PROJECT REPORT

Design and Development of Single Phase Static Electronic Energy Meter with Communication Capability

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In partial fulfillment of the requirements for the award of degree of

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(CONTROL & INSTRUMENTATION, ELECTRICAL ENGINEERING)

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CERTIFICATE

This is to certify that Rohit Chowdhary student of final Semester M.E. Electrical Engineering of Delhi College of Engineering during the session 2006-2007 has successfully completed the project work on:

Design and Development of Single Phase Static Electronic Energy Meter with Communication Capability

and has submitted a satisfactory report on this volume as per requirement of university which may accepted for the partial fulfillment of the degree of Master of Engineering in Electrical Engineering(Controls and Instrumentation).

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Acknowledgement

Dr. Pramod Kumar initiated the founding ideas behind this thesis and provided insight and valuable information into many of the problems that were encountered. His positive attitude throughout the duration of this thesis always put things into perspective whenever difficulties arose. This thesis would not have been possible without him.

There are many other people that have contributed directly or indirectly to this thesis. Some acting as sounding boards, sources of information, or providing resources that contributed to the development of my electronics. While their individual contributions have been small, their efforts have still been greatly appreciated.

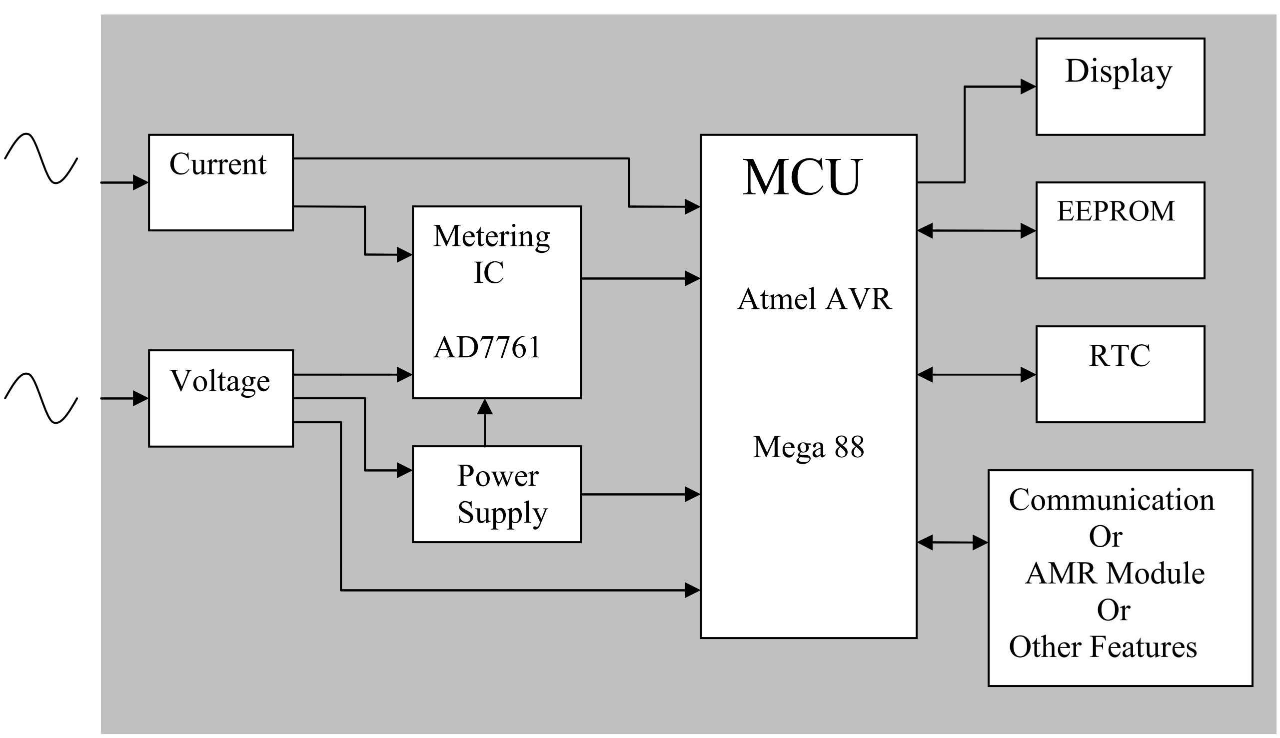
Finally, I would like to thank my family and friends for keeping me sane.

Rohit Chowdhary

ABSTRACT

The accurate measurement of electricity supply and subsequent billing to residential properties has traditionally been achieved through electromechanical meters. Although widely used this solution has several disadvantages including long term accuracy, cost of calibration and limited communication. These issues can be overcome using digital power meters where it is possible to achieve long term accuracy by removing analog components which are prone to drift over temperature and time.

The goal of this project is to design an electronic energy meter which calculates instantaneous power at all power factor and gives low frequency pulse output which is directly proportional to real power .This low frequency pulse output is further used by a microcontroller which calculates energy in terms of Kwh and displays it on LCD. The function of microcontroller is not only limited to display of Energy but it also calculates maximum demand, detects different types of tamper such as magnetic tamper ,neutral missing etc, it serves as an interface between RTC,EEPROM and the LCD display and also interacts with the outside world using the Universal Asynchronous Receiver/Transmitter .Any terminal software can be used for sending commands to the meter and for receiving measurement data.



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1.0 Introduction

Development of Single Phase Static Electronic Energy meter with Communication capability

Significant changes are taking place in the electric energy industry worldwide. Deregulation of the utilities will produce a tougher competitive environment for the suppliers of electricity. Increased demand for electrical energy will require better management of distribution. Suppliers will need to identify ways of supplying a better level of service at a reduced cost. One way to do this is to install a Static electronic electricity meter. Apart from tangible benefits like higher accuracy – especially in the presence of non-sinusoidal waveforms, the electronic energy meter offers more than just the measurement of kWhrs. Given the accuracy, flexibility and powerful network management possibilities offered by static metrology the days of the electromechanical meter are numbered.

Power meters are sometimes referred to as energy meters and vice versa. Per definition, (active) power is a measure of what is required (or consumed) in order to perform useful work. For example, a light bulb with a 100W rating consumes 100 watts of active power in order to create light (and heat). Energy, per definition, is the measure of how much work has been required over a known period of time. In the light bulb example, leaving the bulb on for an hour it will consume 100W * 3600s = 360000Ws (watt-seconds) = 100Wh (watt-hours) = 0.1kWh (kilowatt-hours) of energy.

The electrical energy meter manufactures have focused their research effort towards the development of modem and more precise energy meters for large customer, where the added precision justifies the necessary investment. However, the advent of low cost microcontrollers enables the development of a cost effective electronic electrical energy meter for residential use as well. As the electronic version does not possess rotating parts, it helps in avoiding tampering by unscrupulous persons. Furthermore, for large scale manufacturing, the costs can become lower than those of the electromechanical meters currently in production.

This thesis presents a totally electronic single phase energy meter for residential use, based on Atmel AVR microcontrollers .The design takes into consideration the correct operation in the event of an outage or brown out, by recording the energy consumption in EEPROM memories internally available in the microcontroller. When the supply is restored, the energy consumption computation is properly initialized. Also, a seven digit display is used to show the energy consumption

2.0 Literature Review

2.1 The Problems to be overcome

Energy Meter ASIC can directly measure the input voltage and current and communicate with the microcontroller by means of serial communication; such IC's are easily available but are very expensive as compared to normal IC which cannot communicate with microcontrollers.
One of the most cost effective way to calculate current, voltage and power is to use the inbuilt A/D converter of the microcontroller being used. This method allows us to perform all the necessary parameters without using the expensive metering ASIC.

The current sensing element used is a low resistance shunt (450 micro ohm), this low resistance shunt gives a good linearity over a wide range of current but the inbuilt 10 bit ADC of the microcontroller cannot sense such low signal hence the signal has to be amplified before it given to the A/D converter.

Also the current value varies from a few milliamps to ten amperes, or more. In order to achieve an accuracy of 1% over the whole range, the ADC's would need to have an accuracy of around 16 bits. Since the target device includes only a 10 bit A/D converter the analog front end must amplify small signals. The current front end therefore includes a programmable gain stage, which is controlled by the MCU.

To make accurate measurements, the input signal must be as clean as possible, especially at low amplitudes. Input signals with low amplitude are amplified before being sampled and processed, which means any noise in the signal will be enlarged, too. At the low end of the measurement range input signals have amplitudes below 10mV, which means noise typically not visible on an oscilloscope (say, below 1mV) may distort the signal by as much as 10%.Noise is eliminated using good PCB planning and properly sized and placed filter.

Energy meters are prone to operate in harsh environments; meters are often subject to over-voltages and current spikes. If such disturbances are not properly shielded they may traverse all the way to the MCU and drive it outside operating limits.

There are many techniques available for filtering out unwanted disturbances. Rapid voltage spikes are usually suppressed using varistors, which normally have very high impedance. At a given threshold the impedance very rapidly decreases, causing a short circuit, which then leads the excess energy to ground. Varistors must be picked such that they do not break down if the spike is too large or lasts too long (i.e. if the energy of the spike grows too large).

Much depending on the layout of the circuit board and connectors, some inputs may be prone to pick up radiated noise. In some cases, even the circuit board tracks can perform as antennas and pick up noise from the environment. Induced noise can be throttled using well-placed diodes, which clamp signals between ground and supply voltage.

2.2 Methods currently being used

Most of the energy meters being used are electro mechanical energy meters which are prone to wear and tear in time and hence their accuracy degrades over a period of time. Electro mechanical meters can be tampered easily which leads to heavy losses to the distribution company. All electromechanical kilowatt-hour meters have a rotating disk in them. The disk's rotational speed is proportional to the amount of electricity consumed. The metallic disc is acted upon by two coils. One coil is connected in such a way that it produces a magnetic flux in proportion to the voltage and the other produces a magnetic flux in proportion to the current.

This produces eddy currents in the disc and the effect is such that a force is exerted on the disc in proportion to the product of the instantaneous current and voltage. A permanent magnet exerts an opposing force proportional to the speed of rotation of the disc – this acts as a brake which causes the disc to stop spinning when power stops being drawn rather than allowing it to spin faster and faster. This causes the disc to rotate at a speed proportional to the power being used.

