



Single-phase energy meter with tamper detection
based on ST7FLITE2x

Introduction

This application note describes the design for a single-phase power / energy meter with tamper detection. The design measures active power, voltage, current, power factor and line frequency in a single-phase distribution environment and displays active energy, voltage, current, power factor, line frequency, current date and time. It differs from ordinary single-phase meters in that it uses two current transformers (CT) to measure active power in both live and neutral wires. This enables the meter to detect, signal, and continue to measure the active energy consumed reliably even when subject to external tamper attempts.

ST7FLITE20 is the microcontroller used to perform all the measurements in the meter. As the ST7FLITE30 is pin-to-pin compatible with ST7FLITE20, the ST7FLITE30 can also be used in this application (replacing the ST7FLITE20) but a revalidation is required for finding the accuracy class of the meter.

The active energy consumed is available in the form of frequency-modulated pulse outputs and the accumulated active energy on an LCD display module. Additional features for both consumer types can also be incorporated. These include multiple tariff rates and improved communications, through which meter readings can be taken with less time and with higher accuracy.

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1 Features

- Cost-Effective and Flexible Single-Phase Energy Meter
- ASSP is not used; microcontroller is doing all the measurements and calculations
- Fulfills IEC 61036:1996 + A1: 2000, Static meter for active energy (classes 1 and 2) for $I_b=10A$ and $I_{max}=55A$
- Meter starts at few mA
- Detects, Signals and Continues to Measure Accurately under tamper Condition
- Compact design with Internal Flash memory, SRAM and external EEPROM
- External EEPROM used to store calibration parameters, tampering information and accumulated kWh. This is more secure than using internal EEPROM, as it keeps the data away from the risk being lost on a burnt microcontroller.
- Flexibility to use External or Internal EEPROM by changing only the sales type to ST7FLITE29 (embedded with 256 bytes of EEPROM) without changing the hardware design
- Gain multipliers (Operation Amplifier) are used for wider range of load with $I_b=10A$ and $I_{max}=5.5I_b$
- Large line voltage operable range from 140V to 300V
- Active power, current, voltage, power factor and line frequency measurements
- RTC for displaying current date and time
- LCD module for display accumulated kWh, V_{rms} , I_{rms} , power factor, line frequency, current date and time
- Secure and reprogrammable Flash memory enables flexible firmware updates up to 10k cycles
- Adjustable Active Energy Pulse Output goes up to 32 000 Impulses/kWh
- Large Compensation of Phase difference generated by CTs by hardware (increasing or decreasing capacitor values at current channel)
- One-Time, Quick, and Accurate Digital Calibration gives added benefits like more accurate calibration and no need for Trimming external components

2 Overview

Power meters / Energy Meters are also known as kiloWatt-hour meters. As per definition, energy consumed is a measure of work that is done over a known time period. Suppose, a heater of 2kW is ON for half an hour, the consumed energy will be $2000W \times 1800s = 3\,600\,000W\cdot s$ (Watt-second), which is 1kWh.

The Active Energy Pulse output of 50% duty cycle is an indication of active power consumed, as measured by the power meter. If the active power is higher, the frequency of the pulse will also be higher. The pulse count gives the active energy measured by the meter. The greater the number of pulse counts, the greater the amount of consumed active energy. The pulse output frequency is easily configurable by software. The current software has 3,200 impulses per kiloWatt-hour.

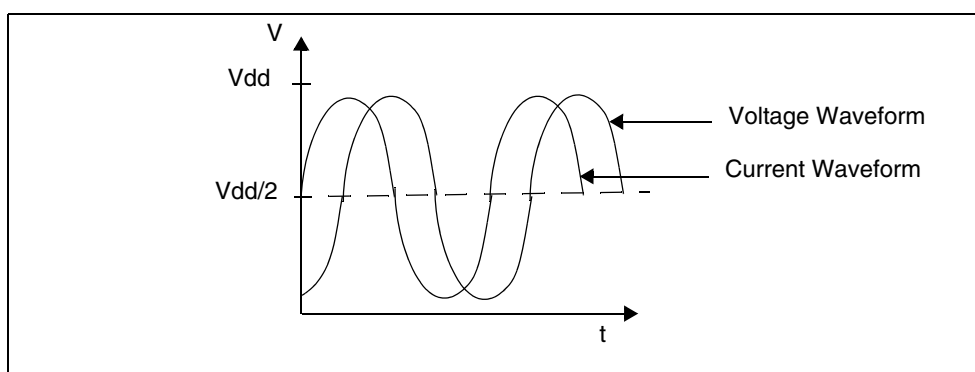
All the measurements can be calibrated by software, so there is no need for any trimming components. With the firmware, phase difference created between voltage and current due to current transformer can also be compensated. Because only one ADC is used to convert both analog voltage and current signal into digital form and there is no dual sampling feature available in the ST7FLITE20 microcontroller, the shift error (the sampling difference between voltage and current) can also be compensated by the firmware. The calibration procedure can be automated, which removes the time-consuming manual trimming required in traditional, electromechanical meters. Digital calibration is fast and efficient, reducing the overall production time and cost. Calibration coefficients, accumulated kWh and tampering information are safely stored on the external EEPROM. This is more secure than internal EEPROM since data would be lost in the event of a burnt microcontroller. Internal EEPROM can be used in place of external EEPROM by changing only the microcontroller (without any change in hardware design), if the consumer or supplier prefers.

The most important part of the meter is the firmware which includes tampering detection functionality in a single-phase meter. The firmware can be modified and updated at any time by using In-Circuit Programming, even when the meter is installed and running. The firmware is entirely written in C except some time critical routines which are written in assembly, which makes modifications easy to implement.

3 Theory

The main objective of this application note is to demonstrate that a low cost energy meter can be implemented without use of an external dedicated device (ASSP). Only a single 10-bit SAR ADC is used to perform voltage and current measurements. The ADC on ST7FLITE20 device accepts input from 0 to V_{dd}. Since the V_{dd} is +5V, the operable range of the ADC is 0 to +5V. Since the ADC is operable in the positive range only, the AC input signals of voltage and current have to be shifted up and centered around +2.5V. This is achieved by biasing one end of the secondaries of current transformers and one end of potential divider with +2.5V. The input waveform of current and voltage to ADC is shown in figure1.

Figure 1. AC input signals to ADC



Four ADC input channels are used, three for current and one for voltage measurement. One of the current channels is multiplexed with two current gain factors x128 and x512. The sampling rate for each channel is 5kHz. This higher rate of sampling is there to reduce the quantization noise. The active energy consumed is calculated based on instantaneous value of power. The sampling rate is 5kHz, so, with a 50Hz sinewave the number of samples per cycle is 100. The sampling time is 200μs. After every 200μs, one current and voltage sample is taken and multiplied to get an instantaneous power sample. The discrete summation of these power samples over time gives the active energy.

When the phase difference between voltage and current is 0, the active power will be at the maximum which is equal to total power, and the reactive power will be 0.

If $v(t) = V\sin(\omega t)$ and $i(t) = I\sin(\omega t - \phi)$, the instantaneous power:

$$= (VI/2)(\cos(\phi) - \cos(2\omega t - \phi))$$

$$P(t) = v(t) \times i(t)$$

After averaging, we get $\cos(2\omega t - \phi) = 0$ for a cycle of sinewave. So, the theoretical average power (**P**) is $VI\cos(\phi)/2$. If i_k and v_k are respectively the instantaneous values of the current and the voltage, the discrete formula of average power with regular, simultaneous, voltage and current samples is:

$$P_d = (1/N) \sum_{k=0}^{N-1} v_k \times i_k$$

So, the average active energy over a time period with N samples is:

$$E_d = t_{\text{sampling}} \sum_{k=0}^{N-1} v_k \times i_k$$

There is delay (δ) between each voltage and current sample, due to this the real phase shift angle (α) between $v(t)$ and $i(t)$ is different than theoretical phase shift angle (ϕ). So, there is a discrete error (ε_d):

$$P_d = P + \varepsilon_d$$

$$\varepsilon_d = \frac{V \times I}{2 \times N} \sum_{k=0}^{N-1} \cos(2\alpha + 2K\omega t - \phi)$$

The average ε_d will be 0. So, $E_d = E$.

