7756 and EEPROM through the SPI port. The microcontroller sends out the display "CAL MODE" to the LCD. The system SPI port is made available to control both the ADE7756 and the EEPROM. Once the meter is calibrated, the external controller will write the coefficients to the EEPROM through the external interface with the necessary coefficients. For a mapping of registers addressed within the EEPROM, see Table II.

If the microcontroller does not sense the calibration signal, it will begin to format the I/O, clear all registers (within the micro), and load data from the EEPROM into the microcontroller and ADE7756 registers. Once the microcontroller loads all necessary data, it enables an interrupt timer and goes into the program idle mode.

During idle mode, the microcontroller waits for an interrupt. Two interrupts are used in this application. The first interrupt is brownout detect. The second interrupt is a timer interrupt.

Pin 21 RBO/INT is used by the microcontroller to sense an external interrupt (from the ADE7756). The interrupt enable register (Register 10H) in the ADE7756 enables the brownout interrupt. If power is lost (see Line Voltage Sag Detection, ADE7756 data sheet), the interrupt pin $\overline{IRQ}$ goes low. The microcontroller senses the interrupt and the ENERGYDUMP subroutine is called to store data in the EEPROM. See section on ENERGYDUMP for a more detailed description on this subroutine.

A second interrupt will occur when the internal timer reaches a set value. This interrupt is used by the microcontroller to adjust the rate at which the microcontroller samples the accumulated energy register. When the interrupt occurs, the microcontroller reads the accumulated energy register, multiplies the results by the calibration coefficient, and displays the new value. A creep routine can be implemented in this section of code by evaluating the level of accumulated energy during the interrupt. See section on creep for a detailed explanation. If implemented, the microcontroller will clear the accumulated energy for the last reading or else it will add it to the current value of the accumulated energy register in its memory and display the results.

ANSI AND IEC STANDARDS

The ANSI standard for governing the specifications of solid-state meters are covered in ANSI C12.16-1991 entitled *Solid-State Electricity Meters.* Additional documents include; ANSI C12.1-1995, Code for Electricity Metering and ANSI C12.10-1997 *American National Standard for Watthour Meters*. ANSI C12.20-1998 *American Standard for Electricity Meters 0.2 and 0.5 Accuracy Classes*.

CLASS-IEC vs. ANSI

The class designation for the ANSI meter is defined as the maximum specified continuous load in amperes at which the meter operates. For example, a Class 100 meter is a meter that will operate to a maximum current of 100 amps. The range of classes include 10, 20, 100, 200, and 320 currents. The IEC class refers to the accuracy of the meter. A Class 1 IEC1036 meter will operate to an accuracy of better than 1% over a defined current range. The ANSI equivalent to the IEC standard is defined as its accuracy class. These classes include 1, 0.5, and 0.2 accuracy classes.

ADE7756 REFERENCE DESIGN LINEARITY ERROR

The linearity error for the meter was measured over a dynamic range of 1000:1 and found well within a 1% error. Power factor was measured at 0.866 (lead) and 0.5 (lag) and found to be within the ±2% at 3 amps as per the ANSI specification.