In an induction type meter, creep is a phenomenon that can adversely affect accuracy, it occurs when the meter disc rotates continuously with potential applied and the load terminals open circuited. A creep test is when the meter is tested for the error due to creep. These meters due to their mechanical nature loose their reliability in terms of accuracy.

2.3 The ADE 7761 and the ATMEGA AVR

The ADE7761 is a high accuracy, fault-tolerant, electrical energy measurement IC intended for use with 2-wire distribution systems. The part specifications surpass the accuracy requirements as quoted in the IS 13799 standard. The only analog circuitry used on the ADE7761 is in the ADCs and reference circuit. All other signal processing (such as multiplication and filtering) is carried out in the digital domain. This approach provides superior stability and accuracy over extremes in environmental conditions and over time. The ADE7761 incorporates a fault detection scheme by continuously monitoring both phase and neutral currents. A fault is indicated when the currents differ by more than 6.25%.

The ADE7761 includes a power-supply monitoring circuit on the VDD supply pin. Internal phase matching circuitry ensures that the voltage and current channels are matched. An internal no-load threshold ensures that the ADE7761A does not exhibit any creep when there is no load.

FUNCTIONAL BLOCK DIAGRAM

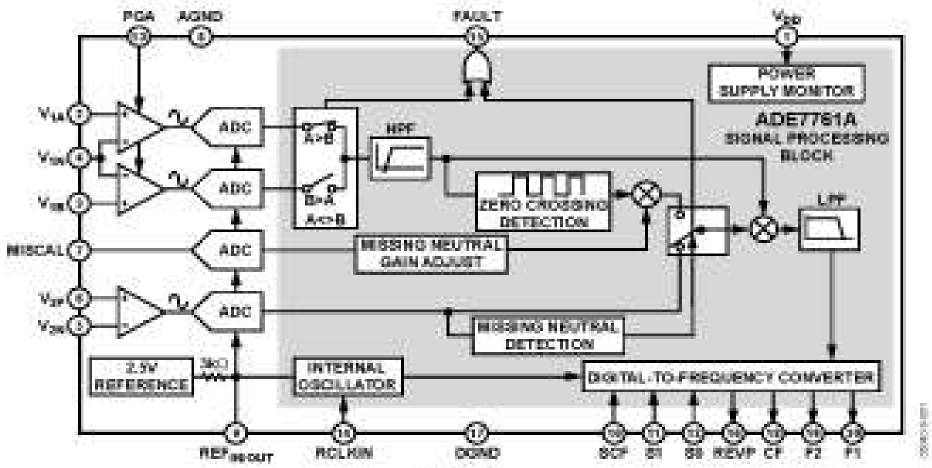


Figure 1.

The ATmega88 is a low-power CMOS 8-bit microcontroller based on the AVR enhanced RISC architecture. By executing powerful instructions in a single clock cycle, the ATmega88 achieves throughputs approaching 1 MIPS per MHz allowing the system designer to optimize power consumption versus processing speed.

The AVR core combines a rich instruction set with 32 general purpose working registers. All the 32 registers are directly connected to the Arithmetic Logic Unit (ALU), allowing two independent registers to be accessed in one single instruction executed in one clock cycle. The resulting architecture is more code efficient while achieving throughputs up to ten times faster than conventional CISC microcontrollers.

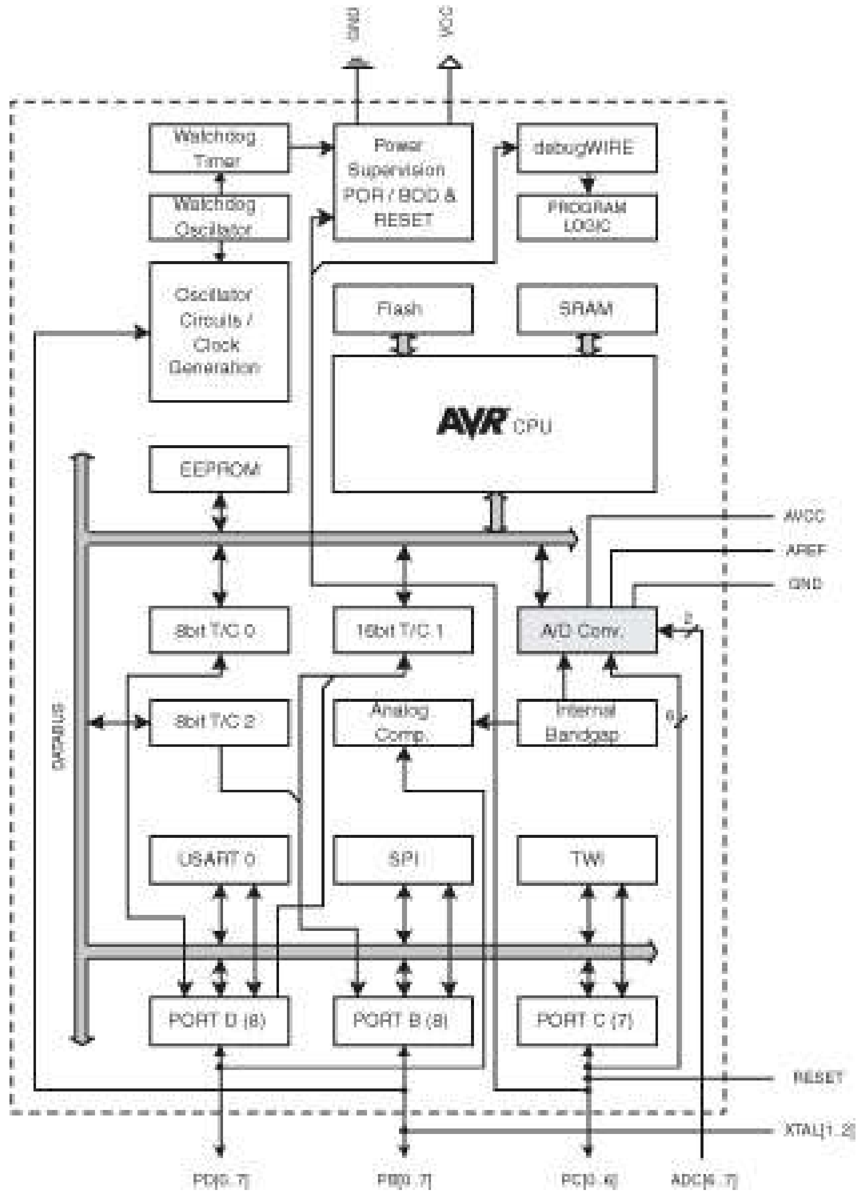

GND
VCC
Watchdog Timer
Watchdog Oscillator
Oscillator Circuits / Clock Generation
Power Supervision POR / BOD & RESET
debugWIRE
PROGRAM LOGIC
Flash
SRAM
AVR CPU
EEPROM
AVCC
AREF
GND
8bit T/C 0
16bit T/C 1
A/D Conv.
2
DATABUS
8bit T/C 2
Analog Comp.
Internal Bandgap
6
USART 0
SPI
TWI
PORT D (8)
PORT B (8)
PORT C (7)
RESET
XTAL[1..2]
PD[0..7]
PB[0..7]
PC[0..6]
ADC[6..7]

Figure 2

3.0 Scope of thesis

3.1 Advantages of Electronic Energy Meter

Electronic Energy Meters offers numerous advantages over traditional Ferraris Wheel meter. Some of them a listed below:-.

- Highly reliable, stable and accurate as compared to electromechanical meters
- No mechanical parts, therefore no corrosion or wear and tear
- Consumes very less power
- Software calibration is possible thereby eliminating the needs of mechanical trim pots which can vary over a period of time.
- Can be made immune to various types of tampers such as load reversal and earth, magnetic tampers, neutral disconnect etc.
- Can be read automatically hence eliminates the chances of human error in recording of data from the meter
- Can be configured to meet the local requirement
- Has a self diagnostic capability
- In addition to electricity the solid state meter can also recode other parameter of the load and supply such as maximum demand, power factor and reactive power used etc.
- Can have the capability of storing and displaying Energy consumption at different times for multiple tariffs. This feature is known as TOD feature.
- Since the microcontrollers today have a re-programmable memory it is possible to de-bug and re-program for up gradation at site thereby saving huge amt of money
- Consumers can benefit from lower electricity bills by using smart card controlled energy meters that lowers the operational cost of providing service, reading meters and processing data
- Can have communication capability such as optically isolated port RS232,RS485,GSM,CDMA,RF,IrDA etc

3.2 Initial Specification

The design is targeted for domestic consumer as per the Indian Standard for Energy Meters. The meter under normal as well as various fault condition, should work within accuracy limits, the various fault condition are laid in IS 13799 and CBIP Report 88 for Electronic Energy Meters.

Starting with these specifications, a design must be created.

3.3 Objective

The final objective if this thesis was to design a Electronic Energy meter which conforms to the specification specified .This required hardware design using the ADE 7761 and writing the software in microcontroller for calculating various parameters and displaying them to LCD.

4.0 Design

4.1 Overall Topology

As explained earlier, there are two different parts in this particular design .One being the metering part and the other being the microcontroller part. Both section are designed separately and are then integrated to form the complete meter. The power supply for the whole circuit is developed from main supply. Power supply consists of a regulator since the microcontroller and the metering chip requires regulated 5 Volts DC supply.

The energy metering part consists of and application specific integrated circuit which calculates the amount of energy being consumed and gives energy output in the form of pulses. All calculation performed in the metering chip are done in the digital domain leading to high accuracy output. Mains AC voltage is given to the metering chip through a transducer which converts 240 Volts to 250 millivolts leaving headroom for over voltages. Similarly current from the load is converted in milliamp by the means of current transformer and low resistance shunt. The metering chip can also detect tamper condition such as earth load or reverse current and the same are indicated through LED's which are connected to the IC pins.

The microcontroller section is a little more complex than the metering section. The analog front end is the part, which interfaces to the high voltage lines. It conditions high voltages and high currents down to a level where the signals can not harm the more delicate electronics. It converts high voltages and high currents to voltages sufficiently small to be measured directly by the ADC of the microcontroller. The nominal line voltage of the meter is 230V and the maximum rated current is 10A, both of which obviously are way too large signals to be fed directly to any microcontroller. The measuring transducer converts line voltage and line current to voltages with amplitudes of no more than 1V peak-to-peak.

