

Creating a Reactive Energy Pulse Output Based on the ADE7753

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INTRODUCTION

This application note describes how to create a pulse output based on reactive energy readings from the ADE7753. The ADE7753 is an energy metering IC complete with rms, active, apparent, and reactive measurement capabilities. The quantities measured in the ADE7753 are read out through an SPI serial to parallel interface. For this example, the reactive energy pulse output application was implemented on a PIC16F877 microcontroller from Microchip.[®]

OVERVIEW

Definition of Reactive Energy

Reactive power is defined by the IEEE Standard Dictionary 100-1996 as:

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

where V_n and I_n are 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. Reactive energy is the accumulation of reactive power over time. It should be positive for an inductive load, where the current is leading the voltage.

Calculating Reactive Energy

There are two main ways of calculating reactive power—indirectly, using the power triangle or directly, using a low-pass filter.

Figure 1 shows the relationship between the active, reactive, and apparent energies that is assumed in the power triangle approach:

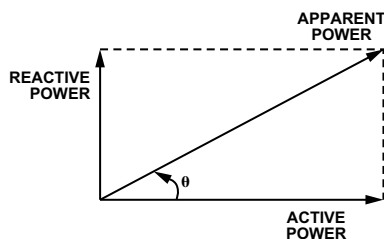


Figure 1. Power Triangle

$$\text{Reactive Energy} = \sqrt{\text{Apparent Energy}^2 - \text{Active Energy}^2}$$

This relationship holds up well at the fundamental frequency but significant error is introduced when harmonics are present.

In one type of direct reactive energy calculation, a constant 90° phase shift over frequency with an attenuation of 20 dB/decade is introduced. The cutoff frequency of the low-pass filter is set much lower than the fundamental frequency such that there is a 90° phase shift at any frequency higher than the fundamental. These frequencies are attenuated by 20 dB/decade. This solution is susceptible to variations in line frequency, which can be overcome by compensating the gain based on the line period. This is the method used by the ADE7753 to calculate reactive energy. The ADE7753 also has a period register that may be used by the microcontroller for gain compensation based on the line period.

Pulse Output in the ADE7753

The ADE7753 provides a pulse output proportional to active energy. This pulse output is ideal for use in calibrating the active energy functionality against a reference meter. For this calibration, a steady load is applied to the energy meter being calibrated and to the reference meter. The pulse output from the meter under calibration is compared to that from the reference meter. Gain and offset compensations are performed by adjusting active energy gain and offset registers, CFDEN, WGAIN, and APOS, until the pulse output from the meter under test matches the reference meter both at the base current, I_b , and a lower test current, I_{min} . Figure 2 shows the ADE7753 signal chain used to calculate and calibrate the active energy register, AENERGY and the CF pulse output.