There is also error due to non-simultaneous sampling, which is shift error (ε_{ns}):

$$\varepsilon_{ns} = \frac{V \times I}{2} \left[\delta \sin(\phi) + \frac{\delta}{N} \sum_{k=0}^{N-1} \cos(2\alpha + 2K\omega t - \phi) \right]$$

$$P_{ns} = P + \varepsilon_{ns} + \varepsilon_d$$

$$P_{ns} = P + \varepsilon_{ns}$$

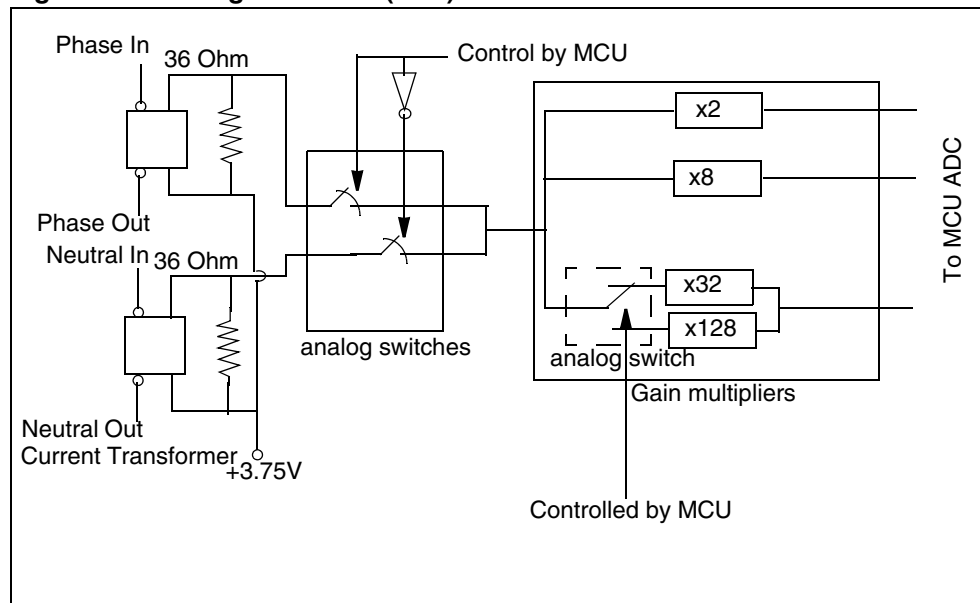
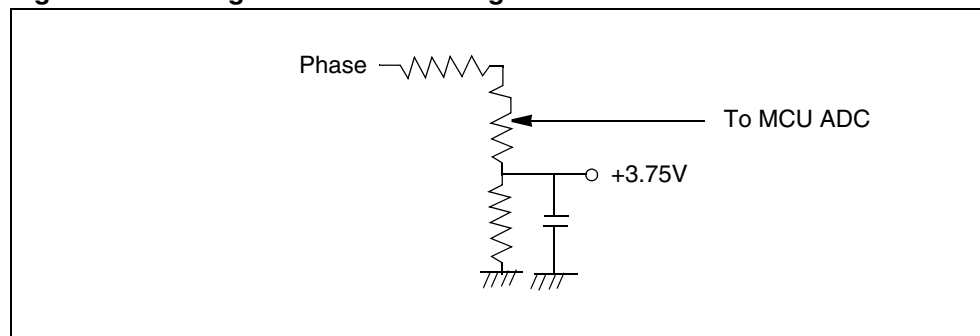
The total active energy including not simultaneous sampling will be:

$$E_{ns} = E_d + \sum \varepsilon_d$$

3.1 Analog front end

The ADC used in this application is only one 10-bit SAR ADC for current as well as voltage sampling. The voltage is reduced by potential divider and lifted up by $V_{dd}/2$ (e.g. 2.5V) and then given to one of the ADC channels of ST7Lite20 microcontroller to get the digital converted value after every 200us. The Lite2 timer RTC2 interrupt is used to get 200us.

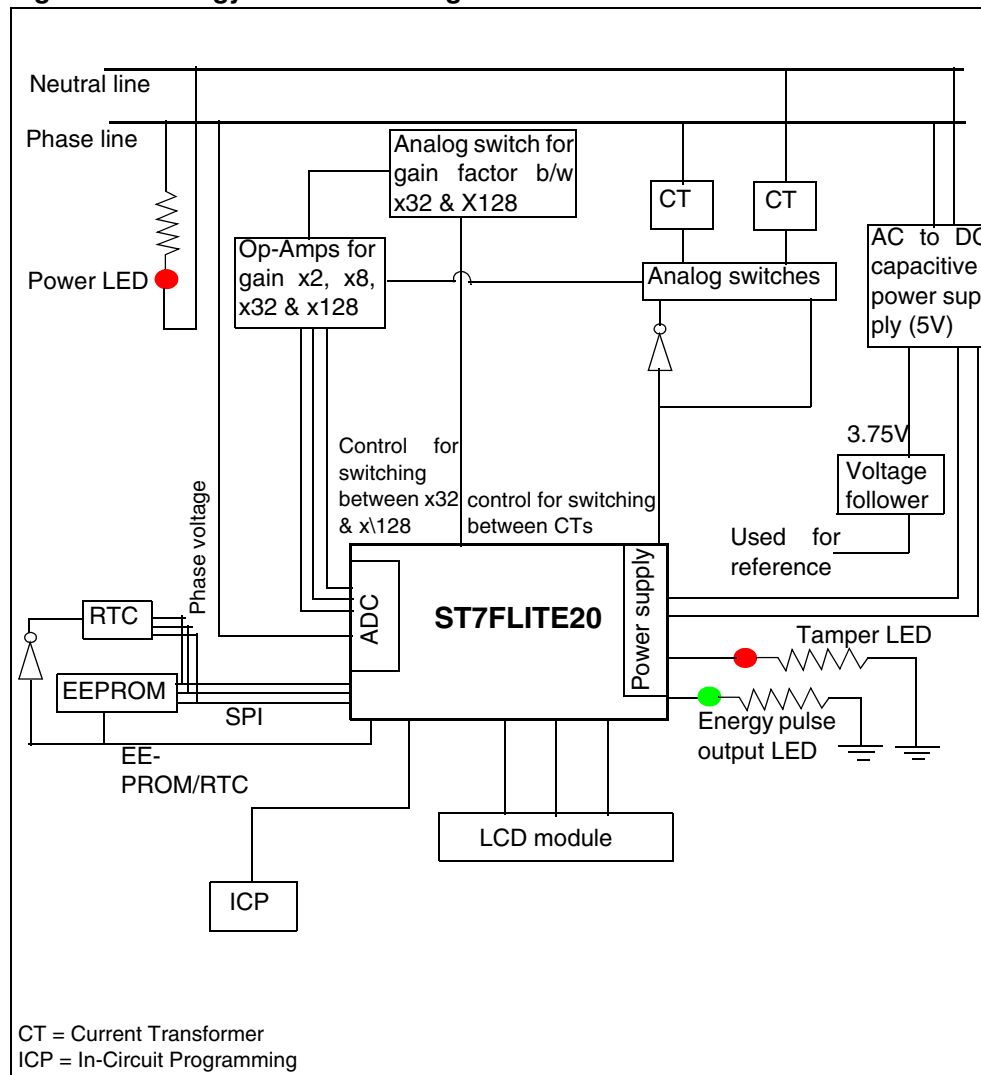
The current value is measured using a current transformer with a 1:5000 turn ratio and with 36 Ohm shunt resistance. The voltage induced across the current transformer is lifted up by $3V_{DD}/4$ (e.g. 3.75V) to make the induced voltage unipolar (because the microcontroller works in one direction only). Two analog switches are used for tampering detection phenomena. The output of both switches are connected, but the inputs are different, one from phase line and the other one from neutral line. The output goes to gain multipliers e.g. operational amplifiers. There are four gain multipliers implemented by three operation amplifiers and with one analog switch. The gain factors are x2, x8, x32 and x128. The x32 and x128 are multiplexed using one op-amp and one analog switch. The output of the gain multipliers goes to the ADC channels of the microcontroller. The active channel for current is selected based on current range.