The pulse output given by the metering chip is directly proportional to the energy consumed; this pulse is connected to an input pin of the microcontroller. The microcontroller then continuously reads the value of the input pin and maintains a internal Kwh register. Since the meter constant of the meter designed is 3200 imp/Kwh therefore the internal Kwh register is updated after every 32 pulses and is stored in EEPROM. Hence the least count of the energy stored is 0.01 Kwh. This Kwh value stored in the EEPROM is the actual energy in Kwh consumed by the consumer and is continuously displayed on the LCD display for billing purpose by the microcontroller.

4.2 Power Supply design

The power supply is a low-efficiency, but cost-effective and compact design. It is intended to provide just the amount of power needed by the meter at a cost as low as possible.

The following table summarizes typical current consumption of the main parts of the meter.

TABLE 1 – Typical current consumption of main meter sections

Section	**Includes**	**Continuous**	**Peak**
Front End	Op-Amps, Switch 4066	0.3 mA	0.3 mA
Metering	ADE 7761	3 mA	4 mA
Microcontroller	AVR	1.8 mA	3 mA
LED’s	All LED’s	3 mA	3 mA
Display	LCD display	0.5 mA	0.5 mA

Peak currents are brief, mainly occurring when the metering chip indicates tampering through LED’s. The worst-case scenario is when all LED’s are lit.

Typically, the power supply needs to be able to supply less than ten milliwatts (at 5 volts), but it must also be able to deliver the brief bursts of energy required.

The below schematic is identical to the power supply section of the meter, as illustrated in the schematic at the end of this document, but component numbers are not the same.

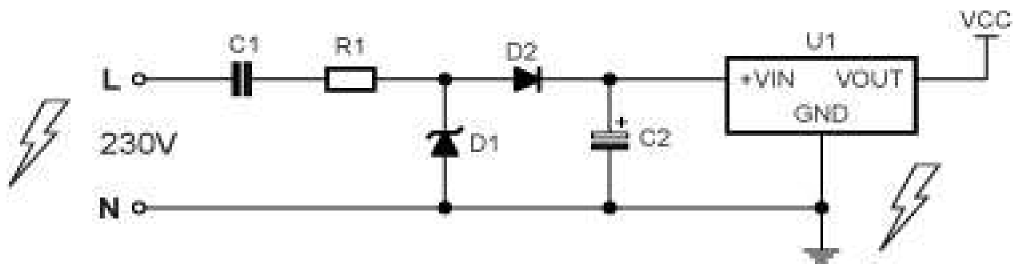


Figure 3-Power Supply

The power supply is based on halfway rectification. During negative half-wave capacitor C1 is charged and during positive half-wave the capacitor is drained. Zener diode D1 (minus the forward voltage of diode D2) dictates to which voltage C2 is charged. Voltage regulator U1 uses the energy stored in C2 to produce a stable output voltage. Resistor R1 controls the charge and discharge of C1 and also limits the current flow through zener diode D1.

4.3 Current Measuring element

Before voltage and current are sampled, both signals need to be conditioned to the appropriate signal level. All energy meters contain both voltage and current sensing elements. Current sensing is a more difficult problem. Current sensor requires wider measurement dynamic range, it also needs to handle a much wider frequency range because of the rich harmonic contents in the current waveform. As the energy consumption in a household continue to increase, the needs for measuring high current is no longer limited to industrial applications.

The two most common sensor technologies today are the low resistance current shunt and the current transformer (CT).

Low Resistance Current Shunt

Current shunt is the lowest cost solution available today. A simple model for this current measurement device is shown in Figure 4

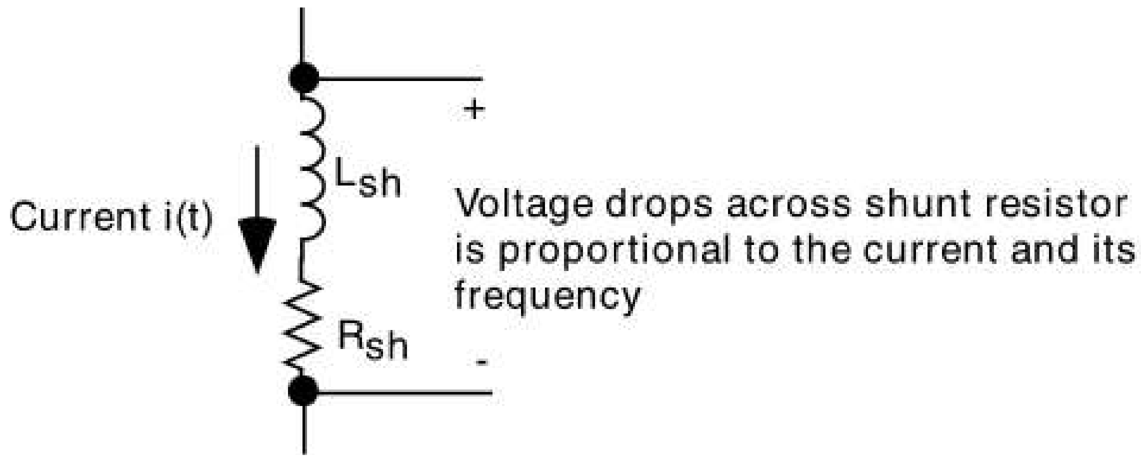


Figure 4. A simple model of the shunt with parasitic inductance

Low resistance current shunt offers good accuracy at low cost and the current measurement is simple. When performing high precision current measurement, one must consider the parasitic inductance of the shunt. The inductance is typically in the order of only a few nH. It affects the shunt's impedance magnitude at relatively high frequency. However, its effect on phase is significant enough, even at line frequency to cause noticeable error at low power factor. Figure 5 shows the phase shift resulting from a 2nH inductance in a 200 micro-ohm shunt.

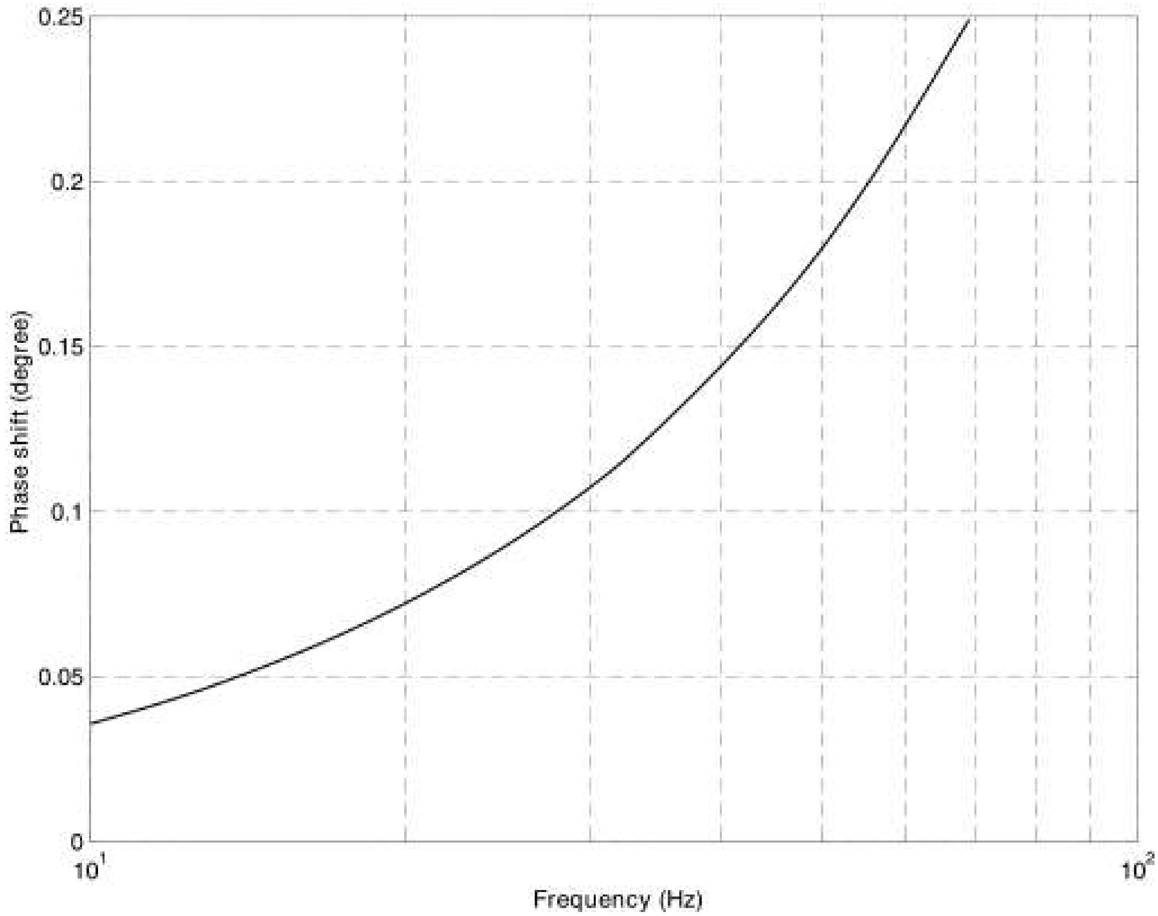


Figure 5 Phase shift caused by the self-inductance of a shunt (2nH in a 200µΩ shunt)

The percentage measurement error caused by any phase mismatch between the voltage and current signal paths can be approximated by the following formula:

$$\textit{Measurement Error} \approx \textit{Phase mismatch (in Radians)} \times \tan(\varphi) \times 100 \text{ ----- (1)}$$

In the above expression, φ represents the power factor phase angle between the voltage and current. As one can see, a phase mismatch of 0.1° will result in about 0.3% error at power factor of 0.5. Therefore, special care needs to be taken to ensure phases are precisely matched between the internal signal paths for the voltage and current.

Shunt is rather low cost and reliable. It is a popular choice for energy metering applications. However, because the current shunt is fundamentally a resistive element, the heat it generates is proportional to the square of current passing through. This self-heating problem makes shunt a rarity among high current energy meters.