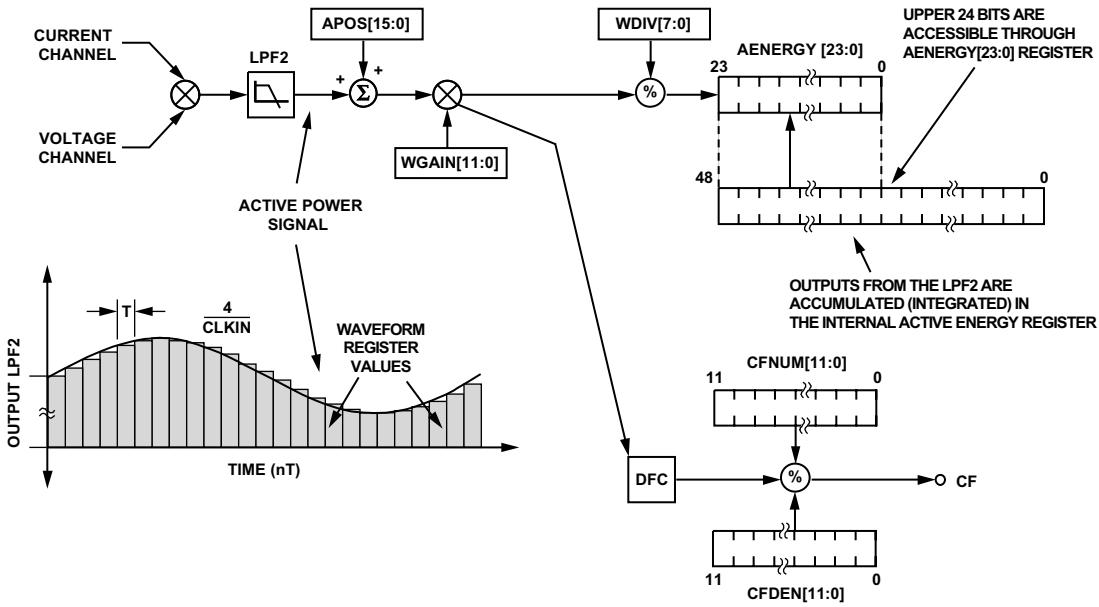


Figure 2. Active Energy AENERGY Register Signal Chain

Every time an LSB is accumulated in the active energy register, AENERGY, a pulse is generated at the digital to frequency converter. Once $(CFNUM+1)/(CFDEN+1)$ pulses have been generated by the digital to frequency converter, a CF pulse is issued on Pin 11. Figure 3 demonstrates how the digital to frequency converter outputs pulses based on the accumulated active energy.

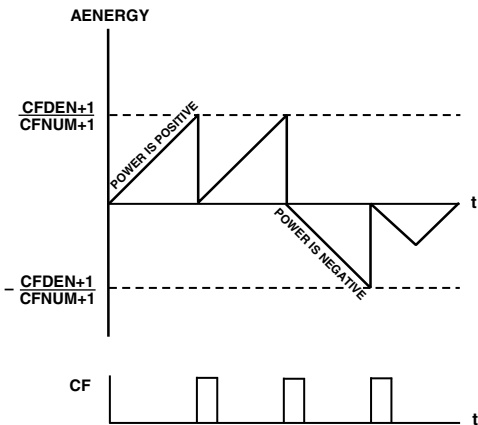


Figure 3. CF Pulse Output Diagram

The ADE7753 does not provide gain or offset correction registers for reactive energy. A reactive energy pulse output simplifies calibration of this portion of the meter and must be produced external to the ADE7753.

DESIGN GOALS

The ADE7753 provides reactive energy readings but does not have a pulse output dedicated to reactive energy. The goal for this design is to produce a reactive energy pulse output derived from the measured reactive energy in the ADE7753.

The reactive energy pulse output should have the same scaling as the active energy pulse output so that at a power factor of 0, the reactive pulse output has the same frequency as the active energy pulse output at a power factor of 1. As the active energy pulse output is typically calibrated to 3200 imp/kWh, the reactive energy pulse output in this example is also calibrated to 3200 imp/kVARh.

The reactive energy pulse output should be accurate to $\pm 2.5\%$ from $0.05I_b \leq I < 0.1I_b$ and $\pm 2\%$ from $0.1I_b \leq I < I_{max}$, as required by the IEC62053-23 specification for Class 2 reactive energy meters. A $\pm 2\%$ frequency variation should induce less than an additional 2.5% error.

DESIGN ARCHITECTURE

The ADE7753 provides reactive energy readings every half line cycle. The frequency of the reactive energy readings is based on the number of half line cycles included in the accumulation. This number is set by the LINECYC register in the ADE7753. To place the ADE7753 in line cycle accumulation mode:

1. Set the number of half line cycles for the accumulation in the LINECYC register, address 0x1C
2. Enable line cycle accumulation mode by setting the CYCMODE bit in the MODE register, address 0x09.
3. Set the CYCEN bit in the \overline{IRQ} enable register, IRQEN (address 0x0A), so that the \overline{IRQ} line will go low when line cycle accumulation readings are available.
4. Reset the status register by reading the RSTSTATUS register, address 0x0C.

5. Wait for the $\overline{\text{IRQ}}$ interrupt to go low and read the RSTSTATUS register (address 0x0C). The first line cycle accumulation energy readings after writing to the LINECYC register must be discarded because the accumulation time for this reading may not correspond to the new value in the LINECYC register.
6. Reset the status register by reading the RSTSTATUS register, address 0x0C.
7. Wait for the $\overline{\text{IRQ}}$ interrupt to go low and read the RSTSTATUS register, address 0x0C.
8. Read the LVARENERGY register, address 0x08.
9. Repeat steps 7 through 8 as desired.

Note that the line cycle accumulation readings available after the first line cycle accumulation interrupt may not be correct. It takes one line cycle accumulation period to lock on to a new value in the LINECYC register.