Figure 2. Analog Front End (AFE) for current**Figure 3. Analog Front End for voltage**

4 Meter hardware

The block diagram of meter hardware is shown below:

Figure 4. Energy meter block diagram



4.1 Main blocks

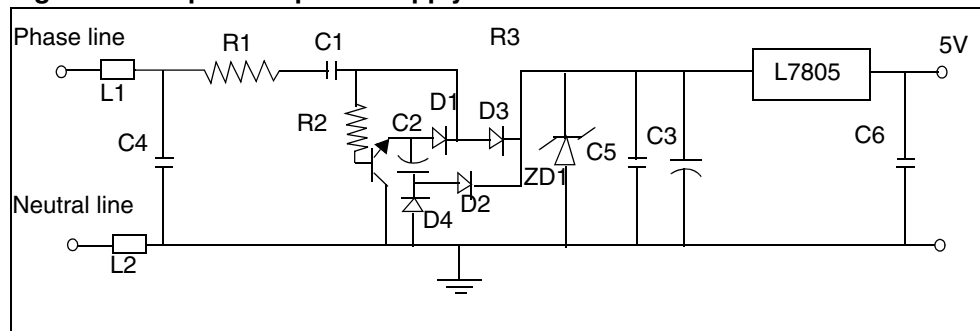
These are the main blocks in the Meter:

- 5V Power supply block
- 3.75V reference block
- Current Transformer block
- Voltage divider block
- Tamper detection block
- Gain switching block
- EEPROM block
- RTC block
- LCD Module
- In-Circuit Programming block
- Calibration through PC GUI
- Microcontroller block

4.1.1 5V power supply block

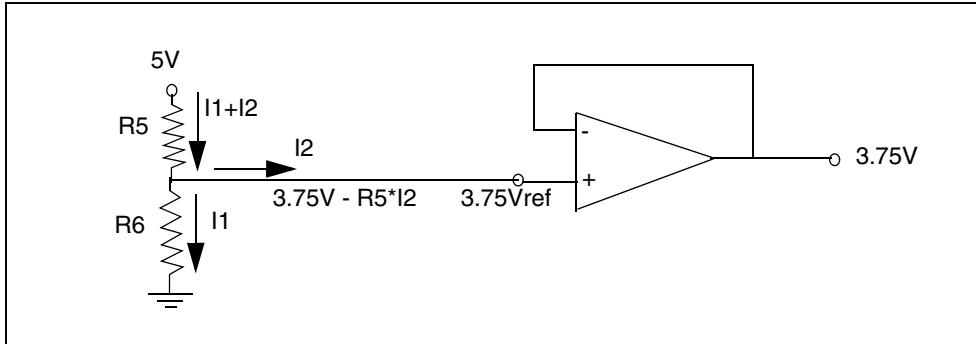
The 5V capacitive power supply is based on full-wave rectification. The positive half wave is used to charge the capacitor and as well as negative half wave of sinewave is also used to charge the capacitor in the same direction. The zener diode (ZD1) tells to which voltage the C3 is charged. Voltage regulator U1 utilizes the energy stored in C3 to produce a stable output voltage. Resistor R1 controls the charge and discharge of C1 and also limits the current flow through zener diode ZD1. Two inductors (L1 and L2) are used to reduce the noise in power supply.

Figure 5. Capacitive power supply



4.1.2 2.5V reference block

A potential divider is used to get a 3.75V reference. As some current (I_2) flows towards the voltage follower (refer to [Figure 6](#)), the current through R5 is higher than that through R6. If $R_5 = R_6$, there is a voltage drop of $R_5 \cdot I_2$ in the reference. This voltage drop is variable, which depends on the current flow through reference I_2 . If I_2 is negligible and constant, this 3.75Vref will be ~3.75 and constant. So, a voltage follower is used to get ~3.75V constant reference.

Figure 6. 2.5V reference circuit

4.1.3 Current transformer block

The current transformer used has a turn ratio of 1:5000 and ~350 Ohm resistance, the shunt resistance used is 36 Ohms (refer fig. 2), so, the effective resistance will be:

$$R_{\text{shunt}} = \frac{350 \times 36}{350 + 36} = 32.64 \Omega$$

After multiplication of secondary current with R_{shunt} , the voltage V_{shunt} for max current will be:

$$V_{\text{shunt}} = \frac{55\text{A}}{5000} \times R_{\text{shunt}} = 359\text{mV}$$

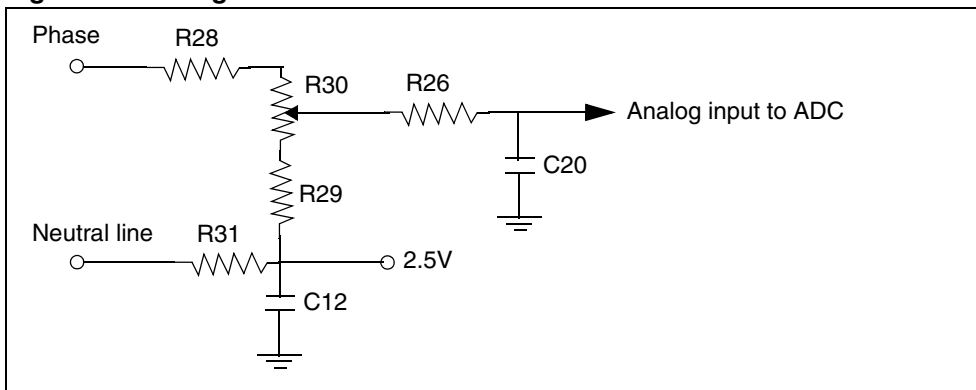
V_{shunt} is multiplied with gain stage to give actual value to input to microcontroller ADC. The minimum multiplication factor is x2. The MAX current is chosen such that the operational amplifier should not saturate. So, with x2 the max value of V_{AIN} is:

$$V_{\text{AIN}}(\text{MAX}) = 359\text{mV} \times 2 \times \sqrt{2} = 1.015\text{V}$$

The peak to peak voltage is 2.03V. There is safe margin of ~0.47V for a gain factor of x2.

4.1.4 Voltage divider block

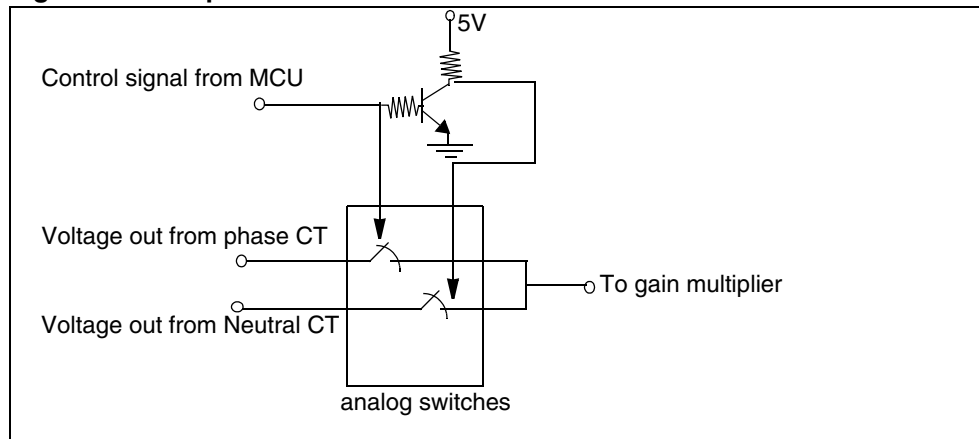
The voltage is reduced using a potentiometer and referenced at 3.75V.

Figure 7. Voltage divider circuit

4.1.5 Tamper detection block

Two analog switches and one control pin with one fast switching transistor is used to detect tampering.

