Design and Implementation of a Microcontroller Based Wireless Energy Meter

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ABSTRACT

Efficient use of energy becomes more crucial when increase in the cost of energy is observed. Since energy management is required to define the amount of consumed energy in a specific period of time, utilization of Energy Meters is essential. It is possible to measure the consumed energy by using a simple energy meter. But sometimes the limited functionality of these meters restricts their area of application; especially in inaccessible positions or in the situations where visibility of the meter is poor, it is not possible to use such an appliance. A possible solution is a Wireless Energy Meter (WEM) which is able to send its data via wireless communication to a PC where monitoring and analysis of the data will be easily made. This measurement system is aimed to be used in measuring energy related quantities of transformers and high voltage towers at remote locations.

This document describes the design and implementation of a digital Wireless Energy Meter (WEM) based on AVR microcontroller. Calculation of the phase difference between current and voltage using Zero Cross Detection capability of the microcontroller is a distinct feature of this project. Hall Effect Sensor is used to measure the current signal and a resistive voltage divider is used to measure the voltage.

Key words: Energy Meter, Wireless, AVR Microcontroller, Hall Effect Sensors, Resistive Voltage Divider, Zero Cross Detection

ÖZ

Enerjinin etkili kullanımı enerji fiyatındaki yükseliş gözlemlendiği zaman çok büyük önem kazanır. Enerji kontrolü belirli bir zaman dilimi içerisinde tüketilen enerji miktarını tanımlamak için gerekli olduğundan, enerji ölçü aleti kullanımı çok önemlidir. Tüketilen enerjiyi basit bir enerji ölçü aleti kullanarak ölçmek mümkündür. Fakat bazen bu ölçü aletlerinin kısıtlı fonksiyonlara sahip olması bunların kullanım alanlarını kısıtlar. Özellikle erişimi mömkün olmayan veya ölçü aletinin görünümünün zayıf olduğu durumlarda bu tür bir uygulamayı kullanmak mümkün değildir. Bu duruma muhtemel bir çözüm bilginin analiz ve izlemesinin kolayca yapılabileceği bir PC ye kablosuz iletişim aracılığı ile bilgi gönderebilecek bir kablosuz enerji ölçü aleti (WEM) kullanmaktır. Bu ölçü sistemi, uzak yerlerdeki yüksek gerilim merkezleri ile enerji ile ilgili transformatör değerlerini ölçmek için kullanılmayı amaçlamaktadır.

Bu döküman AVR mikro denetleyiciye dayanan dijital kablosuz enerji ölçüsünün tasarım ve uygulamasını tanımlamaktadır. Mikro denetleyicilerin Sıfır Geçiş algılayıcısı özelliğini kullanarak akım ve gerilim arasındaki faz farkını hesaplamak, bu projenin ayırt edici bir özelliğidir. Hall Etkisi sensörü; akım sinyalini ve dirençli gerilim bölücü; gerilimi ölçmek için kullanılır.

Anahtar kelimeler: Enerji Ölçü Aleti, Kablosuz, AVR Mikro Denetleyicileri, Hall Etkisi Sensörleri, Dirençli Gerilim Bölücü, Sıfır Geçiş Algılayıcısı

DEDICATION

This thesis is dedicated to my parents

for their love, endless support

and encouragement.

Reza Shahrara

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I wish to express my thanks to my supervisor, Prof. Dr. N. Süha Bayındır. This thesis would not have been complete without his expert advice and unfailing patience, all through my research.

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INTRODUCTION

1.1 Purpose and Description of Project

The primary aim of this project is to design a digital Energy Meter using AVR microcontroller, and then wirelessly transmit the measured data to a PC and to implement the designed circuit on a Printed Circuit Board (PCB) and in the last step to write a program as a Graphical User Interface (GUI); under Microsoft Visual Studio C# regarding to monitoring the received data.

A general Block Diagram of the energy measurement and data transmission system designed in this project is shown in Figure 2.8.

ATmega32 is a low power AVR, 8-Bit microcontroller which is used in this project. All preparations of the design are based on the properties of this microcontroller due to its versatile features in programming and data transmission.