Current Transformer (CT)

Current Transformer (CT) is a transformer which converts the primary current into a smaller secondary current. CT is the most common sensor among today’s high current solid-state energy meters. CT can measure up to very high current and consumes little power. Because of the magnetizing current, CT typically have a small phase shift associated with it (0.1°-0.3°). If un-calibrated, it will lead to noticeable error at low power factor (see earlier discussion on parasitic inductance in current shunt). In addition, the ferrite material used in the core can saturate at high current. Once magnetized, the core will contain hysteresis and the accuracy will degrade unless it is demagnetized again. Figure 6 shows a typical hysteresis curve of a ferrite material.

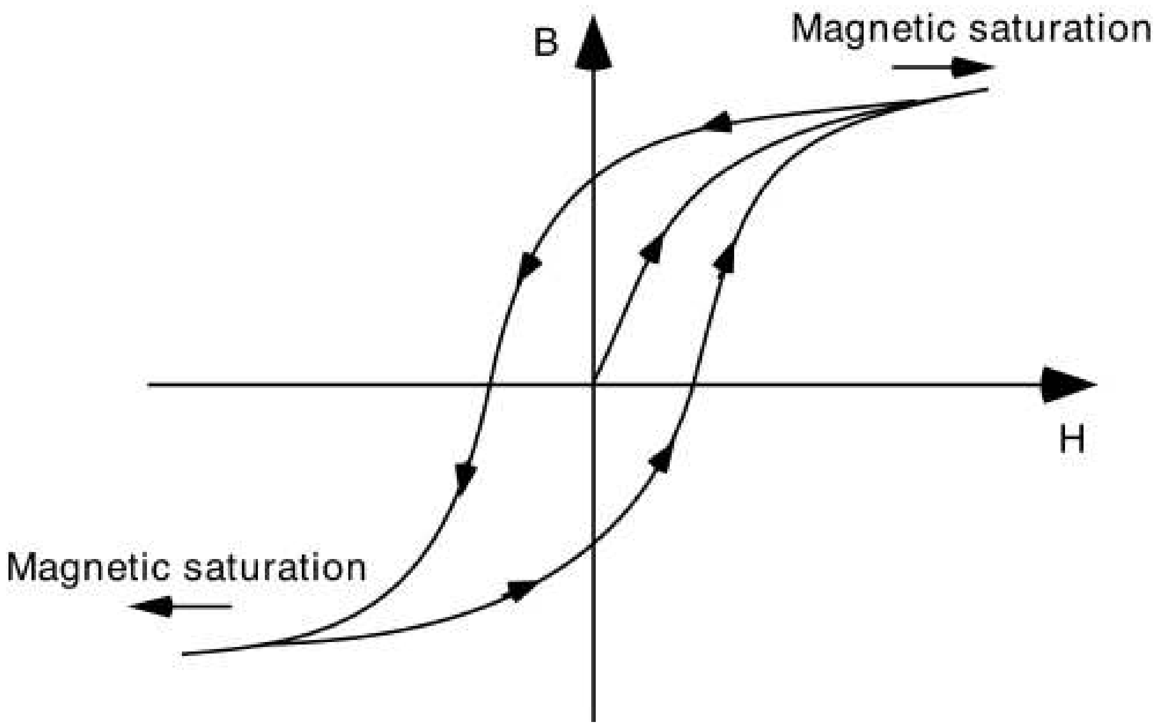


Figure 6. Hysteresis curves of a ferrite material

CT saturation can occur when current surges beyond a CT's rated current, or when there is substantial dc component in the current (e.g. when driving a large half-wave rectified load). Today's solution to the saturation problem is to use ferrite material with very high permeability. This typically involves using Mu-metal core. However, this type of CT's have inconsistent and larger phase shift comparing with the conventional iron core CT's. Energy meters based on Mu-metal core CT's would require multiple calibration points for both current level and temperature variations.

The following table summarizes the strength and weakness of the technologies described:

Table 2 – Strengths and weakness of Shunt and CT

Current Sensing Technology	Low Resistance Current Shunt	Current Transformer
Cost	Very Low	Medium
Linearity over measurement range	Very Good	Fair
High Current measuring capability	Very Poor	Good
Power consumption	High	Low
DC/high current saturation problem	No	Yes
Output variation with temperature	Medium	Low
DC offset problem	Yes	No
Saturation and Hysteresis problem	No	Yes

In our design we are using both a low resistance shunt and current transformer.

4.4 ADC and Microcontroller

The work of microcontroller has already being discussed earlier .The calibration pulses from the metering chip is counted by the MCU and the energy register inside the controller is updated. When there is sufficient energy accumulation in the register the LCD display is updated with the new value. The software is designed in such a way that in every ten min the Maximum Demand for past half hour is calculated .This method is called a sliding step window method, this results in calculation of MD six times in an hour rather that two times in an hour. The microcontroller also has to communicate with external peripherals such has RTC for real time and date, EEPROM for storage of data and the display module for displaying data on LCD.

To calculate the RMS value of voltage and current the built in ADC is used. The built in ADC of the Atmel AVR ATMega88 is 10 bits. To measure current over a dynamic range of 1: 50 we need at least 16 bit ADC. To be able to make the ADC work, the analog references must be connected. The analog references are providing the ADC with the boundaries of the voltage range that it should work within. The analog references are applied to specific pins on the part: AGND and AREF. The choice of analog references must be made within certain limits. The ADC in AVR parts can measure voltage levels between AGND and AREF. AGND should be connected to GND, and AREF should be connected to a stable analog voltage reference, which must be less or equal to AVCC.

The ADC converts an analog input voltage to a 10-bit digital value through successive approximation. The minimum value represents GND and the maximum value represents the voltage on the AREF pin. Optionally, AVCC or an internal 1.1V reference voltage may be connected to the AREF pin by writing to the REFSn bits in the ADMUX Register. The ADC is made to run in a free running mode that is it automatically starts a new conversion when the previous one has ended. The microcontroller firmware takes care of the channel selection by changing the MUX register when the conversion is complete.

ADC's inherently have certain errors such as offset error, differential error etc. These errors have to be taken care in the design part of the microcontroller software.

The main objective is to calculate the RMS values of voltage current and instantaneous power using the on chip 10 bit ADC in the ATMEGA AVR. The A/D converter on the AVR accepts input voltages in the range between Vrefl to Vrefh and since the A/D is uni-polar, operating from a +5Vdc supply, Vrefl is limited to Vss and Vrefh is limited to Vdd.(1.1V) . Thus, the AC input signals of voltage and current have to shifted up and centered around 0.55 volts. This is achieved by biasing one end of the secondaries of the voltage and current transformers. The resulting waveform is shown in Figure

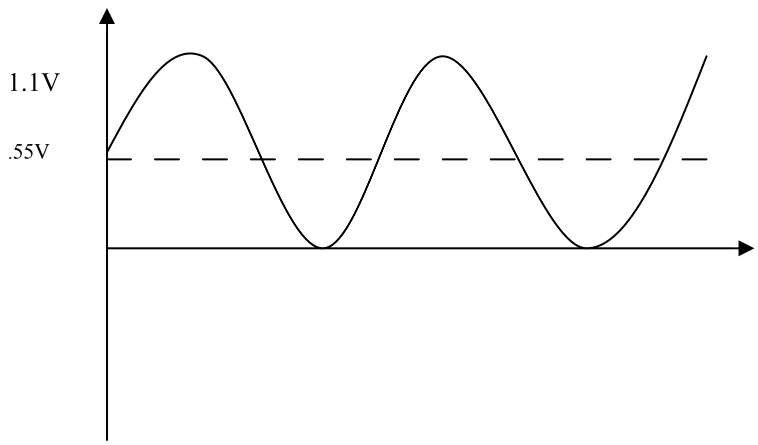


Figure 7

As explained earlier ADC is running in the Free Running Mode, therefore as soon a conversion cycle finishes the ADC channel is changed by microcontroller and whenever a current channel sampling is finished it is multiplied with instantaneous voltage to get the instantaneous power. The reconstructed power waveform for voltage and current is shown below.

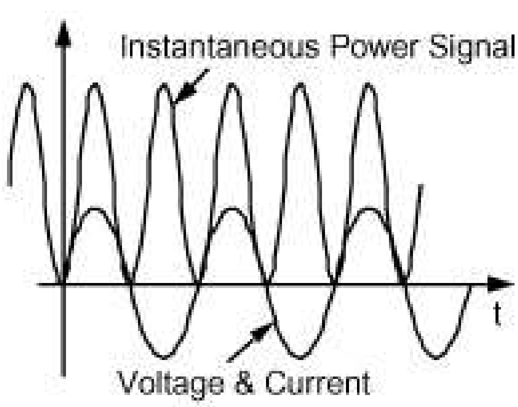


Figure 8 - Instantaneous power for in-phase voltage and current

This produces the maximum instantaneous power as the voltage and current are in phase, however, if the current lags the voltage, the resulting power is reduced. Figure 9 shows the example when current lags by 60º.

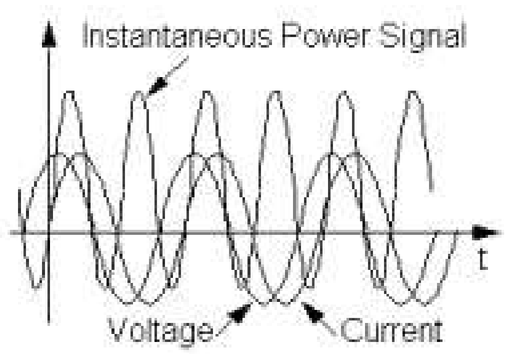


Figure 9. Instantaneous power for current lagging voltage by 60º

Mathematically the instantaneous power signal p(t) is the product of the voltage v(t) and current i(t).

$$p(t) = v(t) \cdot i(t) \text{ ---------------(2)}$$

where:

$v(t) = V\sin(\omega t)$ and $i(t) = I \sin(\omega t + \theta)$

In software the instantaneous power is calculated by summing up each product of voltage and current for a total of 400 samples. After 400 samples the result is divided by a scaling coefficient, called the calibration coefficient. The coefficient is a scaling factor which also takes into account analog circuit tolerances.