Figure 8. Tamper detection circuit



4.1.6 Gain switching block

Gain multipliers are used to get the large load range with $I_b=10A$ and $I_{max}=55A$. In this application, there are four gain multipliers x2, x8, x32 and x128. A particular gain factor is actively used by the microcontroller, depending on the signal strength. For the lowest signal strength x128 gain factor is used. The operational amplifiers are used in non-inverting mode.

$$\text{Gain} = \left(1 + \frac{R_F}{R_1}\right)$$

where R_F is negative feedback resistance
 R_1 is resistance at inverting terminal of Op-amp

The exact gain factors are:

$$x2 = \left(1 + \frac{470E}{470E}\right) = 2$$

$$x8 = \left(1 + \frac{1.5K}{220E}\right) = 7.818$$

$$x32 = \left(1 + \frac{16K \parallel 51K}{390E}\right) = 32.23$$

$$x128 = \left(1 + \frac{51K}{390E}\right) = 131.77$$

When the voltage after x2 multiplier decreases below $\sim 2.03V_{p-p}/4 (= \sim 0.508V)$, the gain factor will change to x8 or when the voltage after x8 multiplier increases after $\sim 2.03V$, the gain factor will change to x2. There is some hysteresis also implemented for this. So, when upper half of sinewave after x2 decreases below $\sim 0.508V/2 (= \sim 0.254V)$, the active gain

factor will change to x8 or when upper half of sinewave after x8 increases after 1.015V, the active gain factor will change to x2. The Irms will be:

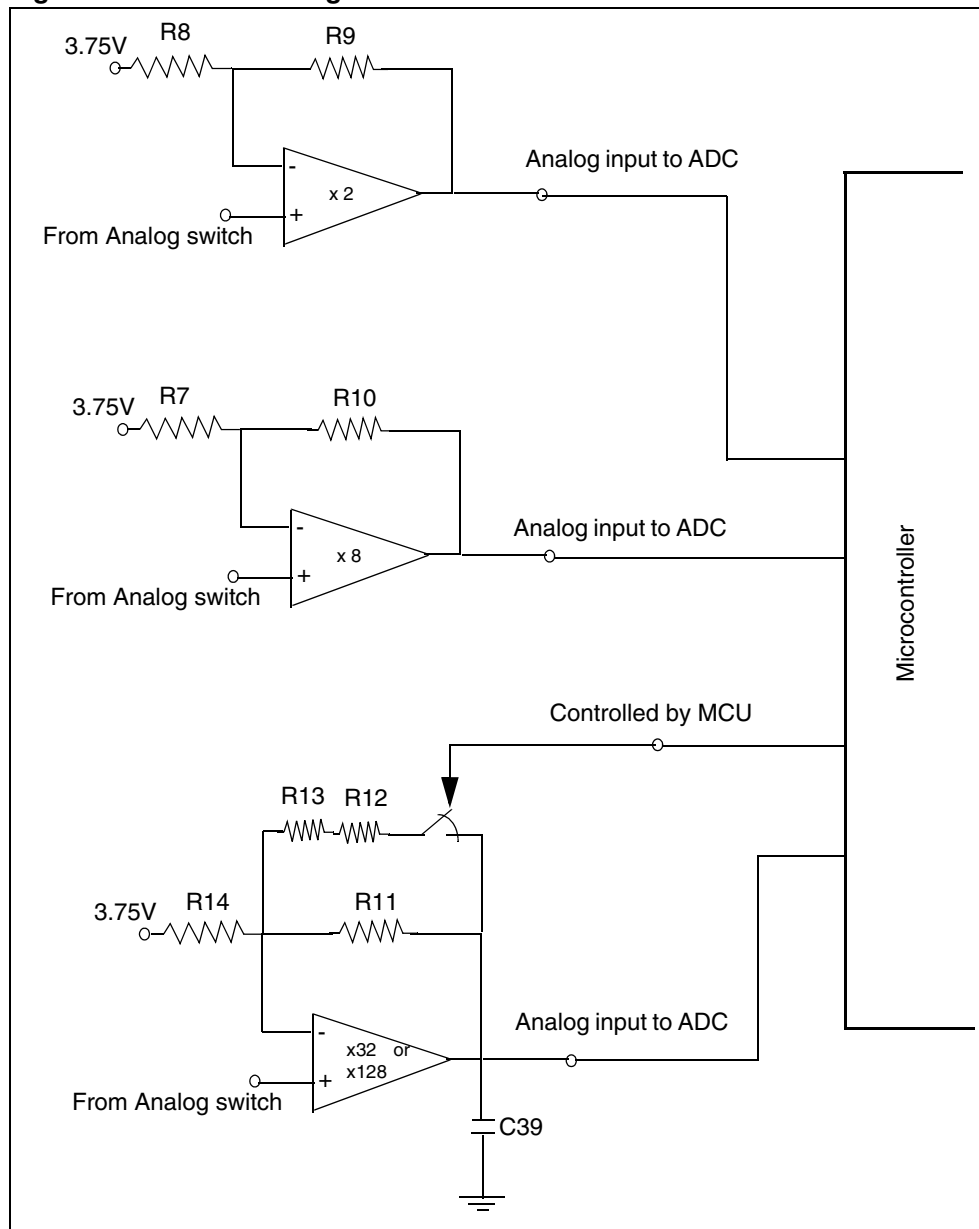
$$\frac{\sqrt{2} \times I_{rms} \times (R_{shunt} \times x2)}{5000} = 0.253V$$

The same logic applies with the x8 voltage multiplier. Below ~0.508V, the gain factor increases to x32. At this level, when the voltage increases higher than 2.03V, the gain factor drops back to x8. The Irms can be calculated (using just the upper half of the sinewave):

$$I_{rms} = \frac{13.7 \times 7.818}{32.23} = 3.32A$$

The same logic applies with the x32 voltage multiplier. Below ~0.508V, the gain factor increases to x128. At this level, when the voltage increases higher than 2.03V, the gain factor drops back to x32. The Irms can be calculated (using just the upper half of the sinewave):

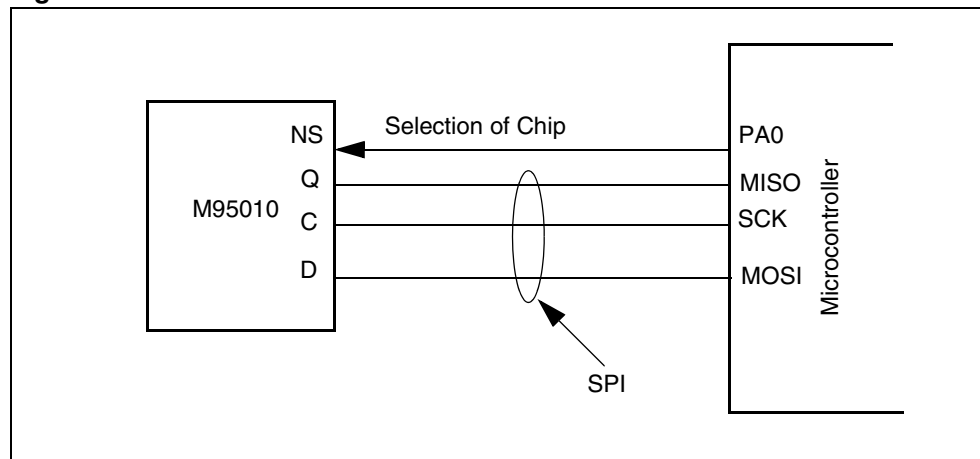
$$I_{rms} = \frac{3.32 \times 32.23}{131.77} = 0.81A$$

Figure 9. Gain switching circuit

4.1.7 EEPROM block

After power up, the accumulated kWh data, tampering information and calibration parameters are read by the microcontroller and stored in the form of RAM variables. When the meter is tampered, the tampering information (meter is tampered and tampered channel) will be stored in the EEPROM immediately. When power goes off, the accumulated kWh data will be stored in the EEPROM.