Atmega32 with two 8-bit and one 16-bit Timer/Counters with Separate Prescalers, Compare Modes and Real Time Counter with Separate Oscillator, let us calculate the Phase Difference between current and voltage easily. Analog values of measured current and voltage signals as well as their zero cross detected signals are applied to the microcontroller which evaluates the rms values of V and I as well as its Power Factor. The microcontroller also calculates the Apparent Power (S), in volt amperes

(VA), Real Power or Active Power (P) in watts (W), and Reactive Power (Q), in volt amperes reactive (VAR) and Energy values and then exports these quantities via serial port to a wireless serial adaptor which is used to transmit the data wirelessly to a PC .With the written program under Microsoft Visual Studio C#; the monitoring of these data will be possible.

Applying this technique; makes it possible to use any wireless transceiver device which is one of the benefits of this project in comparison with the similar projects. Bluetooth Serial Adaptor is used for data transmission in this thesis due to its high capability and convenience. This tiny adaptor allows any device with a standard 9-pin serial port to communicate wirelessly. LM-058 is the device which is used for this purpose. LM-058 Bluetooth Serial Adaptor can communicate with another Bluetooth serial adaptor or other Bluetooth-enabled devices such as a laptop computer, personal digital assistant (PDA) or mobile phone.

1.2 Literature Review

In [1] the development of an Energy Meter (EM) with an interface to a wireless sensor network based on IEEE 802.15.4 [2] technology is presented. The developed platform consists of two notable components to measure different kinds of the power consumption.

These two elements are the ICradio Module 2.4G [3] and the Energy Measurement IC ADE7753 [4].

ICradio Module 2.4G is a compact radio, specified for ZigBee / IEEE 802.15.4 network applications. This devise is based on ATmega1281 controller AT86RF230

2.4GHz radio chip from Atmel and is usually used for evaluation purposes. ADE7753 is a single phase multifunction Energy Metering IC.

In [5] an AC Meter development for IP based Wireless AC Energy Monitors is described which has four main sections: power supply, signal filtering, Wireless Energy Metering and microcontroller.

In [6] an electronic system is described to measure the active, reactive and apparent energies delivered to a load of an AC voltage line. The proposed system is directly connected to a PC monitoring the power consumption.

In [7] Design and Implementation of Bluetooth Energy Meter is presented. The interface between a Meter Reader, PC and the Energy Meter via a Bluetooth can be categorized into three main distinctive portions. The first portion consists of the interface between a PC and the Bluetooth radio module. The second portion comprises the interface between the Bluetooth radio module and the microcontroller; the interfaces in the first portion and second portion are both using the standard RS-232 protocol. The last section is about the interface between microcontroller and Energy Meter, whereby the communication link is conforming to the Serial Peripheral Interface (SPI) standard.

Last reviewed literature [8] is a case study of an inexpensive student designed power monitoring instrument used for campus of the Rowan University submetering. This system is constructed with an Energy Metering IC connected to a PIC microcontroller. Access to the measured values can be possible via Serial interface.

1.3 Contributions

In almost all reviewed related literatures; for sensing the energy; Energy Meter Sensors are used. Therefore in order to control the measured data, calculating and then transmission, at least one additional microcontroller should be operated. Data transmission will be possible via a specific device with unique properties.

In this thesis all related calculations and transmission of the measured data via serial port to a serial adaptor is done with only one simple AVR microcontroller.

The aim of this project is to design a digital Energy Meter using AVR microcontroller, and then wirelessly transmit the measured data to a PC. Graphical User Interface (GUI) is written under Microsoft Visual Studio C# regarding to monitoring the received data. ATmega32 is the microcontroller used in this thesis which can transfer its measured data to serial port. Bluetooth Serial Adaptor is the device that is not uniquely selected.

In this feature WEM is able to transmit its measured data wirelessly to a PC. With the help of computers' capabilities monitoring or even comparison of the measured data with the received data from other wireless energy meter devices; is possible.

The desired Wireless Energy Meter (WEM) is successfully implemented based on AVR microcontroller.

Chapter 2

MEASUREMENT OF ENERGY RELATED

QUANTITIES

2.1 General Theory and Principles

2.1.1 Real Power

For time varying voltages and currents, the power delivered to a load is also time varying. This time varying power is referred to as instantaneous power. The real power is the average value of the instantaneous power [9].