In order to turn these reactive energy readings available every LINECYC half line cycle into a pulse output, a VAR threshold that should result in a VARCF pulse being issued, must be set. This reactive energy pulse output level is done similarly to the CFNUM+1/CFDEN+1 ratio in the active energy CF signal path (see Figure 4). In this implementation, there is just one variable that sets the amount of reactive energy needed for a pulse to be output, the VARCFLEVEL.

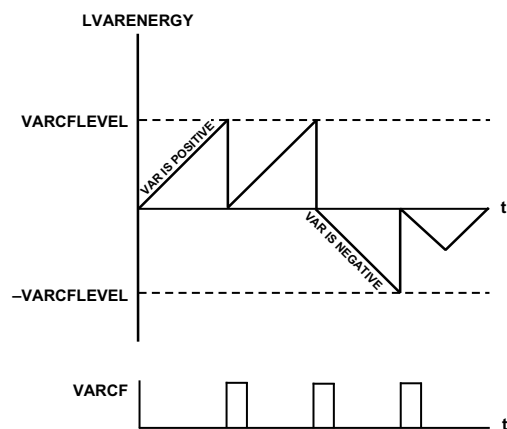


Figure 4. VARCF Pulse Output Implementation

In the ADE7753 CF signal chain, the active energy values are updated every $\text{CLKIN}/4$ where CLKIN is 3.579545 MHz. Reactive energy values are not available as frequently. Even with LINECYC set to one for a half line cycle accumulation time, new values are only available every 10 ms with a line frequency of 50 Hz.

To solve this problem, reactive energy is accumulated more often inside the microcontroller. The rate of reactive energy accumulation inside the microcontroller is based on a trade-off between microcontroller computing bandwidth and acceptable pulse output ripple. If the MCU can be devoted entirely to generating a pulse output, the accumulation rate can be much higher than for an MCU that is already burdened with other tasks. In this example, the MCU is entirely devoted to creating a reactive energy pulse output so a fast accumulation rate of 10 kHz was chosen, yielding a frequency output jitter of 100 μs .

In the ADE7753 active energy normal accumulation mode, there are two thresholds that result in the issuing of a CF pulse, a positive and a negative threshold. If the energy customer consumes or provides enough energy to the utility in normal accumulation mode within a certain amount of time, a CF pulse is issued. It is important to have a positive and a negative threshold instead of just accumulating the absolute value of the energy so that in the event that the sign of the energy is changing, the CF output remains accurate. In normal accumulation mode, the AENERGY active energy register on the ADE7753 uses a signed accumulation so x amount of positive energy followed by x amount of negative energy cancel each other. The same phenomenon should occur with the CF pulse output so that the relationship between the active energy register and the CF output frequency is maintained.

The positive and negative thresholds for issuing a VAR pulse are even more important as the sign of the reactive energy is more likely to change than the active energy. The occurrence where the customer stops using electricity from the utility and starts giving power back is much less frequent than the load changing from capacitive to inductive.

The active energy CF signal chain includes gain and offset compensation (see Figure 2). These compensations are also implemented for the VARCF pulse output. As previously mentioned, the ADE7753 method of reactive energy calculation requires gain compensation over line frequency. This compensation is performed through a look up table method. A no-load threshold is implemented to prevent VARCF pulses from being issued for too light of a load. The no-load prevents creep. This comprises the entire VARCF signal chain as shown in Figure 5.

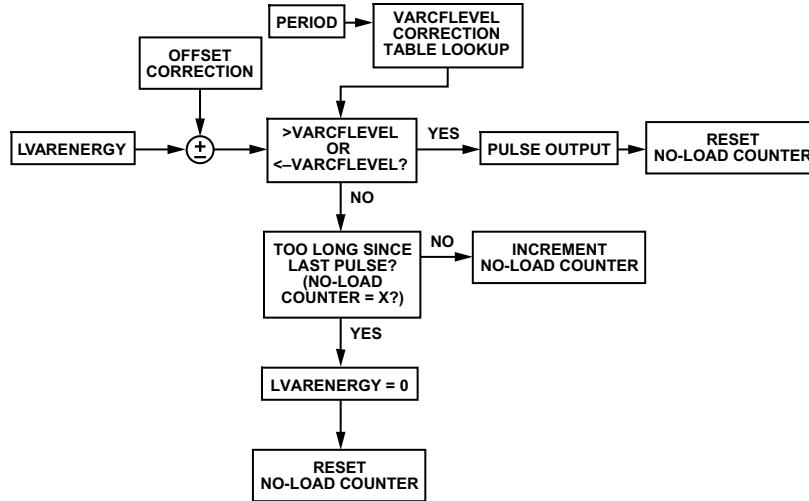


Figure 5. VARCF Signal Chain

DESIGN CALCULATIONS

This section describes the reactive energy pulse output gain, offset, and line frequency compensation techniques.