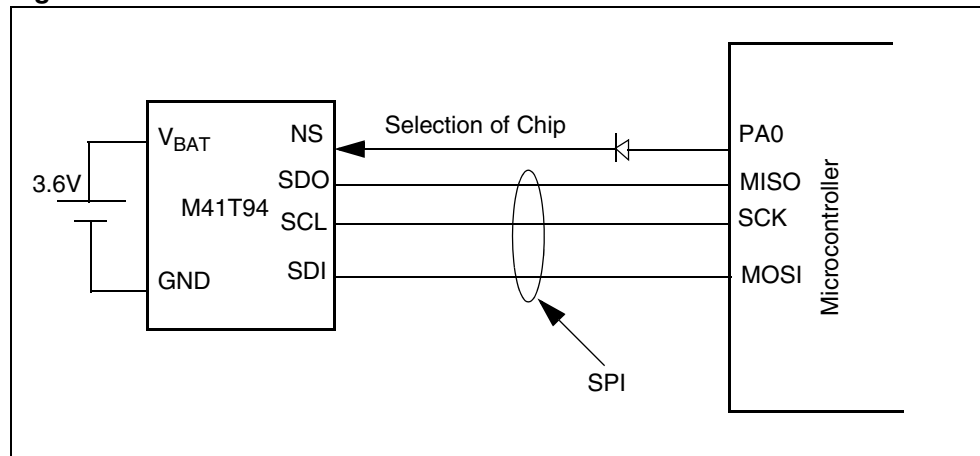
Figure 10. EEPROM circuit



4.1.8 RTC block

RTC block is used to show current date and time. When power goes down, RTC will be entered in low power mode and then power will be given by rechargeable battery of 3.6V, so that internal RTC registers gets updated according to the real time. When power goes up, supply is given by Vcc and battery charging is started.

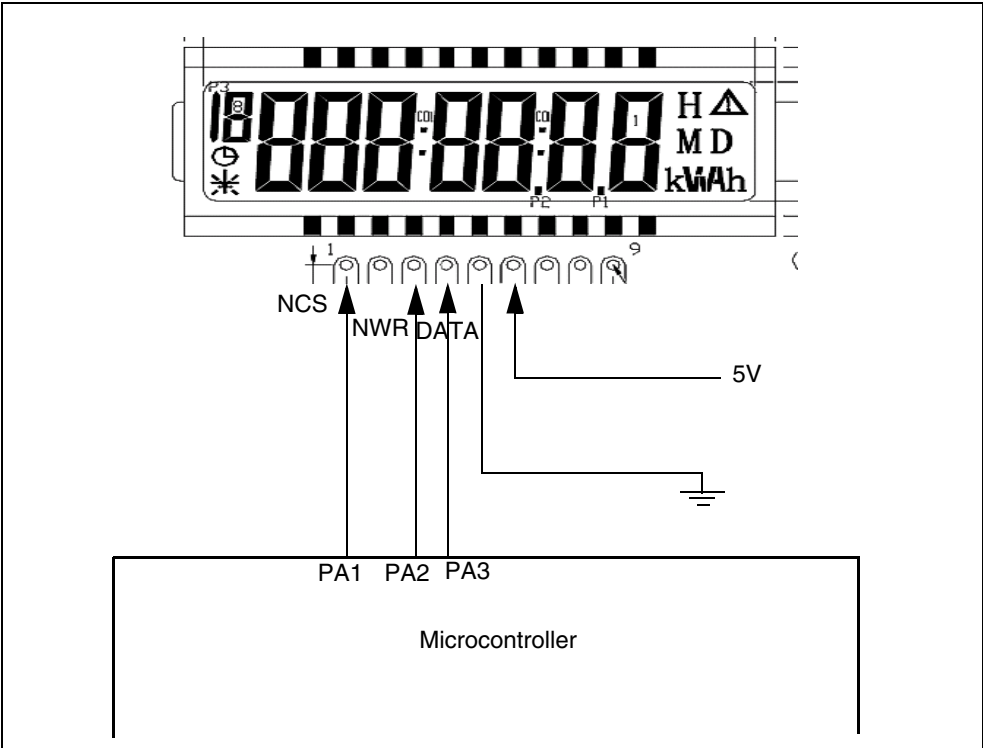
Figure 11. RTC circuit



4.1.9 LCD module

GDM093 module is used to display accumulated kWh, instantaneous rms voltage, instantaneous rms current, instantaneous power factor and line frequency. This LCD module uses HT1621 controller. This module has 18X4 segment.

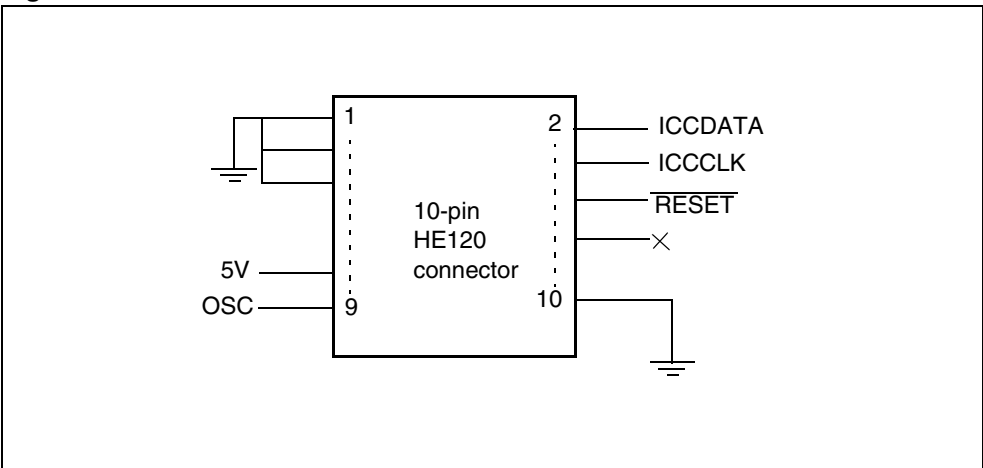
Figure 12. LCD circuit



4.1.10 In-Circuit Programming block

By using In-Circuit Programming, the microcontroller can be programmed even when the meter is installed and running. There are only five pins used from the 10-pin HE10 ICC connector. One oscillator pin is also optional. In all, there are only four mandatory pins.

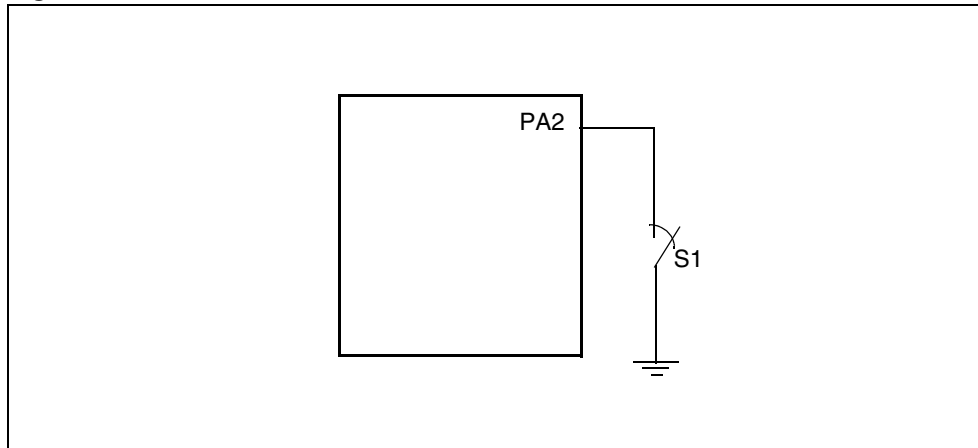
Figure 13. ICP connector



4.1.11 Calibration through PC GUI

Calibration of the meter and initialization of the RTC can be done using the PC GUI. To enter calibration mode the user has to press switch S1 within 30 seconds of power-on of the meter.

Figure 14. Calibration mode



4.1.12 Microcontroller block

The microcontroller is the heart of the energy meter, it does all the calculations and measurements. Only a 20-pin package is used. Refer to [Figure 4](#) for more details.