The Average Power depends on the rms value of voltage and current and the phase angle between them.

$$P = \tfrac{1}{2}V_m I_m \cos(\theta_v - \theta_i) = V_{Rms}I_{Rms} \cos(\theta_v - \theta_i) \qquad (2.1)$$
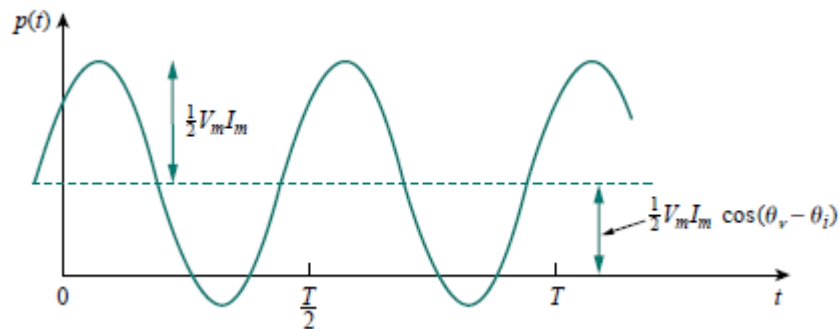
Figure 2.1: The instantaneous power *p(t)* entering a circuit [10].

For AC sinusoidal voltage and current, the real power (P), in watts, dissipated in an AC R-L, R-C, R-L-C circuit is dissipated in the resistance only.

$$P = I^2 R \qquad (2.2)$$

2.1.2 Apparent Power

The Apparent Power (S), in volt amperes (VA), is the product of the rms value of voltage and current.

$$S = \frac{1}{2}V_m I_m = V_{Rms} I_{Rms} \tag{2.3}$$

2.1.3 Power Factor

The Power Factor (pf) is the cosine of the phase difference between voltage and current. Power factor can also be found by dividing real power (P) by apparent power (S); so we have:

$$pf = \frac{P}{S} = \cos(\theta_v - \theta_i) \tag{2.4}$$

$$P = \text{Apparent Power} \times \text{Power Factor} = S \times pf \tag{2.5}$$

2.1.4 Reactive Power

The Reactive Power (Q), in volt amperes reactive (VAR), is the power which oscillates between the supply and the reactance of the load and can be calculated from (2.6)

$$Q = V_{Rms} I_{Rms} \sin(\theta_v - \theta_i) \tag{2.6}$$

It is clear that the Reactive Power is the imaginary part of the Complex Power S.

$$S = P + jQ = \text{Re}\{S\} + j\,\text{Im}\{S\} \tag{2.7}$$

$$S = I^2{}_{Rms} Z = I^2{}_{Rms}(R + jX) = P + jQ \tag{2.8}$$

Where

$$P = V_{Rms} I_{Rms} \cos(\theta_v - \theta_i) = \text{Re}\{S\} = I^2{}_{Rms} R$$
$$Q = V_{Rms} I_{Rms} \sin(\theta_v - \theta_i) = \text{Im}\{S\} = I^2{}_{Rms} X \tag{2.9}$$