Gain

Reactive energy readings from the ADE7753 are accumulated over time to produce the reactive energy pulse output. The accumulator level that results in a pulse output must be chosen. This level is similar to the CF ratio in the active energy signal path in the ADE7753. The accumulator level sets the pulse output frequency for a given load.

From the Energy Scaling table in the ADE7753 data sheet, the ratio of the full-scale reactive energy LVARENERGY register to the active energy LAENERGY is 0.347:

$$LVARENERGY_{FS} = 0.347 \times LAENERGY_{FS}$$

The accumulated active energy for a given load is:

$$LAENERGY = PF \times \text{Average Value at } FS \times \text{Accumulation Time}(s) \times \%FS \times CLKIN / 4 \times 2^{-25}$$

where Average Value at FS is 0xCCCCD, the average LPF2 word value at full-scale with WGAIN = 0—see the Integration Time Under Steady Load section of the ADE7753 data sheet.

$$\text{Accumulation Time}(s) = \frac{LINECYC}{2f_l}$$

%FS is the active energy percent of full scale which is based on the level of the analog inputs. If the current and voltage inputs are set to half of the analog input range, the active energy is 1/4 of full scale.

So the expected LVARENERGY register reading with the default clock frequency, one half line cycle accumulation time and with both inputs at half-scale, is 19.4:

$$LAENERGY = PF \times 0xCCCCD \times \text{Accumulation Time}(s) \times \%FS \times CLKIN / 4 \times 2^{-25}$$

$$LAENERGY = PF \times 0xCCCCD \times \frac{1}{2 \times 50} \times \left(\frac{1}{2} \times \frac{1}{2}\right) \times \frac{3.579545 \times 10^6}{4} \times 2^{-25} = 55.9$$

$$LVARENERGY = 0.347 \times LAENERGY$$

$$LVARENERGY = 0.347 \times 55.9 = 19.4$$

As the LVARENERGY register only holds whole numbers, the value of the register will always be a whole number. The ADE7753 only allows register access to the 24 MSBs of the reactive energy but stores 15 LSBs in an internal register. These LSBs will accumulate and adjust the LVARENERGY reading between 19 and 20 accordingly, such that the average LVARENERGY register reading for this load is 19.4.

The ADE7753 data sheet calibration section details the steps required to calibrate an energy meter. The specifications for the example meter are:

- Meter Constant: MeterConstant (imp/kWh) = 3200
- Maximum Current: $I_{max} = 60 \text{ A}$
- Line Voltage: $V_{nominal} = 220 \text{ V}$
- Line Frequency: $f_l = 50 \text{ Hz}$
- Test Current: $I_b = 10 \text{ A}$

In this example I_{\max} and V_{nominal} scale to half of their respective analog input ranges. So for this meter, the maximum CF output with the current equal to I_{\max} and the line voltage equal to V_{nominal} is:

$$CF = \frac{\text{Meter Constant (imp / kWh)} \times \text{Load (kW)}}{3600 \text{ s / h}} \times \cos(\varphi)$$

$$CF_{\max} = \frac{3200 \times 60 \text{ A} \times 220 \text{ V} / 1000}{3600 \text{ s / h}} \times \cos(0) = 11.73 \text{ Hz}$$

Since we would like to be able to compare our VAR pulse output to the CF pulse output, the expected reactive energy pulse output at a power factor of 0 is fixed to be the same as our expected active energy pulse output at a power factor of 1.