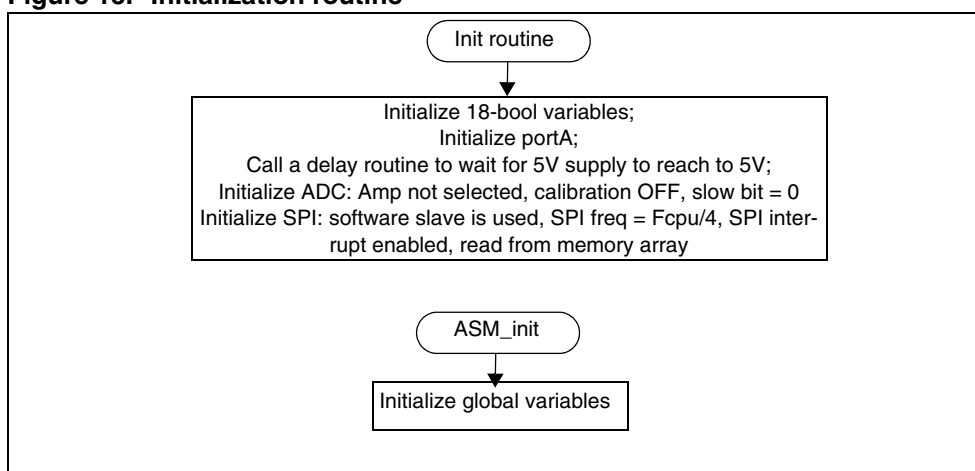
5 Software routines

This section of the application note describe each function contained in the firmware. A general description and flow diagram are provided for each routine.

5.1 Initialization routine

The two routines are used for initialization. The `ASM_init` routine is used to initialize the global variables, which is done using the `_stext` routine, the auto startup routine. After this routine the `init` routine is called which initializes different bool variables, portA register, ADC bits and SPI.

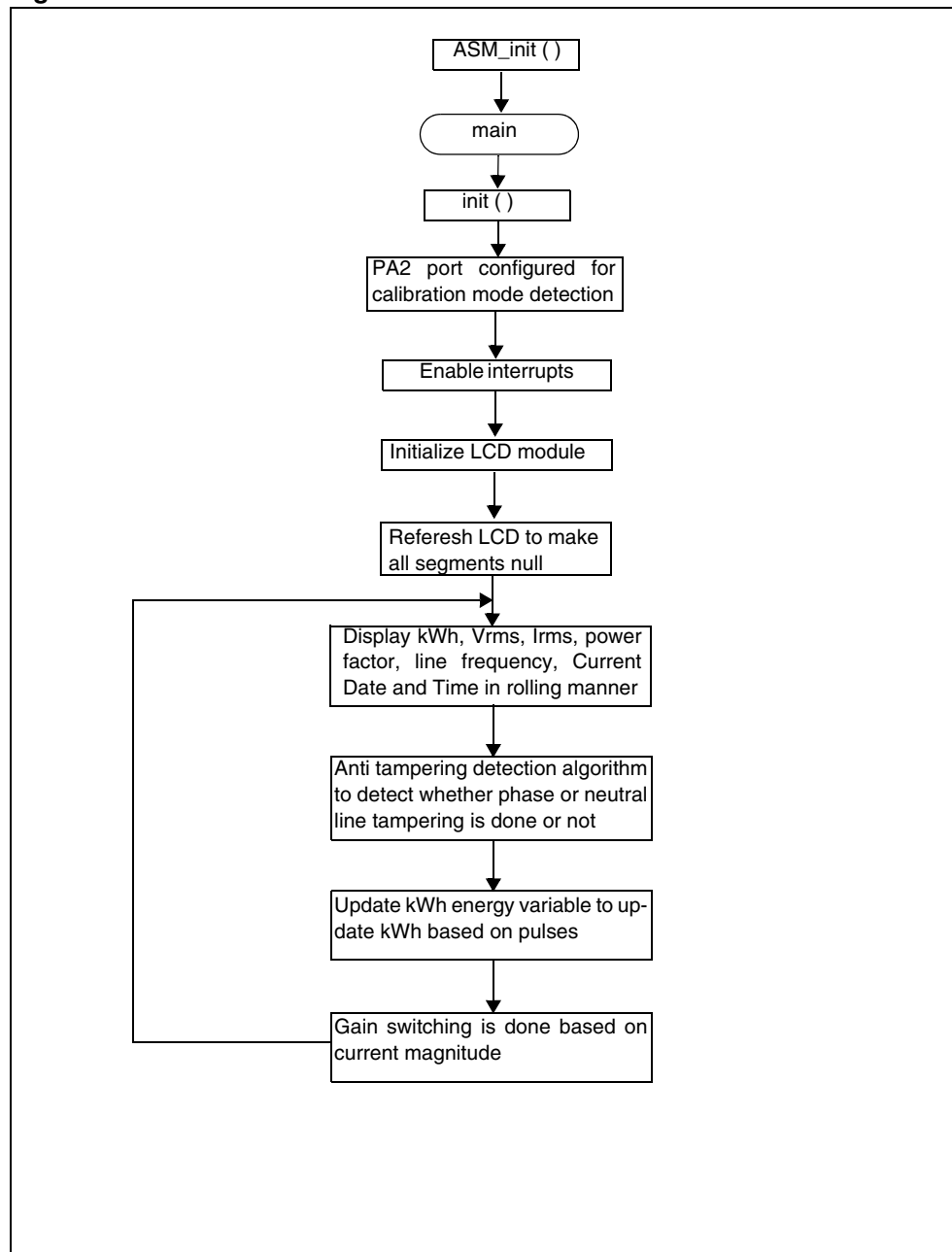
Figure 15. Initialization routine



5.2 Main routine

The main routine is called after `ASM_init` (`_stext`), which called different functions.

Figure 16. Main routine



5.3 Lite timer time base2 interrupt routine

This routine is the heart of the MCU, which is generated after every 200 μ s. This means with a 50Hz sinewave the number of samples per cycle is 100. In this interrupt routine, the voltage and current samples are taken by changing the active channel for ADC. One current sample is taken in between the two voltage sample. The two voltage samples are taken to minimize the error due to a shift in sampling time for voltage and current sample. Multiplication and accumulation of $V \cdot I$ is done separately for each current gain.