4.5 Metering Section

The energy calculation part is done by an ASIC, which gives out pulses which are directly proportional to Energy being consumed. The design of metering part is fairly simple as most of the functions are performed by the chip itself. The voltage is dropped down using a register network and current is given to the chip using a current transformer.

4.6 Communication Section

As the original RS-232 standard was defined in 1962 and before the days of TTL logic, it is no surprise that the standard does not use 5V and ground logic levels. Instead, a high level for the driver output is defined as between +5V to +15V, and a low level for the driver output is defined as between -5V and -15V. The receiver logic levels were defined to provide a 2V noise margin. As such, a high level for the receiver is defined as between +3V to +15V, and a low level is between -3V to -15V.

Figure 10 illustrates the logic levels defined by the RS-232 standard. It is necessary to note that, for RS-232 communication, a low level (-3V to -15V) is defined as a logic 1 and is historically referred to as "marking." Similarly, a high level (+3V to +15V) is defined as logic 0 and is referred to as "spacing."

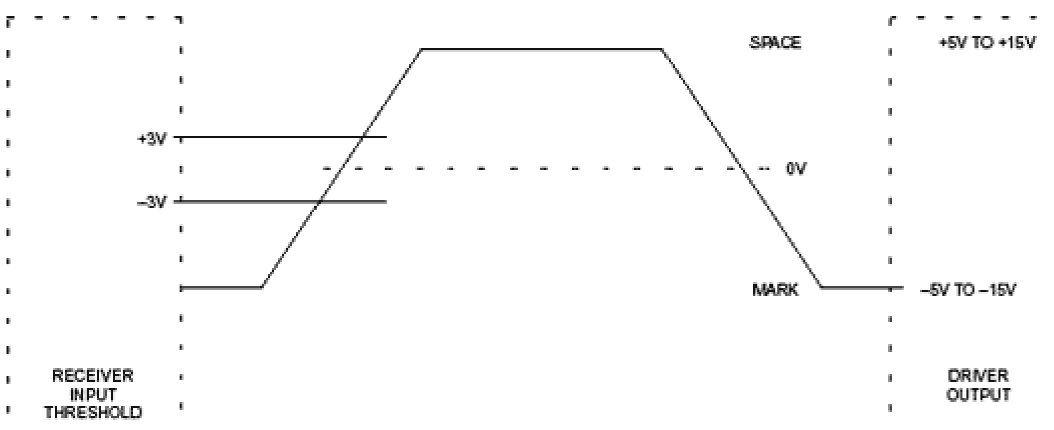


Figure 10 Logic Levels of RS232 Standard

The Energy meter designed is working on +5 Volts power supply, for communication through RS232 port a power supply of +10 Volts and -10 Volts is required. The output of the MCU cannot be more than +5 Volts and less than 0 Volts .For Rs232 communication between the microcontroller and PC a level converter is used. The function of level converter is to transform the input from the microcontroller to level which is as per RS232standard.

The MAX232 IC which is used as level converter work's with a +5 Volts power supply and requires very less current and external components for its functioning. The data received by the PC is decoded using Base computing software which is written in Visual C#.

5.0 Implementation

5.1 Supply Section

The transformer less power supply has a linear regulator which provides stable +5 volts for the functioning of microcontroller and ASIC. The figure is reproduced for reference.

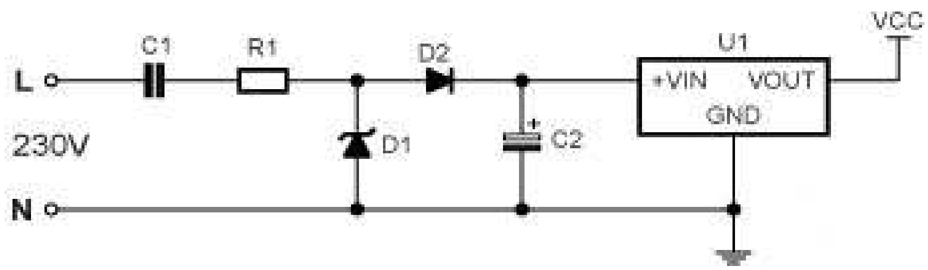


Figure 11. Power Supply

The dropout voltage for the regulator is about 5V. When input voltage falls below the dropout level, the device ceases to regulate. The regulator input must be kept above this level, even at the end of the drain cycle and at worst-case current consumption.

As a starting point, the zener diode is specified to 15V. This leaves much headroom for capacitor C2 to discharge before reaching minimum input voltage of the regulator. Next, the size of capacitor C2 is calculated. The minimum size is derived based on the general discharge function of the capacitor, as follows:

Equation 3- To calculate size of charging capacitor

$$V = V_0 \times e^{-\frac{t}{RC}} \Rightarrow C = -\frac{t}{R \times \ln\left(\frac{V}{V_0}\right)}$$

Here t is the discharge time, V_0 is the initial voltage, V is the voltage after discharge and R is the load discharging the capacitor. If the worst-case current consumption is 14mA (see table above), then the equivalent load resistance is R = 5V/14mA = 357 Ω. Worst-case current consumption takes place when driving all the LED's. The length of the drive pulse is 100ms, by default. Assuming the voltage of the charged capacitor is allowed to drop to regulator minimum during the length of one display pulse, the smallest size of the capacitor is as follows:

Equation 4 – Calculating minimum size of capacitor C2

$$C = -\frac{0.1\text{s}}{214\Omega \times \ln\left(\frac{5\text{V}}{15\text{V}}\right)} = 425.3\,\mu\text{F} \approx 470\,\mu\text{F}$$

Next, capacitor C1 is calculated. The size of the capacitor should be as small as possible, since it dictates how much power is drawn from the mains lines. Also, the larger the capacitor, the more expensive it is. The minimum size of the capacitor is derived from the basic functions of stored charge (Q = CU) and current (I = Q/t). For capacitor C1 it is no longer required to use the above worst-case current (14mA), since capacitor C2 will store energy enough to maintain the current briefly. Assuming 10mA continuous current, and that the capacitor is drained over one 50Hz half cycle, and that voltage is 80% of nominal, then the required minimum size of the capacitor is as follows:

Equation 5 - Calculating Minimum Size of Capacitor C1

$$C = \frac{I \times t}{U_{MAINS}} = \frac{0.01\text{A} \times 0.01\text{s}}{0.8 \times 230\text{V}} = 0.543\,\mu\text{F} \approx 680\text{nF}$$

The capacitor needs to be fully charged each half-cycle. The charge time is dictated by resistor R1, the size of which can be derived using the so-called 5RC rule of thumb. The 5RC rule says that for a step change in voltage the capacitor charges to within 1% of its final value in five time constants (RC). Specifying that the capacitor should be (almost) fully charged at the peak of the positive half-wave, the maximum size of resistor R1 can be estimated as follows:

Equation 4. Calculating Maximum Size of Charge Limit Resistor.

$$t = 5 \times R \times C \quad \Rightarrow \quad R = \frac{t}{5 \times C} = \frac{0.005s}{5 \times 680nF} = 1470\Omega$$

Another limitation on resistor R1 is that it must be small enough for capacitor C2 to charge enough during one half-cycle. The larger R1 is, the less C2 is charged each cycle. On the other hand, it is unreasonable to specify R1 such that C2 charges to, say, 99% during one half-cycle since this would make R1 very small and the power consumption in zener diode D1 very large. Instead, a decent charge level is selected and R1 is specified accordingly. For example, setting R1 = 470 Ω the meter works nicely (input voltage to regulator typically stays above 13V at all times).

5.2 Measuring Transducers

The analog front end or the measuring transducer is the part, which interfaces to the high voltage lines. It conditions high voltages and high currents down to a level where the signals cannot harm the more delicate electronics. It converts high voltages and high currents to voltages sufficiently small to be measured directly by the ADC of the microcontroller. The nominal line voltage of the meter is 230V and the maximum rated current is 10A, both of which obviously are way too large signals to be fed directly to any microcontroller.

The voltage outputs from the current transducers are connected to the ADE7761A at Channel V1. It has two voltage inputs, V1A and V1B. These inputs are fully differential with respect to V1N. However, at any one time, only one is selected to perform the power calculation .The maximum peak differential signal on V1A − V1N and V1B − V1N is ±660 mV. However, Channel 1 has a programmable gain amplifier (PGA) with user-selectable gains of 1 or 16. This gain facilitates easy transducer interfacing. Since we are using a shunt in our design therefore we have selected a gain of 16 at these channels.

Figure 12 shows the maximum signal levels on V1A, V1B, and V1N. The maximum differential voltage is ±660 mV divided by the gain selection. The differential voltage signal on the inputs must be referenced to a common mode (usually AGND).

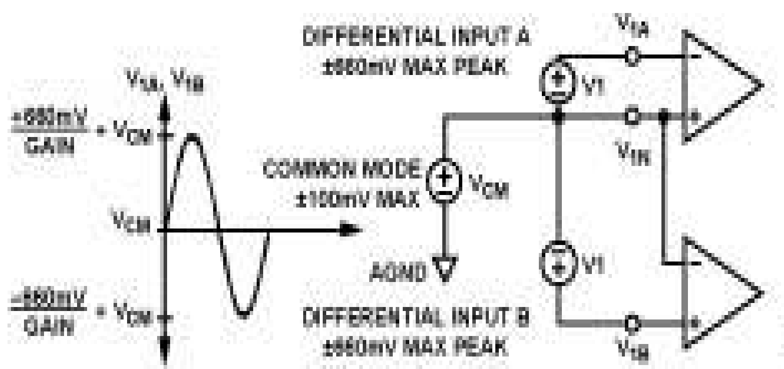


Figure 12

The output of the line voltage transducer is connected to the ADE7761A at this analog input. Channel V2 is a single-ended, voltage input. The maximum peak differential signal on Channel 2 is ±660 mV with respect to V2N. Figure 13 shows the maximum signal levels that can be connected to Channel 2.