With the microcontroller accumulation rate set to $100 \mu\text{s}$, the accumulator level that results in a pulse being issued, the VARCFLEVEL, is set to 0x3FA9 (16297 decimal):

$$\text{VARCFLEVEL} = \frac{\text{LVARENERGY}[24:0]}{\text{VARCF} \times \text{MCU Accumulation Time (s)}} \quad (1)$$

$$\text{VARCFLEVEL} = \frac{19.4}{12 \times 100 \times 10^{-6}} = 16297 \text{d} = 0\text{x}3\text{FA}9$$

Offset

The LVARENERGY register offset is determined by setting the power factor to 1. At a power factor of 1, no reactive energy should be measured. The VARCOFFSET can then be calculated from the frequency output.

Rearranging Equation (1) yields

$$\text{LVARENERGY} = \text{VARCFLEVEL} \times \text{VARCF} \times \text{MCU Accumulation Time (s)}$$

In this implementation, three bytes are used to set the offset: one is for sign of the offset, the second is for any whole offset, and the third is for fractional offset. The fractional offset is stored as an unsigned integer in the microcontroller with the decimal point fixed before the MSB such that:

$$\text{VARCOFFSET} = \text{LVARENERGY}[24:0] \times 2^8$$

The offset compensation is shown in Figure 6.

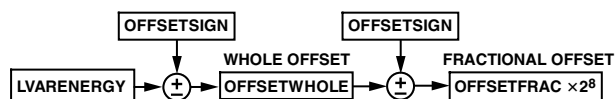


Figure 6. Reactive Energy Offset Compensation

Without looking at the actual sign of the LVARENERGY register, as opposed to the calculated value, it is impossible to tell whether the offset is positive or negative since the pulse output implementation should produce the same frequency for negative and positive VAR loads. So if the VARCF resulting from offset in the LVARENERGY register is 100 mHz, then a guess is made at the sign of the offset and OFFSETSIGN is set to positive. The whole offset, OFFSETHOLE should be set to zero and the fractional offset, OFFSETFRAC should be set to 0x2A (42 decimal):

$$\text{LVARENERGY} = \text{VARCFLEVEL} \times \text{VARCF} \times \text{MCU Accumulation Time (s)}$$

$$\text{LVARENERGY} = 0\text{x}3\text{FA}9 \times 0.1 \times 100 \times 10^{-6} = 0.16297$$

where

$$\text{VARCFLEVEL} = 0\text{x}3\text{FA}9$$

VARCF = 100 mHz, the pulse output frequency due to the offset, at a power factor of 1

$\mu\text{CAccumulationTime (s)} = 100 \mu\text{s}$, the time between microcontroller accumulations.

$$\text{OFFSETSIGN} = \text{SIGN}(\text{LVARENERGY})$$

$$\text{OFFSETSIGN} = 0$$

$$\text{OFFSETHOLE} = \text{INT}(\text{LVARENERGY})$$

$$\text{OFFSETHOLE} = 0$$

$$\text{OFFSETFRAC} = \text{LVARENERGY} \times 2^8$$

$$\text{OFFSETFRAC} = 0.16297 \times 2^8 = 42 = 0\text{x}2\text{A}$$

The OFFSETSIGN flag is used to indicate whether the offset is positive or negative. The fractional offset is accumulated every microcontroller accumulation cycle and every time it overflows, a bit is added or subtracted from the running reactive energy total based on the offset sign flag. A sign bit is needed to know whether to look for a rollover from 0x00 to 0xFF or from 0xFF to 0x00. These transitions are reflected in the carry bit in the status register. Storing the whole part of the offset in a separate register makes it easy to correct for any whole offset every microcontroller accumulation cycle.

No-Load Threshold

The reactive energy no-load threshold in the IEC62053-23 standard for a Class 2 meter is 0.5%lb. This corresponds to 0.0209% of the full-scale reactive energy reading of the ADE7753. The ADE7753 has a more stringent active energy no-load threshold of 0.001% of the full-scale multiplier output. In this example, I_{max} and $V_{nominal}$ are both set to half scale so the ADE7753 active energy no-load threshold is 0.4692 mHz:

$$CF_{no-load_1} = No\ Load\ Threshold_1 \times CF_{max} \times \frac{1}{\%FS}$$

$$VARCF_{no-load_1} = 0.00001 \times 11.73\ Hz \times \frac{1}{0.5 \times 0.5} = 0.4692\ mHz$$

In this example, the reactive energy no-load threshold is implemented by counting the number of half line cycle periods that have passed since the last pulse. A no-load threshold of 0.4692 mHz, or 2131.29 seconds without a pulse, corresponds to 0x034089 (213,129 decimal) half line cycles at 50 Hz. So if 213,129 half line cycles have passed since the last pulse, then the accumulated LVARENERGY is cleared and the half line cycle count resumes from zero.