Figure 2.2 is shown Power Curve for a purely resistive circuit.
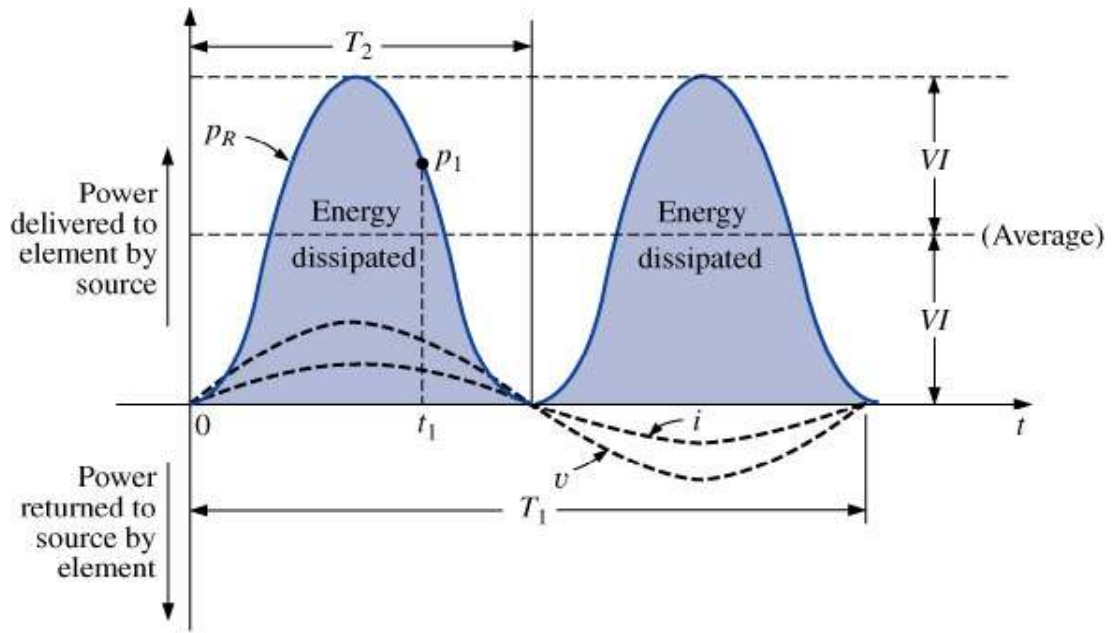
Figure 2.2: Real power dissipated in Resistive circuit

Therefore the equations below can be inferred:

$$v(t) = V_m \sin(\omega t + \theta)$$
$$i(t) = I_m \sin(\omega t)$$
$$p_R(t) = v(t)i(t) = V_{Rms}I_{Rms} - V_{Rms}I_{Rms}\cos(2\omega t)$$
$$\theta = 0°$$

Since the phase angle between current and voltage is zero, the circuit has neither a lagging nor a leading power factor; therefore the load is Resistive and draws only active power.

For a purely inductive circuit, v leads i by 90° as shown in Figure 2.3.

$$\theta = 90 \rightarrow \text{Inductive}$$
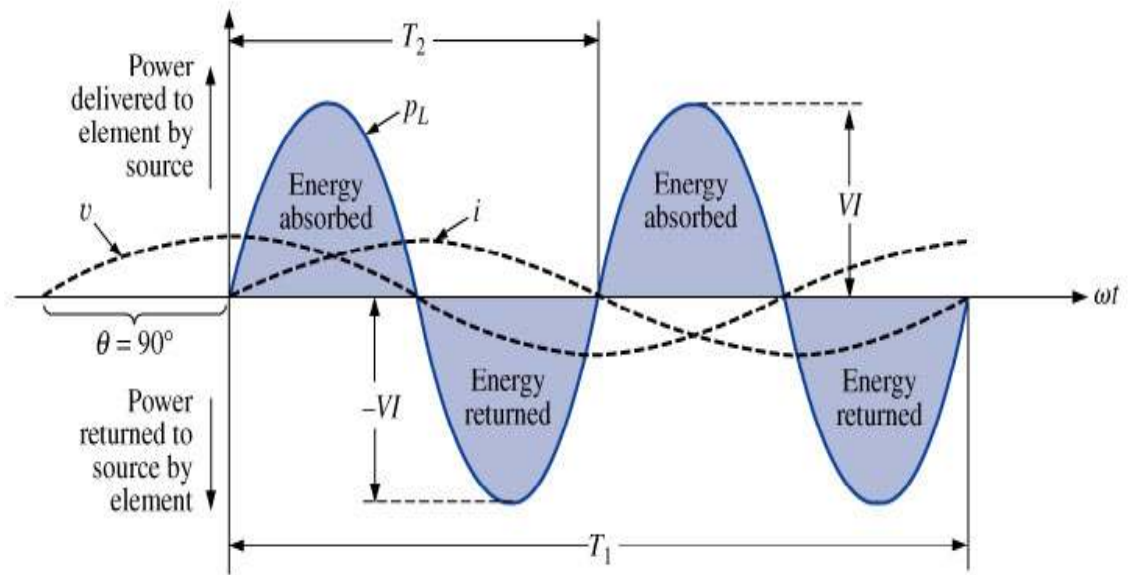
Figure 2.3: Inductive circuit and Reactive Power

The power absorbed or returned by the inductor can be found as below:

$$p_L(t) = V_{Rms} I_{Rms} \sin(2\omega t)$$
$$\theta = 90°$$

The net flow of power to the pure (ideal) inductor is zero over a full cycle, and no energy loss is observed in the transaction.