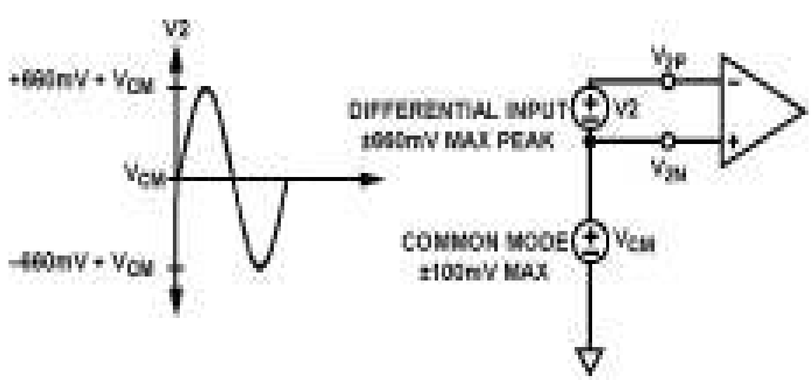


Figure 13

The ADCs digitize the voltage signals from the current and voltage transducers. A high-pass filter in the current channel removes any dc component from the current signal. This eliminates any inaccuracies in the active power calculation due to offsets in the voltage or current signals. The active power calculation is derived from the instantaneous power signal. The instantaneous power signal is generated by a direct multiplication of the current and voltage signals. To extract the active power component, the instantaneous power signal is low-pass filtered. Figure 14 illustrates the instantaneous active power signal and shows how the active power information can be extracted by low-pass filtering the instantaneous power signal. This scheme correctly calculates active power for non-sinusoidal current and voltage waveforms at all power factors. All signal processing is carried out in the digital domain for superior stability over temperature and time.
The low frequency output of the ADE7761A is generated by accumulating this active power information. This low frequency inherently means a long accumulation time between output pulses. The output frequency is, therefore, proportional to the average active power.

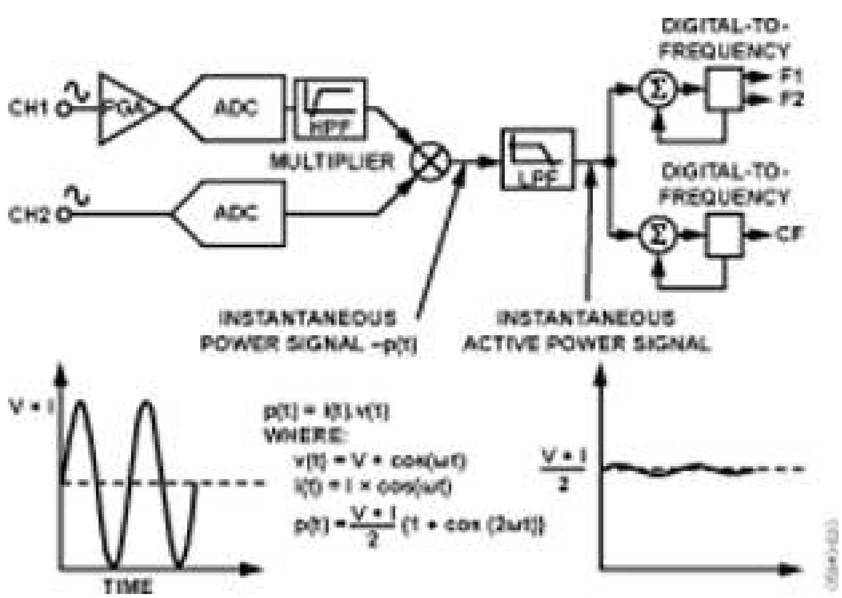


Figure 14

5.3 Analog Front End of ADC's

As discussed earlier there are two different sections in the design, a metering section and a microcontroller section. The analog front end converts line voltage and line current to voltages with amplitudes of no more than 1Volts peak-to-peak for ADC and no more than 1 Volts peak-to-peak for metering chip. The front end is easy to configure for any other line voltage or current, as described in the following.

Line voltage is first downsized using a resistor ladder, then DC-filtered and finally DC biased, as illustrated in Figure 15**.** Note that component numbers are not the same as in the full schematic at the end of this document.

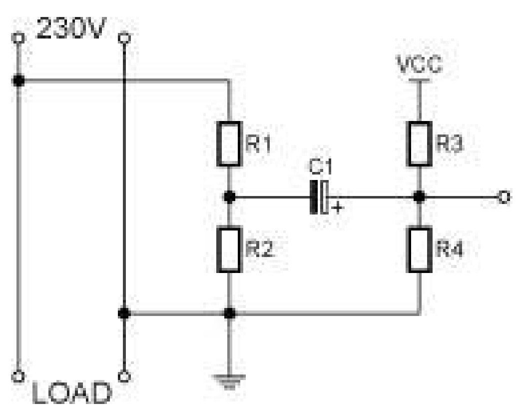


Figure 15

The resistor ladder R1-R2 by default produces a 1.0 Vpp signal when the line voltage reaches 120% of nominal voltage. The DC bias ladder R3-R4 positions the AC signal halfway up the ADC voltage reference. The same voltage measuring transducer is used for both metering and the microcontroller section the difference being that the in the MCU ADC the signal is shifted half way up whereas when being fed to the metering chip it is fed from the output of the register ladder R1-R2.

The voltage front end handles voltages of considerable amplitude, which makes it a potential source of noise. Disturbances are readily emitted into current measurement circuitry, where it will interfere with the actual signal to be measured. Typically, this shows as a non-linear error at small signal amplitudes and non-unity power factors. At unity power factor, voltage and current signals are in phase and crosstalk between voltage and current channels merely appears as a gain error, which can be calibrated. When voltage and current are not in phase crosstalk will have a non-linear effect on the measurements, which cannot be calibrated. Crosstalk is minimized by means of good PCB planning and the proper use of filter components.

The current front end is a little bit more complex than the voltage front end. This is because line voltage remains constant at, say, 230V but line current varies with the load. Line current typically ranges from some mill amperes to ten amperes, or more. In order to achieve 1% measurement accuracy over such a wide range, the ADC would need to have a very high resolution. Since the target device includes only a 10-bit A/D-converter the front end must amplify small-scale signals. The current front end therefore includes a programmable gain stage, which is controlled by the MCU.

The design criteria for the programmable gain stage are not very relaxed; the gain stage must amplify AC signals up to around 100x, but provide little or no DC amplification. This is because the input is a DC-biased AC signal and if the gain stage provides even a small DC amplification the output will saturate. In addition, the gain must be programmable by the MCU and the settling time must be considerably less than a second. Finally, the design must be cost-effective. A good starting point, however, is the operational amplifier; they are common, exist in a wide variety and can be very cost-effective. A little experimentation soon shows that the non-inverting amplifier is not a viable topology for this design, mostly because of the requirements for high AC and low DC gains. Considering the frequency band of interest, AC-coupled, non-inverting amplifiers require very large (and expensive) capacitors for the DC decoupling. Also, a large DC decoupling capacitor leads to very long switching times when gain is altered. Since the gain needs to be variable the DC levels cannot be trimmed to zero. A viable solution is found from inverting amplifier topology, although it still requires a rather (but not very) large capacitor to be used. Gain configuration resistors are readily toggled in and out using low-cost switches from 74HC-series logic, as shown in Figure 16. The gain stage shown has a fast switching time and allows high AC gain but a low DC gain.

Figure 16. Inverting Amplifier with Variable Gain Uses Bilateral Switches (74HC4066).

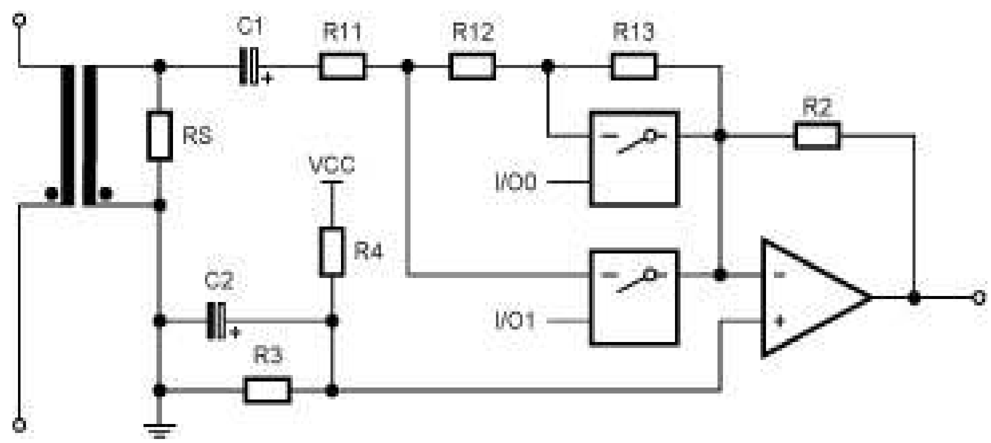


Figure 16

The gain of the inverting amplifier is as follows:

Equation 7. Gain Of Inverting Amplifier

$$A = -\frac{R2}{R1}.$$

Here R1 consists of the series connection of R11, R12 and R13. Gain is adjusted by shorting out one of resistors R12 or R13. This is done using the bilateral switches, which are controlled by two I/O pins of the MCU, shown as I/O0 and I/O1 in the figure. Gain adjustment resistors are dimensioned such that each range has an amplification of about eight times the previous. The number of switches may well be increased and the gain difference decreased, however, it is not recommended to have a larger gain difference than eight between two subsequent ranges. This is because gain differences of around ten, and higher, cause the signal to degrade below 1% accuracy before it can be further amplified.

The table below illustrates how gain is adjusted from the MCU.

Table 3. Adjusting The Gain Of The Inverting Amplifier. R2 = 470 kΩ.

I/O0	I/O1	Range	R1 Impedance	Gain
Low	Low	Low	R11+R12+R13 = 6.8k+39k+330k	-(470/375.8) = -1.25
Low	High	Medium	R11 + R12 = 6.8k+39k	-(470/45.8) = -10.26
High	X	High	R11 = 6.8k	-(470/6.8) = -69.11

Shunt resistor RS and the current transformer are scaled such that a voltage signal of no more than 1V peak-to-peak is present at the amplifier output when maximum current flows through the primary of the current transformer and the amplifier is set to minimum gain.