In this implementation, the reactive energy no-load threshold is set according to the IEC62053-23 specification, using the same concept as the active energy no-load threshold. This reduces the resolution required in the offset register and makes it so that only two bytes are required for counting half line cycles for the no-load threshold instead of the three that would be required for the stricter no-load threshold.

$$CF_{no-load_2} = No\ Load\ Threshold_2 \times CF_{max} \times \frac{1}{\%FS}$$

$$VARCF_{no-load_2} = 0.000209 \times 11.73\ Hz \times \frac{1}{0.5 \times 0.5} = 9.795\ mHz$$

Line Frequency Gain Compensation

This algorithm for producing a reactive pulse output requires an additional gain correction of the LVARENERGY readings over line frequency. To account for a variable line cycle frequency, two 1/f compensations need to be performed on the LVARENERGY readings, one to properly scale the readings based on their accumulation times and another to account for the 1/f attenuation of the reactive energy readings in the ADE7753.

The calculations for the pulse output assume that the gain of the LVARENERGY register is constant. However, the gain of the LVARENERGY register varies with line frequency. For example, at a line frequency of 52.5 Hz, less energy will be accumulated within a half line cycle than at 50 Hz since the accumulation time is shorter. Without gain compensation the pulse output for 52.5 Hz would be slower than for 50 Hz with the same load applied because the 52.5 Hz LVARENERGY readings would be lower. So a 1/f correction factor is required to properly weight the LVARENERGY readings across different accumulation times.

A low-pass filter is implemented on the current channel for calculating the reactive energy. This filter introduces an additional 1/f attenuation in the reactive energy readings.

Typically the line frequency can vary $\pm 5\%$ so the gain of the reactive energy register needs to be compensated to accurately represent the reactive energy during these fluctuations.

The ADE7753 PERIOD register can be used to determine the line frequency:

$$Line\ Period(s) = PERIOD \times \frac{8}{CLKIN}$$

The amount of reactive energy that must be accumulated to output a pulse, the VARCFLEVEL, is adjusted according to this PERIOD reading. In this implementation a lookup table is used for the corrections so that these calculations do not have to be done in the microcontroller.

Table I. VARCFLEVEL Line Frequency Correction Table

PERIOD (Decimal)	Corrected VARCFLevel	Table Index
8512	0x3974	0
8544	0x39E2	1
8576	0x3A52	2
8608	0x3AC1	3
8640	0x3B31	4
8672	0x3BA2	5
8704	0x3C13	6
8736	0x3C84	7
8768	0x3CF6	8
8800	0x3D68	9
8832	0x3DDA	10
8864	0x3E4D	11
8896	0x3EC1	12
8928	0x3F34	13
8960	0x3FA9	14
8992	0x401D	15
9024	0x4092	16
9056	0x4108	17
9088	0x417D	18
9120	0x41F4	19
9152	0x426A	20
9184	0x42E2	21
9216	0x4359	22
9248	0x43D1	23
9280	0x4449	24
9312	0x44C2	25
9344	0x453B	26
9376	0x45B5	27
9408	0x462F	28

Since the line frequency can vary $\pm 5\%$, the correction table must accommodate the nominal PERIOD register reading $\pm 5\%$. The nominal PERIOD register reading at 50 Hz is about 8960 decimal. Therefore PERIOD readings from 8512 to 9408 must be corrected.

It would be easy to use the PERIOD register readings to directly index into a correction table, but at 896 entries, this table would be too big. To index a smaller correction table using the PERIOD register readings there needs to be a formula to calculate the index into the correction table array from the PERIOD register value. If possible, a multiplication should be avoided as with this microcontroller it will take about 200 instruction cycles to perform a 16 by 16 multiplication. The incentive for using a lookup table is to reduce the time it takes to get the proper result. So there needs to be a fast way to index this table.