Figure 17. Lite timer interrupt routine

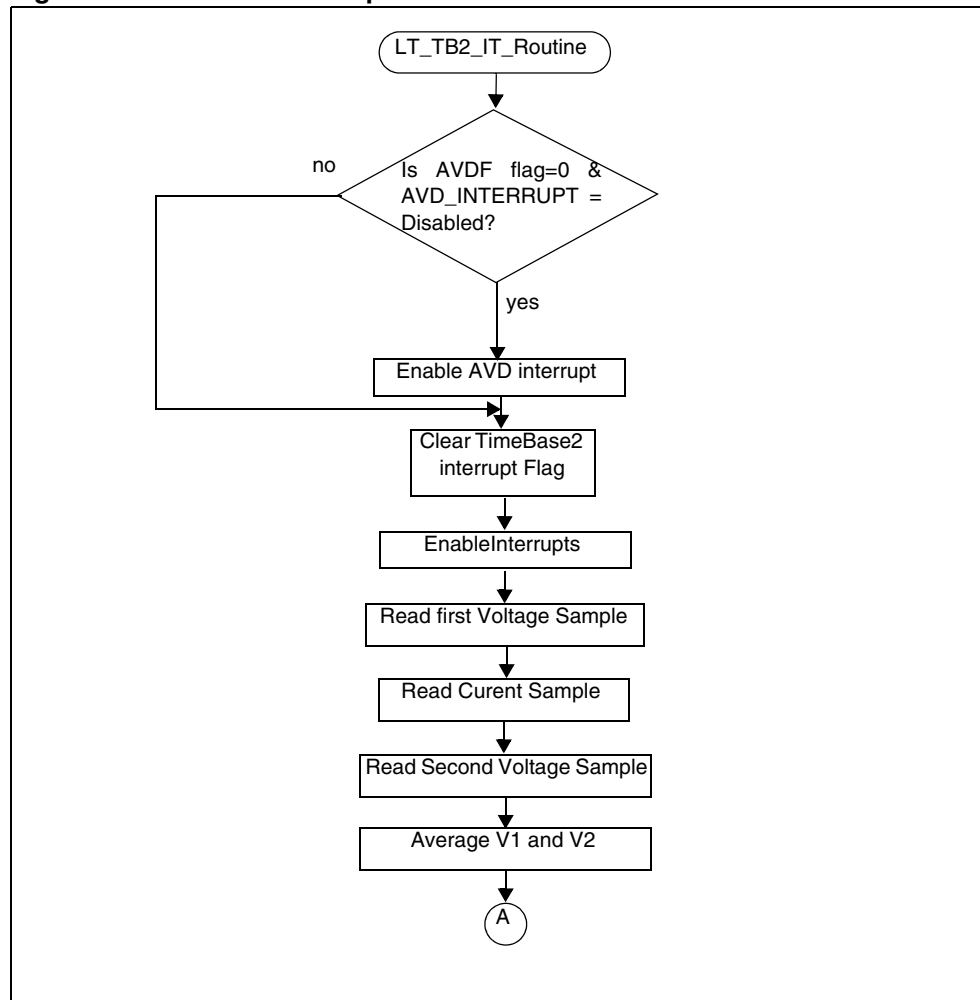
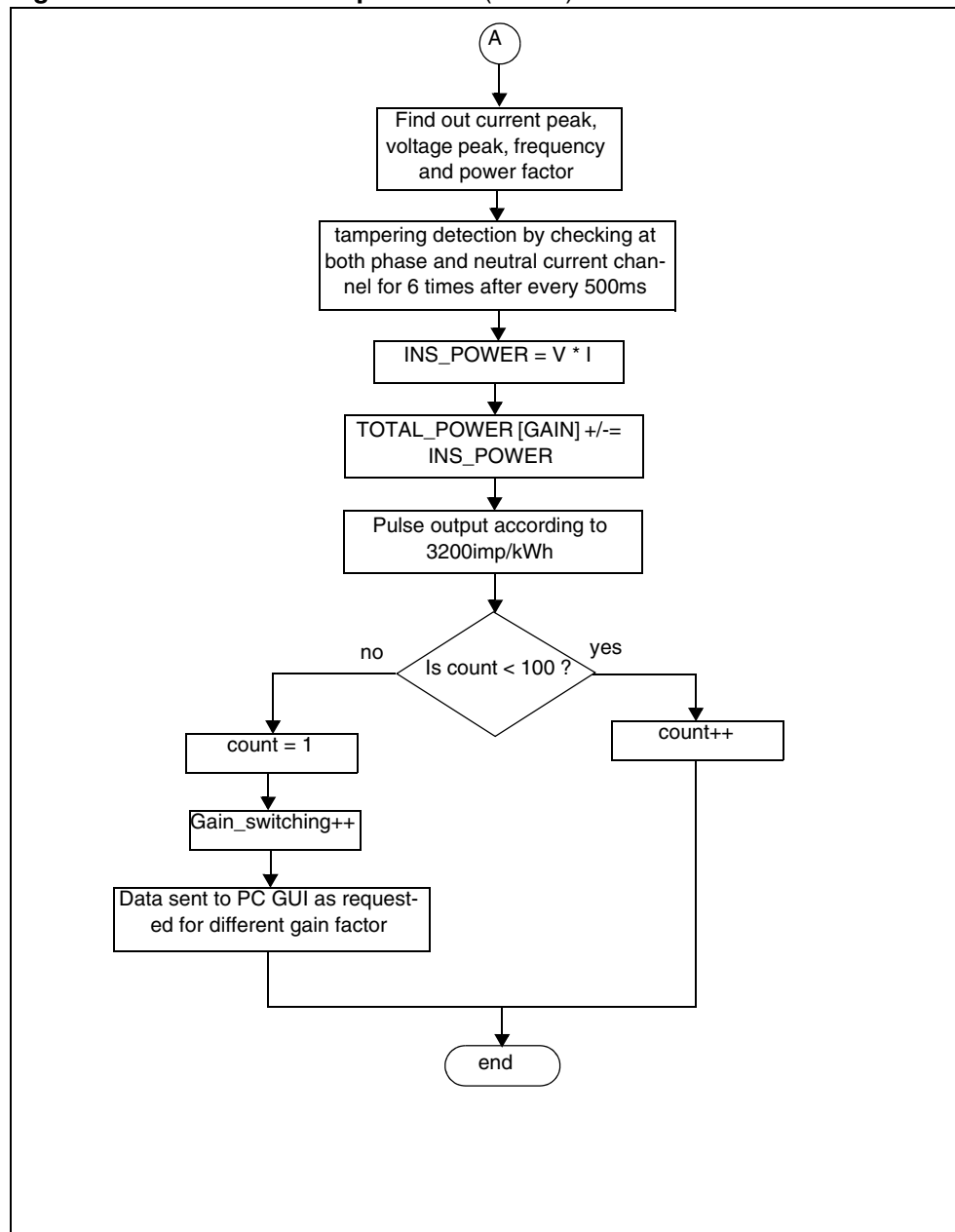


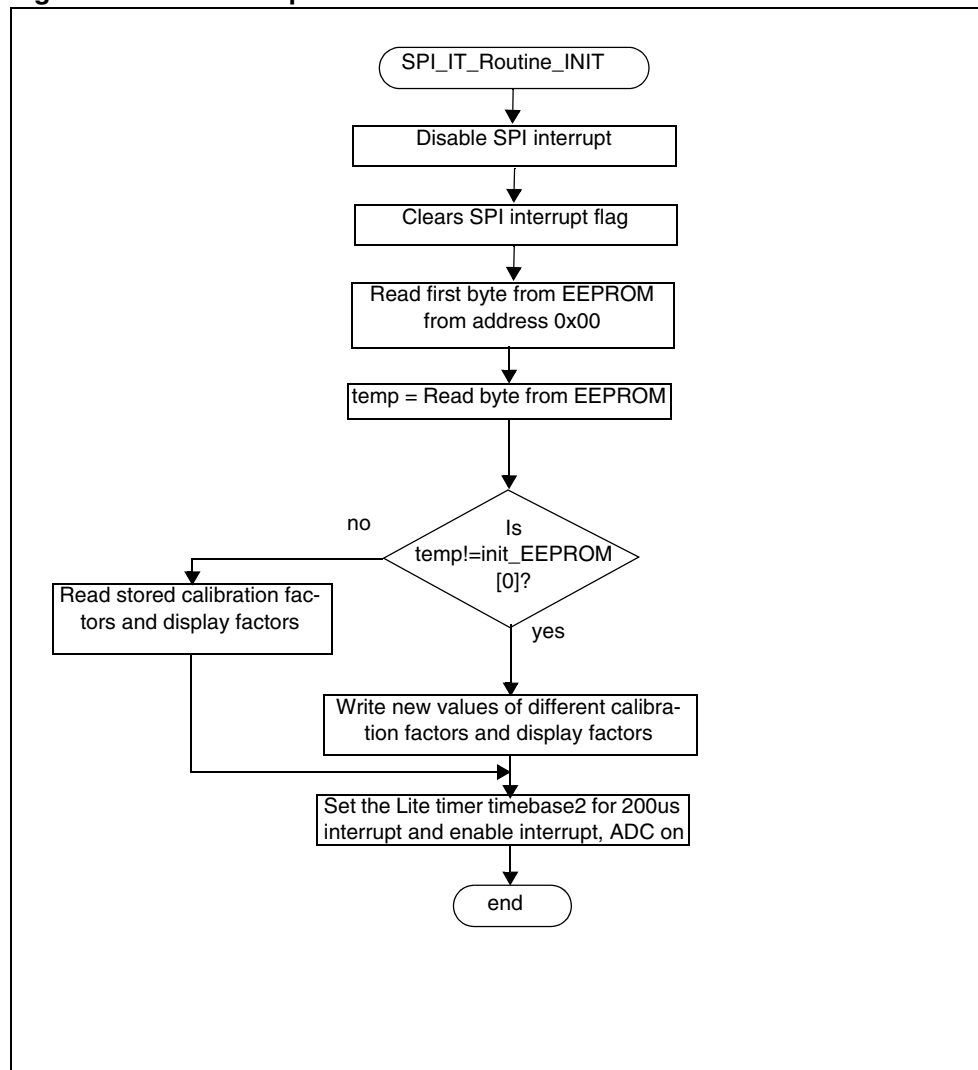
Figure 18. Lite timer interrupt routine (Cont'd)



5.4 SPI interrupt routine

This routine is called just after power up of the application. This routine is used to initialize the EEPROM if the meter is used for the first time or to get the previous accumulated kWh and tampering information. The one pulse comparison factors and display constants are also received from EEPROM.