For a purely capacitive circuit, *i* leads *v* by 90° as illustrated in Figure 2.4.

$$\theta = -90 \rightarrow \text{Capacitive}$$
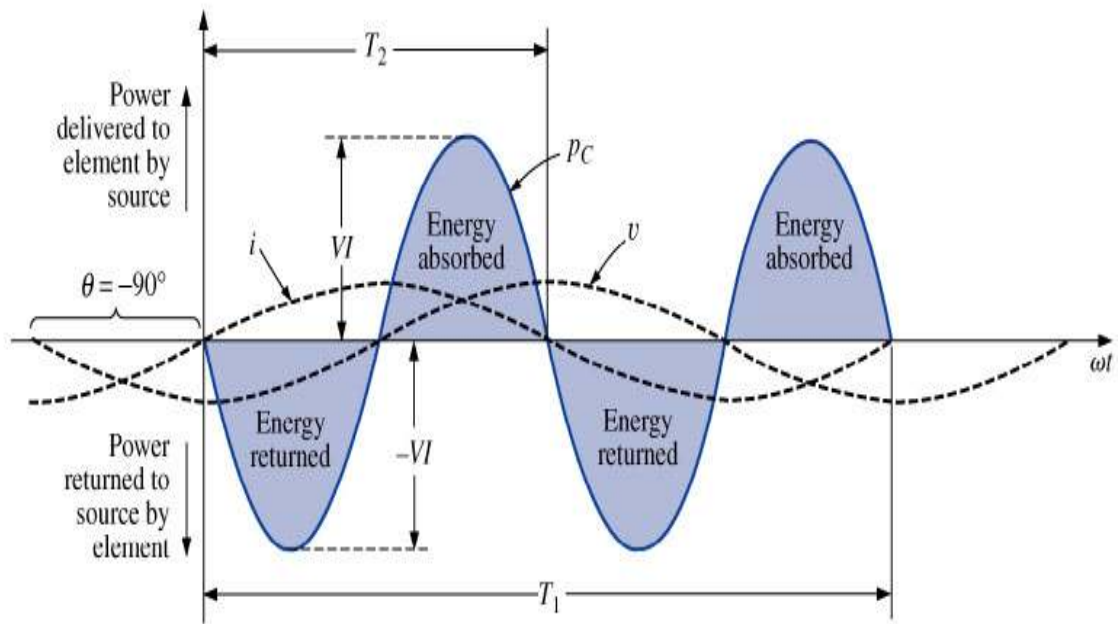
Figure 2.4: Capacitive circuit and Reactive Power

The power absorbed or returned by the capacitor can be found from:

$$p_C(t) = -V_{Rms} I_{Rms} \sin(2\omega t)$$
$$\theta = -90°$$

Similar to the previous case, it is apparent that the net flow of power to the pure (ideal) capacitor is zero over a full cycle, and no energy loss is observed in the transaction as well.

2.1.5 Power and Impedance triangle

It is possible to show the relation between S, P and Q in the form of a triangle, known as the power triangle as shown in Figure 2.5(a). A similar relation between Z, X and R can be shown by the Impedance triangle as shown in Figure 2.5(b).

(a)   (b)

Figure 2.5: Power Triangle (a), Impedance Triangle (b). [10]

If S lies in the first quadrant; the reactive power is positive; which means that the circuit has a lagging power factor and the load is inductive, otherwise if S is in the fourth quadrant the reactive power is reactive; which means that the circuit has a leading power factor and the load is capacitive, as illustrated in Figure 2.6.
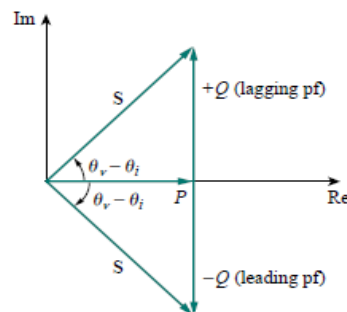
Figure 2.6: Power triangle