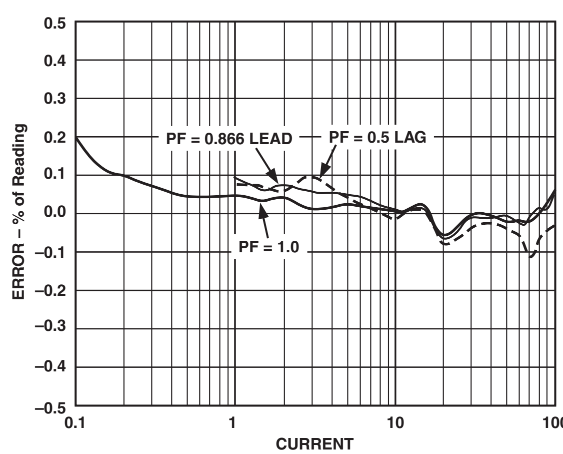

Figure 15. AC Linearity Error

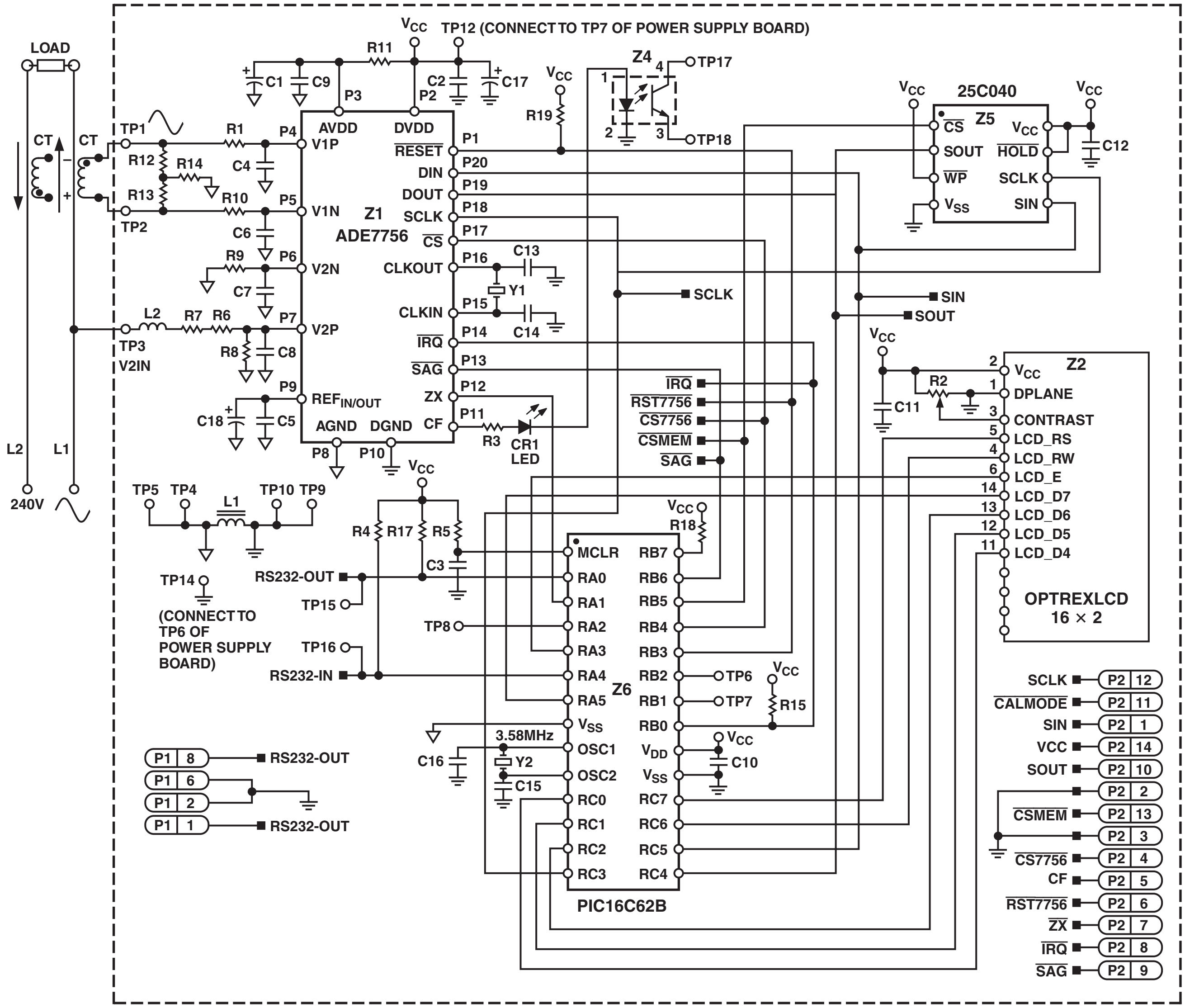

Figure 16. Reference Design Schematic

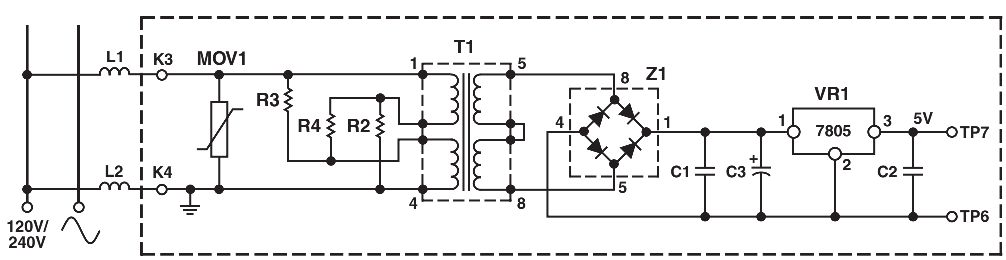

Figure 17. Reference Design Power Supply

BILL OF MATERIALS

Meter Board

Part(s)	Details	Comments
1. C1	220 µF, 6.3 V, 20%	NHE RADIAL ELECT CAP Panasonic ECE-A0JGE221 Digi-key Part #P5204-ND
2. C2–C3, C5, C9–C12	100 nF, 50 V, 10%	CERM CHIP 1206 X7R Surface Mount Panasonic ECJ-3VB1H104K Digi-key Part # PCC104BTR-ND
3. C4, C6–C8	33 nF, 50 V, 10%	CERM CHIP 1206 Surface Mount Panasonic ECU-V1H333KBW Digi-key Part #PCC333BCT-ND
4. C13–C16	22 pF, 50 V, 5%	CERM CHIP 0805 Surface Mount Panasonic ECJ-2VC1H220J Digi-key Part #PCC220CNCT-ND
5. C17–C18	10 µF, 6.3 V, 20%	Tantalum TES Surface Mount Panasonic ECS-T0JY106R Digi-key Part #PCS1106CT-ND
6. CR1	LED Red	LED Red Diffused Round Short Panasonic LN21RPHL Digi-key Part #P300-ND
7. L1	Ferrite Bead	Bead Core Single 3.5 × 9 MM Axial Panasonic EXC-ELSA39 Digi-key Part #P9818BK-ND