For example, using a 2500:1 current transformer, a 68 Ω resistor, and setting amplification to minimum (see above), the voltage at the output is as follows:

Equation 8. Full-Scale Voltage At Amplifier Output.

$$U_{MAX} = \frac{A \times RS \times I_{MAX}}{N} = \frac{1.25 \times 68\Omega \times 10A_{RMS}}{2500} = 0.34V_{RMS} \approx 0.96V_{PP}$$

The input signal of the amplifier must be DC decoupled. This is done using capacitor C1 in the previous figure. It should be noted that R1 + C1 form a high-pass filter (HPF) that may distort signals, especially at high gains. The corner frequency, or the –3dB point, of the HPF is calculated as follows:

Equation 9. Corner Frequency Of HPF.

$$f_{-3dB} = \frac{1}{2 \times \pi \times R1 \times C1}$$

The closer the corner frequency of the HPF is to the frequency band of the interest, the higher is the distortion of phase and amplitude. It is recommended to keep a distance of at least 100x between the two frequencies. At 50Hz line frequency and R1 minimum = R11 = 6.8 kΩ, C1 should not be less than 47 µF. The output signal of the gain stage is biased around the DC level present at the noninverting input of the operational amplifier. Hence, this DC level should be exactly half of the reference voltage of the ADC in the MCU. Assuming a 1.1V reference, the voltage divider R3-R4 should produce a stable 0.55V. The voltage divider should have a large impedance to keep the current consumption low, since high impedance increases noise. For example, assuming 5V supply voltage, a suitable set of values is 3 MΩ + 560 kΩ.

The DC level is stabilized with one, or many, capacitors. To make accurate measurements, the input signal must be as clean as possible, especially at low amplitudes. Input signals with low amplitude are amplified before being sampled and processed, which means any noise in the signal will be enlarged, too. At the low end of the measurement range input signals have amplitudes below 10mV, which means noise typically not visible on an oscilloscope (say, below 1mV) may distort the signal by as much as 10%. Noise is eliminated using good PCB planning and properly sized and placed filter components.

5.4 RTC and EEPROM interfacing

The RTC and EEPROM both are communicated using the standard I2C protocol. The ATMEGA AVR has inbuilt two wire interface pins (TWI) pins. The TWI protocol allows the systems designer to interconnect up to 128 different devices using only two bi-directional bus lines, one for clock (SCL) and one for data (SDA). The only external hardware needed to implement the bus is a single pull-up resistor for each of the TWI bus lines. All devices connected to the bus have individual addresses, and mechanisms for resolving bus contention are inherent in the TWI protocol.

5.5 Voltage and Current Measurement

The firmware calculates RMS (Root-Mean-Square) values of voltage and currents. An RMS value is defined as the square root of the mean value of the squares of the instantaneous values of a periodically varying quantity, averaged over one complete cycle. The discrete time equation for calculating voltage RMS is as follows:

Equation 10. Voltage RMS Calculation in Discrete Time Domain.

$$U_{RMS} = \sqrt{\frac{\sum_{n=0}^{N-1} u^2(n)}{N}}$$

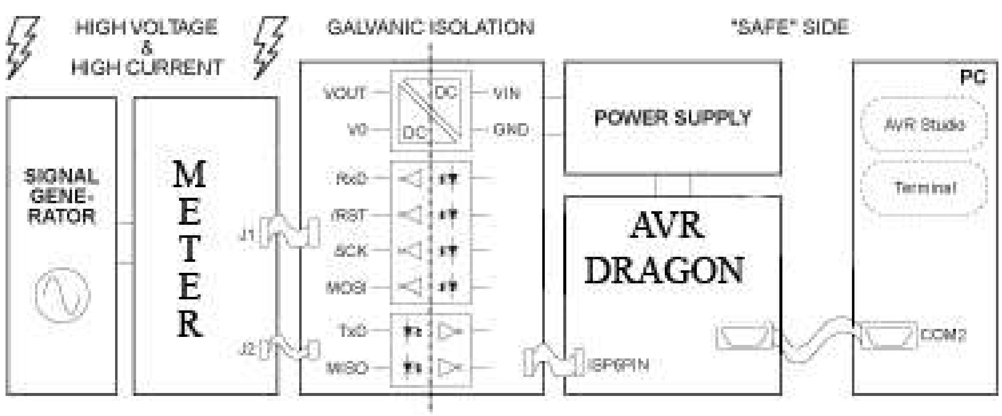
Current RMS is calculated using the same equation, only substituting voltage samples, u(n), for current samples, i(n). Accumulated data is stored 32 bits wide (signed long) and the calculation result is stored as a floating-point number. When properly calibrated, the resulting voltage measurement is in units of volts and current measurements in units of amperes.

5.6 Calibration

No two meters are alike and individual variations are to be expected. Typical tolerance figures for components used in the meter are 5%, which means the assembled meter has an inherent error of the same magnitude. Hence, each meter must be calibrated before accurate measurement result can be obtained. Calibration the procedure is readily carried out in the digital domain. Calibration coefficients are first calculated for each meter individually, then stored in on-chip EEPROM and later retrieved during firmware initialization. The coefficients trim the calculations such that measurement results are accurate within limits. Digital calibration is accurate and efficient, it is quick to perform, requires little or no manual intervention, and does not degrade over time. In addition, calibration data is safely stored in the internal EEPROM.

The meter constantly sends measurement data via the asynchronous interface. To read measurement data (also during calibration), the asynchronous interface must be connected. The asynchronous connector is wired to a microcontroller directly or to a computer via a RS-232 buffer. The asynchronous interface cannot be wired to a RS-232 port directly, since it is not buffered. Connect the asynchronous interface of the meter to AVR Dragon pins labeled ISP. Then use terminal software to read data from the serial port.

Figure 17. Set-Up for Calibration



5.7 Graphical User Interface

A graphical user interface is developed in Visual C# for decoding and analysis of data which is downloaded from microcontroller. Also the same interface can be used for adjusting the values of constant for ADC values and setting up of time and date for RTC.

5.8 Complete Hardware Design

The complete hardware design schematic can be found in Appendix A and B

5.9 Microcontroller Code

The firmware is written in C language and compiles on IAR Embedded Workbench. The firmware is interrupt-driven, which means the main program consists of an endless loop that is halted by interrupt requests on a regular basis. It is important that the interrupt requests arrive regularly since they are used as the time base for calculations. Variations in interrupt intervals will show in the accuracy of measurement results Interrupt requests are generated by the ADC, which is driven by a prescaled system clock.

6.0 Result and Discussion

6.1 Metering Accuracy

The accuracy after adjustment was checked using a standard reference meter and results at various current was as follows

Table 4 - Error in % at different loads and power factor

	10 Amp	5 Amp	1 Amp
Unity Power Factor	0.15%	0.23%	0.15%
0.5 Lag	-0.12%	0.03%	0.13%

6.2 Voltage, Current and Power Display

The voltage was calibrated at a single point of 230Volts where as the current was calibrated at two different points to get linearity over a wide range. Table below shows the value displayed when different values of parameters were given to the meter

Table 5 : Display values of voltage

Voltage Given	230 Volts	288 Volts	192 Volts
Displayed Voltage	230.1Volts	287.8 Volts	191.9 Volts

Table 6 – Display values of current

Current Given	10 Amperes	5 Amperes	1 Amperes
Displayed Current	9.9 Amperes	5.1 Amperes	1.0 Amperes

6.3 Communication

The data transfer was checked using the graphical user interface and all the data transferred was the same as displayed on the LCD by the meter.

7.0 Closure

7.1 Future Work

There is no reason why additional gain ranges could not be implemented, using the same ideology as illustrated in this design. Naturally, there is a limit on how much the input signals can be amplified before noise starts to degrade measurement accuracy, but it is possible to increase the dynamic range above the present. Alternatively, adding more gain ranges and reducing the range difference from current may provide a more linear transfer function and increase the absolute accuracy to better than 1%.

With a little change in hardware and software Pre paid technology using a smart card can be implemented.

No software is ever complete and there are probably as many potential improvements.

Some recommended starting points for software enhancements include:

• Put the MCU to sleep as often as possible.

• Add reactive power, Q, to measurement set.

7.2 Evaluation of Performance

The meter was made to run in parallel with a domestic meter and it was found out that the designed meter was recording the same amount of energy as the domestic meter but with added features like maximum demand, voltage, current display etc.