2.2 Operational Considerations

According to the general theory and principles of the Power calculation; Power factor is the major part of the operation therefore calculation of the phase difference between current and voltage is the prime requirement. To solve this problem Zero Cross Detection method is used and after Detecting the Zero Crossed points; square wave signals are obtained and applied to the microcontroller which can follow these

rising and falling edges (it depends on the written program for microcontroller operation which in this case falling is selected) and with its ability to set or reset the related counter/timers which calculates the time difference between these two signals. Considering the selected oscillator, prescale and frequency values; it is possible to calculate the phase difference in terms of degrees.
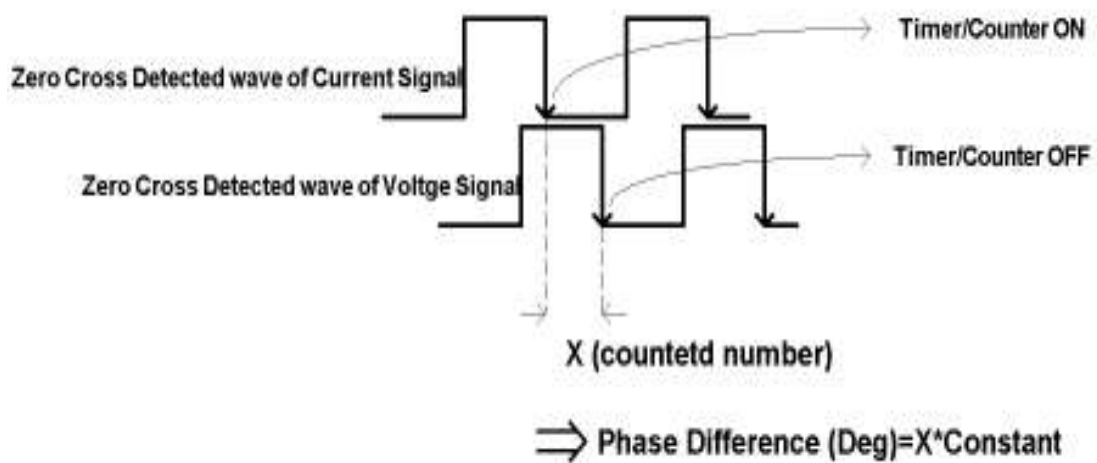
Figure 2.7: Phase Difference Calculation Procedure

As it is shown in Figure 2.7, when microcontroller senses the falling edge of zero cross detected current signal, connected to INT0 pin of microcontroller, timer/counter starts to count until it senses the zero cross detected voltage signal connected to INT1, after stopping the timer/counter regarding to the frequency, selected prescale and oscillator values, calculation of the phase difference in terms of degrees is fulfilled.

After computing the values of the current and voltage and the phase difference; calculation of the all other energy related quantities is possible. ATmega32, with

eight analog to digital (A/D) inputs, which is used for calculating the current and voltage values; is preferred due to the ease in programming and the convenience of transferring data. The general block diagram of constructed WEM is illustrated in Figure 2.7.

In general, all the sensors used for energy meter; work based on two types of signal processing, namely analog and digital. [11] This signal processing uses multiplication and filtering for the extraction of the information required by an energy meter. [12]
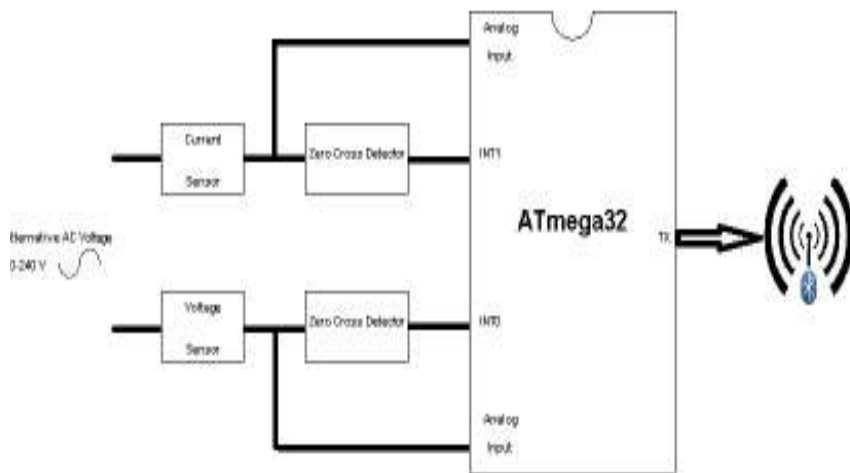
Figure 2.8: Block Diagram of WEM

In following portions in this chapter all the methods used in this thesis are explained and in chapter 3 all used components regarding described methods are clarified.