8. L2	150 Ω	Ferrite SMT 1806 Surface Mount Steward LI1806C151R-00 Digi-key Part #240-1030-1-ND
9. R1, R8–R10	1 kΩ, 1/8 W, 1%	SMD 1206 Resistor Surface Mount Panasonic ERJ-8ENF1001V Digi-key Part #P1.00KFCT-ND
10. R2	10 kΩ, Multiturn Trimpot	Trimmer Pot, Top Adj BC Components CT-94W-103 Digi-key Part #CT94W103-ND
11. R3	820 Ω, 1/8 W, 1%	SMD 1206 Surface Mount Panasonic ERJ-8ENF8200V Digi-key Part #P820FCT-ND
12. R4, R5, R15, R17–R19	10 kΩ, 1/8 W, 1%	SMD 1206 Surface Mount Panasonic ERJ-8ENF1002V Digi-key Part #P10.0KFCT-ND
13. R6–R7	255 kΩ, 1/8 W, 1%	SMD 1206 Surface Mount Panasonic ERJ-8ENF2553V Digi-key Part #P255KFCT-ND
14. R11	10 Ω, 1/8 W, 1%	SMD 1206 Surface Mount Panasonic ERJ-8ENF10R0V Digi-key Part #P10.0FCT-ND
15. R12–R13	2.2 Ω, 1/8 W, 1%	SMD 1206 Surface Mount Panasonic ERJ-8RQF220 Digi-key Part #P3.3RCT-ND
16. R14, R16	00 Ω, 1/8 W, 5%	SMD 1206 Surface Mount 1206 Digi-key Part #P0.0ECT-ND
17. TP1–TP20	Testpoint	
18. Y1–Y2	3.579 MHz Crystal	ECS Inc ECS-35-17-4 Digi-key Part #X079-ND
19. Z1	ADE7756	Analog Devices ADE7756AN

BILL OF MATERIALS (continued)

Meter Board (cont.)