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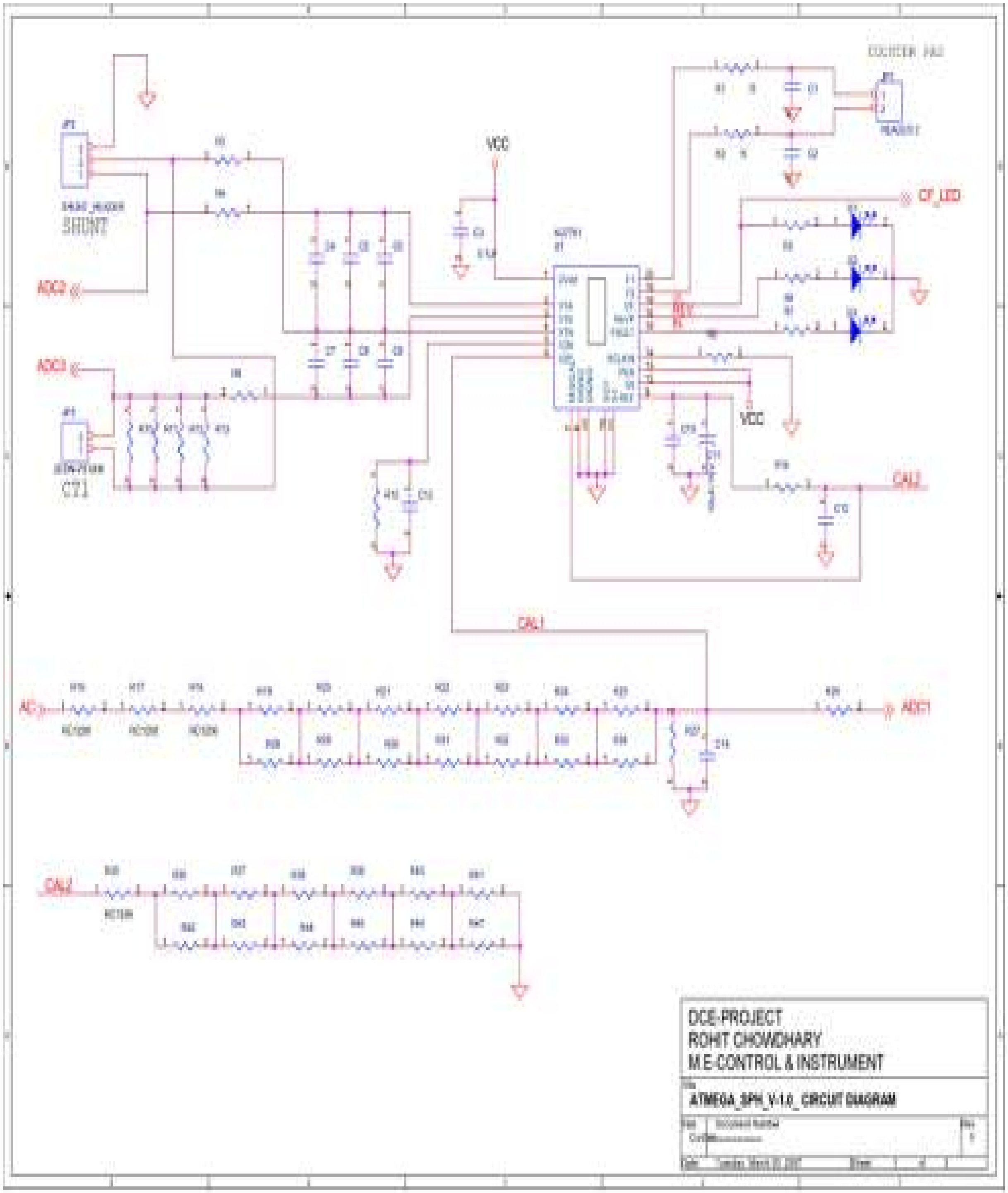
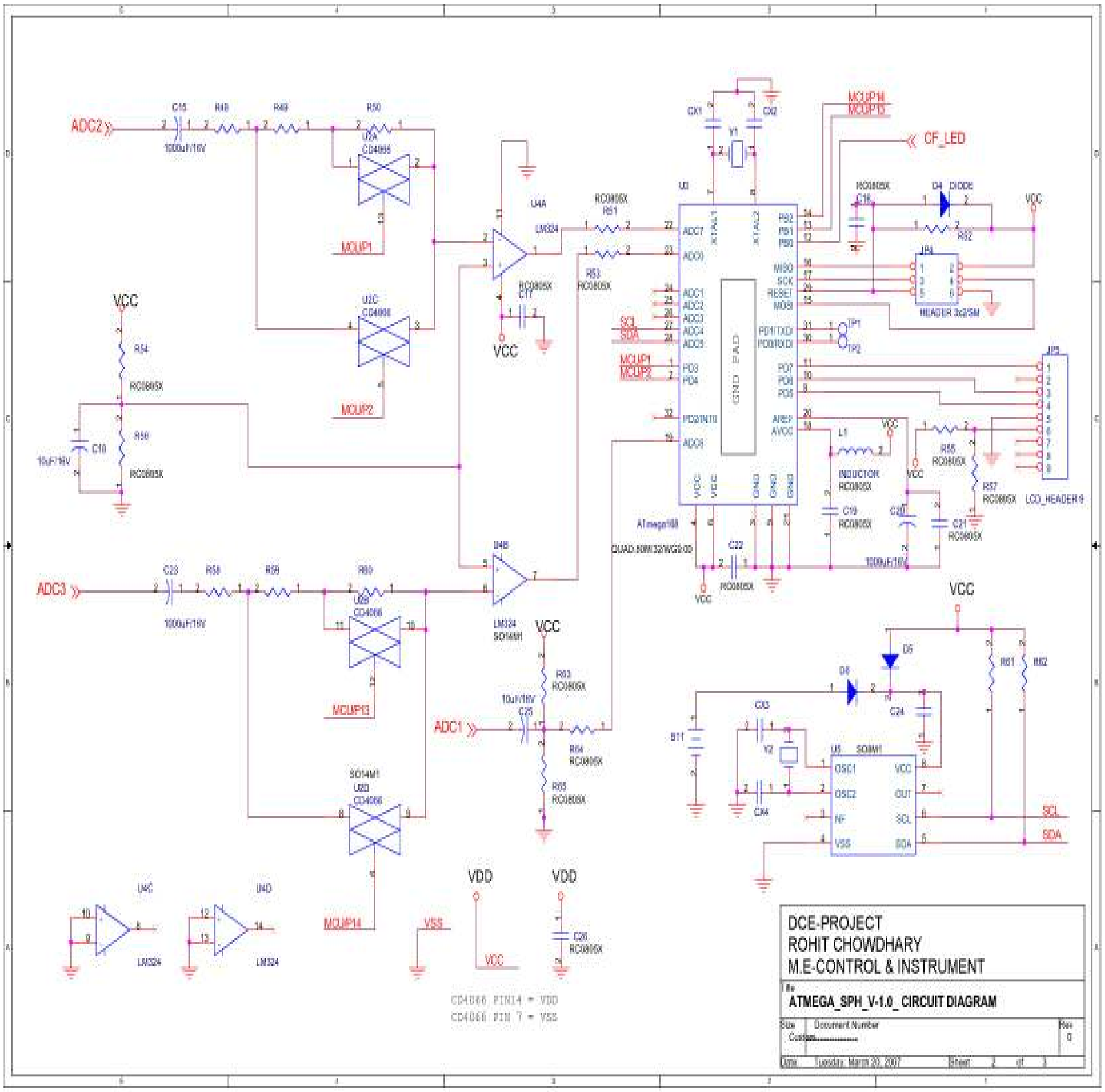
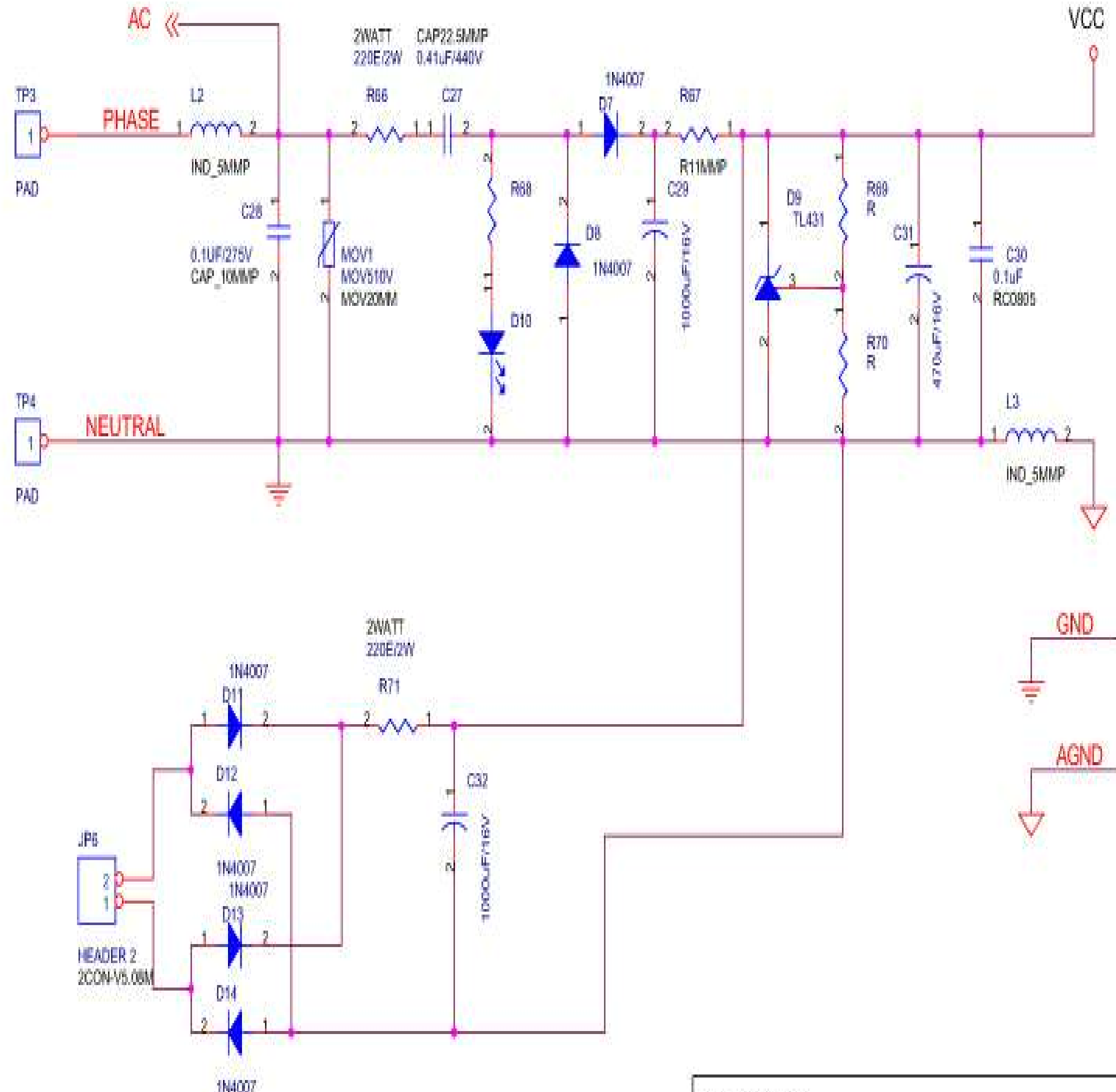
Appendix A – Circuit Diagram





ADC2
ADC3
ADC1
CF_LED
MCUP1
MCUP2
MCUP13
MCUP14
SCL
SDA
VCC
VDD
VSS
CD4066
LM324
ATmega168
GND PAD
HEADER 3x2/SM
LCD_HEADER 9
INDUCTOR
CD4066 PIN14 = VDD
CD4066 PIN 7 = VSS
DCE-PROJECT
ROHIT CHOWDHARY
M.E-CONTROL & INSTRUMENT
ATMEGA_SPH_V-1.0_ CIRCUIT DIAGRAM
Tuesday, March 20, 2007



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ATMEGA_SPH_V-1.0_CIRCUIT DIAGRAM		
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Date: Tuesday, March 20, 2007	Sheet 3 of 3	