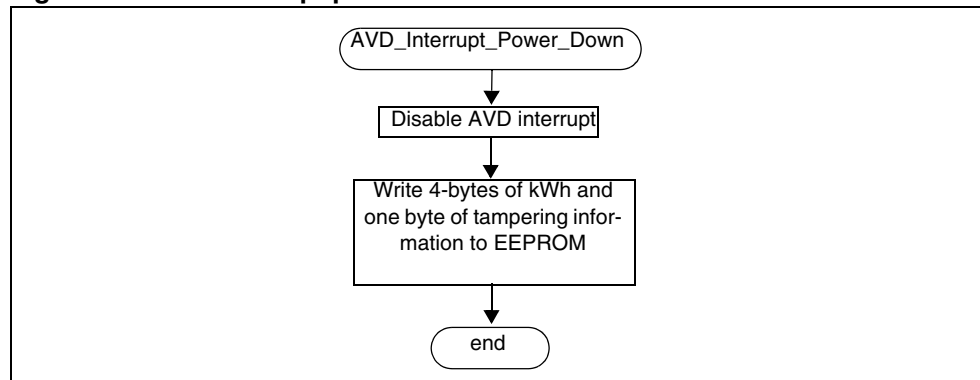
Figure 19. SPI interrupt routine



5.5 AVD interrupt routine

This routine is used to store accumulated kWh and tampering information to EEPROM during power down.

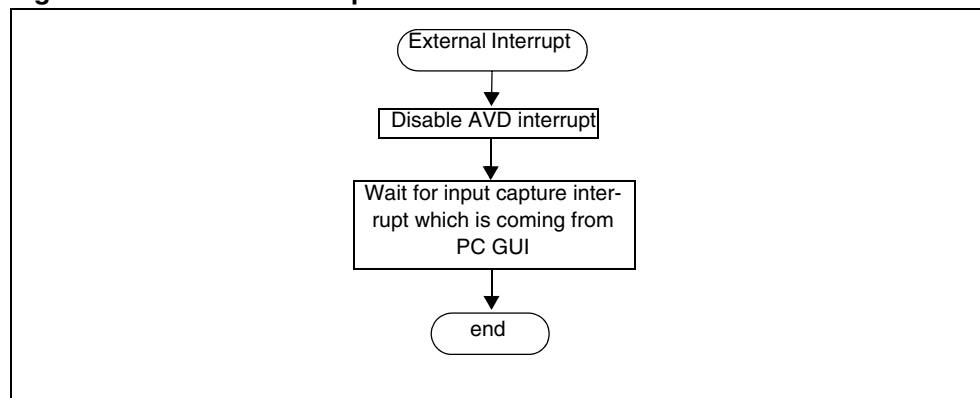
Figure 20. AVD Interrupt power down routine



5.6 External interrupt routine

If the user wants to enter PC calibration mode, he should press the switch within ~30Sec of start of the application. Application will enter into external interrupt routine by pressing the external switch. Now external interrupt routine will wait for interrupt coming from PC GUI.

Figure 21. External interrupt routine



5.7 ART timer input capture interrupt routine

In this application, SCI is simulated using the 12-bit ART Timer. Different commands are received by software SCI, and a response is sent back to the PC GUI using the ART timer overflow interrupt.

6 Results

This section shows the results obtained for the reference design. These results were obtained at a test house using recognized MTE test equipment. There are three types of tests performed:

1. **Load tests:** Voltage and frequency of AC Source is constant, but the load current varies. These tests are performed for resistive load (unity power factor), 0.5Lag and 0.8Lead.
2. **Voltage tests:** Frequency of AC source and load current (basic current) is constant, but the voltage is changed from minimum (140V) to maximum (280V). This test is performed at UPF, 0.5Lag, 0.8Lag and at 0.8Lead.
3. **Frequency tests:** Voltage and load current (basic current) is constant, but the frequency of AC Source is changed from 48Hz to 52Hz. This test is performed at UPF, 0.5Lag, 0.8Lag and at 0.8Lead.

6.1 Load tests

The voltage is 234.5V and the frequency of AC source is 50Hz. Below is the table for the accuracy Vs. load current.

Table 1. Load current Vs% error

Load Current [A]	Load current Vs% Error		
	UPF (%Error)	0.5 LAG (%Error)	0.8 LEAD (%Error)
53 (5.3lb)	-0.71	-0.58	-0.68
50 (5lb)	-0.34	0.08	-0.55
14 (1.4lb)	-0.22	0.06	-0.54
13 (1.3lb)	-0.14	0.09	-0.42
4 (0.4lb)	-0.11	0.11	-0.41
3 (0.3lb)	-0.04	0.23	-0.28
1 (0.1lb)	-0.24	0.54	-0.35
0.8 (0.08lb)	-0.09	0.62	-0.19
0.5 (0.05lb)	-0.11	-0.74	0.4
0.2 (0.02lb)	0.19	-0.39	0.79

The % error is within the $\pm 1\%$ error for the range $0.05 \text{ lb} < I < 5.5 \text{ lb}$, as required for a class1 meter. Here I_{max} is 5.5lb. The startup current is $\sim 11 \text{ mA}$, which is $\sim 0.02\%$ of I_{max} .

6.2 Voltage tests

This test is performed at UPF, 0.5Lag, 0.8Lag and at 0.8Lead. Below is the table for the accuracy Vs. voltage variation.

Table 2. Voltage vs% error

	Voltage Vs% Error			
Voltage [V]	UPF (%Error)	0.5LAG (%Error)	0.8LAG (%Error)	0.8LEAD (%Error)
140	-0.68	-0.35	-0.15	-0.99
280	-0.68	0.0	-0.6	-0.68

6.3 Frequency tests

This test is performed at UPF, 0.5Lag, 0.8Lag and at 0.8Lead.

Table 3. Frequency Vs% Error

	Frequency Vs% Error			
Frequency [Hz]	UPF (%Error)	0.5LAG (%Error)	0.8LAG (%Error)	0.8LEAD (%Error)
48	0.2	0.5	0.48	-0.39
52	0.15	0.2	0.09	-0.23

7 Conclusions

This electricity meter solution demonstrates that a modular low cost, single chip, digital energy meter can be implemented with the ST7FLITE20 microcontroller, which is 20-pin device and has a minimum set of mainly discrete external components. The on-chip 10-bit ADC with external gain circuits is used instead of a dedicated external measurement IC, to perform all the voltage, current and energy measurements. The error in measured energy is within the IEC61036 standard.

The ST7FLITE20 MCU provides a very cost effective solution for a power meter, as it enables the removal of the dedicated energy measurement device and has a large set of on chip peripherals like LVD/AVD, Lite Timer, SPI, 10-bit ADC. The other ICs used are L7805 (positive voltage regulator), BC547 (NPN silicon transistor), PN2222A (NPN high speed switching transistor), TS1854 (Quad rail-to-rail low power operational amplifiers), M95010 (1Kbit serial SPI bus EEPROM) and M41T94 (RTC).

The internal EEPROM of ST7FLITE20 microcontroller can also be used by changing the sales type of the microcontroller and with some minute firmware changes.

The modular design approach enables the hardware and software to be reused and thus speed up the design cycle for a power meter development. The schematics, Bill of Materials, gerber files and software are all available at the ST website.

8 Calibration coefficients

There are nine calibration coefficients in all. There are four current offset calibration parameters, one voltage offset calibration parameter, four one pulse comparison constants for all the four current gain factors.

9 Revision history

Table 4. Document revision history

Date	Revision	Changes
23-May-2006	1	Initial release.

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