Part(s)	Details	Comments
20. Z2	LCD Module 16 × 2 Char.	Optrex America Inc DMC-16230U Digi-key Part #73-1030-ND
21. Z4	1-Channel Opto-Coupler	PS2501-1, Opto-Isolator NEC PS2501-1 Digi-key Part #PS2501-1-ND
22. Z5	EEPROM 512 × 8	IC Serial 8 Pin Dip Microchip Technology 25C040/P Digi-key Part #PS2501-1-ND
23. Z6	PIC16C62B	IC Micro Ctrl 2K × 14 OTP 28SDIP Microchip Tech. PIC16C62B-04/SP Digi-key Part #PIC16C62B-04/SP-ND
24. CT	TZ-79, 2500:1 Ratio	TZ-79 Cased Current Transformer TAE HWA Trans Co. Part#TZ-79
25. PCB		Stk #08007087A
26. Case	Meter Case	Marwell Corp, #SP-2376-AD

Power Supply Board

Part(s)	Details	Comments
1. C1	100 nF, 50 V, 10%	CERM CHIP 1206 X7R Surface Mount Panasonic ECJ-3VB1H104K Digi-key Part #PCC104BTR-ND
2. C2	220 μF, 6.3 V, 20%	NHE RADIAL ELECT CAP Panasonic ECE-A0JGE221 Digi-key Part #P5204-ND
3. C3	330 μF, 50 V, 20%	NHE RADIAL ELECT CAP Panasonic ECE-A1HGE331 Digi-key Part #P5278-ND
4. L1	Ferrite Bead	Bead Core Single 3.5 × 9 MM Axial Panasonic EXC-ELSA39
5. L2	Ferrite Bead	Bead Core Single 3.5 × 9 MM Axial Panasonic EXC-ELSA39
6. MOV1	Metal Oxide Varistors	AC 275 V, 140 Joules Farnel N0. 580-284, Siemans, S20K275
7. R2–R4	00 Ω, 1/8 W 5%	SMD 1206 Surface Mount Resistor Panasonic ERJ-8GEY0R00V Digi-key Part #P0.0ECT-ND
6. T1	Transformer	10VCT.110A DUAL Tamura/Microtran 3FD-210 Digi-key Part #MT2096-ND
7. TP1–TP7	Testpoints	
8. VR1	5 V Regulator	IC +5 V REGULATOR TO220F NJM NJM7805FA Digi-key Part #NJM7805FA-ND
9. Z1	Bridge Rectifier	BRIDGE RECTIFIER 1 A 100 V DB-1 Microsemi Corp DB102 Digi-key Part #DB102MS-ND
10. PCB		Stk #08007088A

Integrity
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Certificate of Compliance

The following product was found to comply with the requirement stated below when tested in accordance with the test procedures described in the accompanying test/measurement report. Reference report number 66345.c1

Manufacturer:	Analog Devices 804 Woburn Street Wilmington, MA 01887		
Model Number:	ADE 7756		
Standard:	ANSI C12.1-1995		
	Section	4.7.3.4	Test # 18
	Section	4.7.3.11	Test # 25
	Section	4.7.3.12	

Approved By:

Steven M. Burgess Immunity Section Manager	Steven M. Burgess
Date	4/26/01

Remarks: *Testing is performed using calibrated equipment traceable to the National Institute of Standards and Technology (NIST).*

This certificate is valid for products tested as described in the accompanying test report. Specific modifications necessary to meet the above requirement, recommended by Integrity Design & Test Services, Inc. are described therein.

E01630–1–9/01(0)

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