In a microcontroller it is easy to divide by 2^n by right shifting the operand. Since 896 entries are evenly divisible by 2^5 , or 32, this is an efficient way of indexing the correction table. The table has $896/32 + 1 = 29$ entries, resulting in a worst case 0.4% error. With more resolution and therefore more entries in the table, the percent error would be reduced. The index into the correction table is the $(\text{PERIOD} - \text{PERIOD}_{\text{nominal}})/32 + 14$. The entries for the table are calculated by multiplying the nominal VARCFLEVEL by $(\text{PERIOD}/\text{PERIOD}_{\text{nominal}})^2$ so that when the line frequency is higher than nominal, the VARCFLEVEL is lowered to accommodate the lower LVARENERGY register readings.

For example, if the PERIOD is 9408 and the nominal PERIOD is 8960, the array index should be 28:

$$\text{INDEX} = (\text{PERIOD} - \text{PERIOD}_{\text{nominal}}) / 32 + 14$$

$$\text{INDEX} = (9408 - 8960) / 32 + 14 = 28$$

The lookup table entry for a PERIOD of 9408 with a nominal PERIOD of 8960 and a nominal VARCFLEVEL of 0x3FA9 is calculated to be:

$$\text{Lookup Table Value} = \text{VARCFLEVEL}_{\text{nominal}} \times \left(\frac{\text{PERIOD}}{\text{PERIOD}_{\text{nominal}}} \right)^2$$

$$\text{Lookup Table Value} = 0x3FA9 \times \left(\frac{9408}{8960} \right)^2 = 17967.44 = 0x462F$$

Firmware Architecture

The flowchart for the firmware implementation used to create the VARCF pulse output is shown in Figure 7.

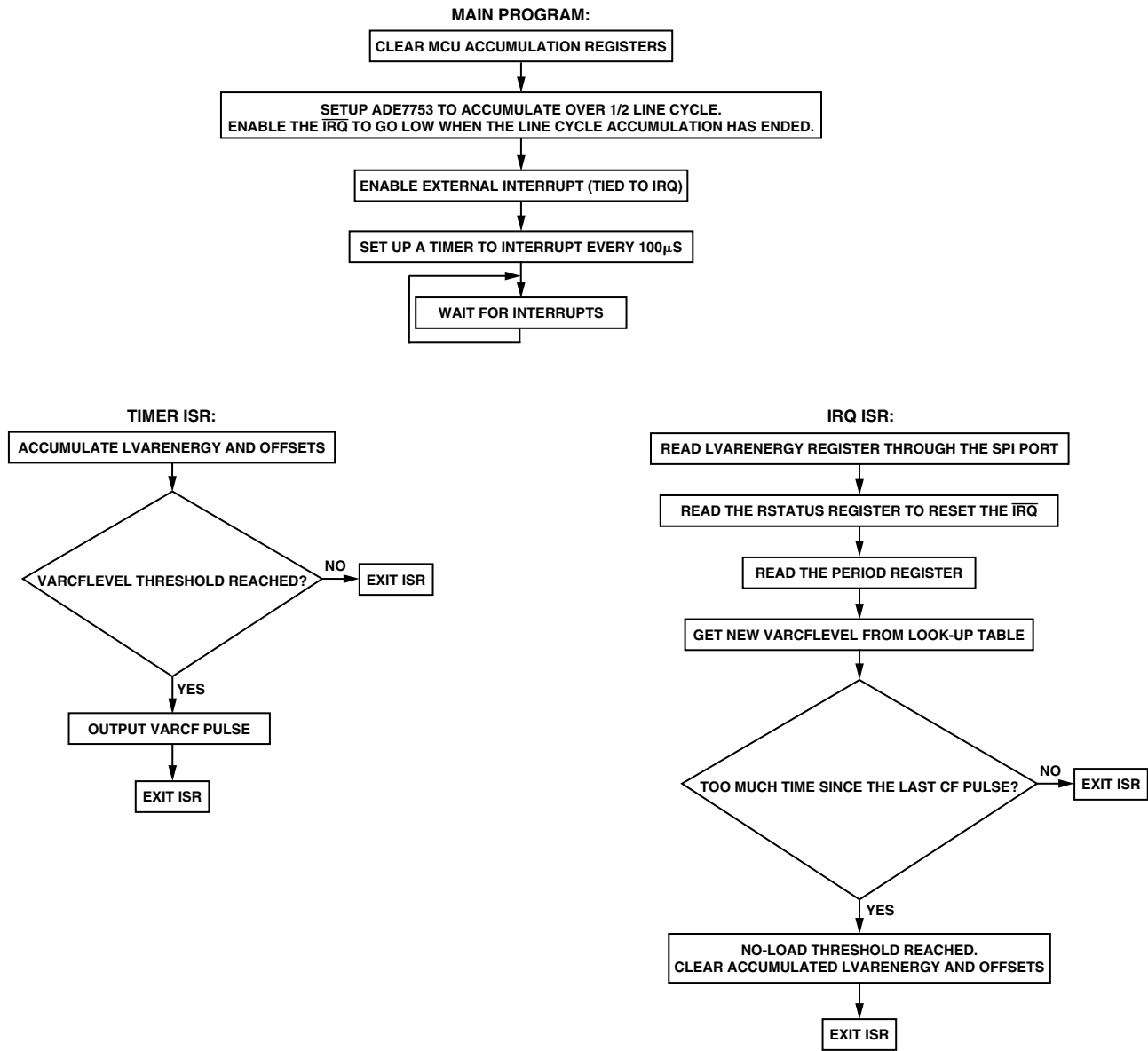


Figure 7. Microcontroller Flow Chart

RESULTS

Linearity

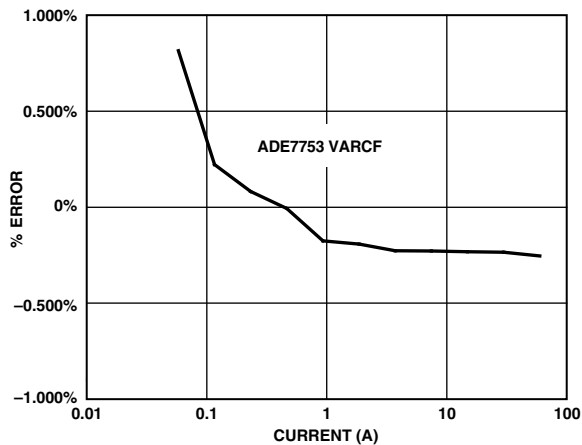


Figure 8. VARCF Linearity

The VARCF linearity error shown in Figure 8 is within the IEC 62053-23 Reactive Energy Class 2 specification for current variation. The specification requires:

Less than $\pm 2.5\%$ error from $0.05I_b \leq I < 0.1I_b$

Less than $\pm 2\%$ error from $0.1I_b \leq I < I_{max}$.

This meter was calibrated with an I_b of 10 A and an I_{max} of 60 A. Thus there must be less than $\pm 2.5\%$ error from 0.5 A to 1 A. There must be less than $\pm 2\%$ error from 1 A to 60 A.

Performance with Line Frequency Variation

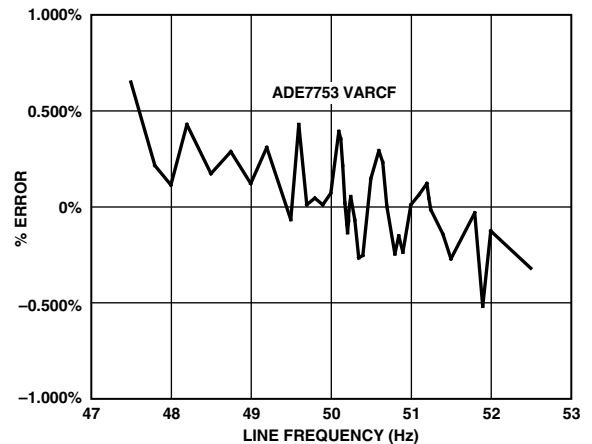


Figure 9. VARCF Performance with Line Frequency variation

Figure 9 shows the performance of the VARCF pulse output over line frequency. The gain of the VAR readings must be compensated over line frequency because the digital to frequency converter accumulates at a constant frequency and assumes a fixed period for its input. An additional gain compensation is performed for the ADE7753 to account for the gain attenuation of the LPF used to calculate reactive energy. A look-up table is used to perform the gain compensation, so the error characteristic has a sawtooth pattern. This results from the frequencies that are on the edge of two compensation bins and hence are not compensated ideally.

This VARCF implementation is within the IEC 62053-23 Reactive Energy Class 2 specifications for variation over the line frequency influence quantity. The specification requires less than $\pm 2.5\%$ error induced from $\pm 2\%$ frequency variation.

The graph shown above is for $\pm 5\%$ frequency variation and is well within this specification.