2.2.1 Current Sensing

Current Sensing however, poses much more difficult problems due to the rich harmonic content in the current waveform. Current sensor not only requires a much wider measurement dynamic range, but also needs handling of a much wider frequency range.

Considering advantages and disadvantages, selection of which type of methods to be used for sensing the current is challenging, so the chosen appropriate possible solution is to employ one of the Hall Effect Sensor or Current Transformer (CT).

2.2.2 Hall Effect

Hall Effect is a phenomenon whereby a conductor carrying an electric current perpendicular to an applied magnetic field develops a voltage gradient which is transverse to both the current and the magnetic field [13].

2.2.3 Hall Effect Sensor

The Hall Effect is an ideal sensing technology; in terms of measurement especially at high frequency. The Hall element is constructed from a thin sheet of conductive material with output connections perpendicular to the direction of current flow. When subjected to a magnetic field, it responds with an output voltage proportional to the magnetic field strength. The voltage output is minor (μV) and needs additional electronics to achieve useful voltage levels. When the Hall element is combined with the associated electronics, it forms a Hall Effect sensor [14].

General Sensor based on the Hall Effect is shown in the Figure 2.8.
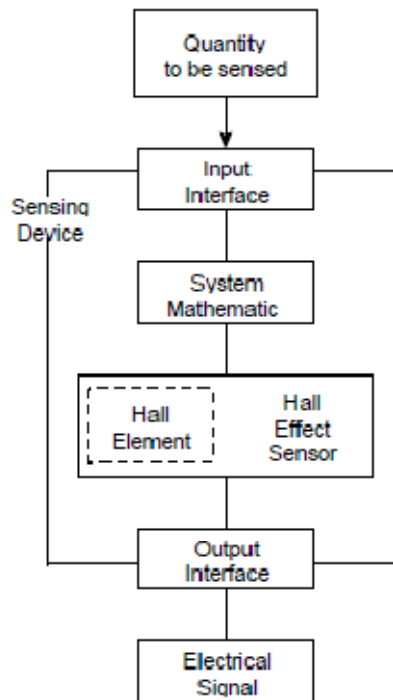
Figure 2.9: General Sensor based on the Hall Effect [14]

2.2.4 Current Transformer (CT)

Current Transformers (CT's) are instrument transformers that are utilized to supply a reduced value of current to meters, protective relays, and other instruments. Isolation is provided by CT's from the high voltage primary, grounding of the secondary for safety is permitted, and the magnitude of the measured current is stepped down to a value that can be safely handled by the instruments [15].

2.2.5 Voltage Sensing

Voltage sensing is usually obtained by using either the voltage division method or a step down potential transformer. Decision making about which method should be used, is related to the work necessities. Both mentioned approaches are used in this project.

2.2.6 Voltage Division

Voltage Division is the most common way to divide down the line voltage based on Ohm's law. Relationship between input voltage V_{in} and Output voltage V_{out} is as below.
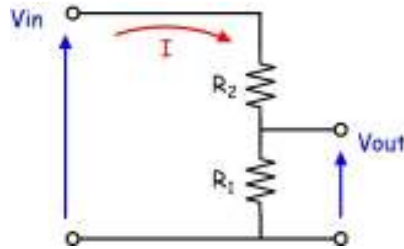
Figure 2.10: Voltage Division Circuit

$$V_{out} = V_{in} * \frac{R_1}{R_1 + R_2} \qquad (2.10)$$

2.2.7 Voltage Transformer

Voltage transformer is an electromagnetic device which consists of two or more coils wound on a magnetic core and changes the voltage level in a circuit, under fixed frequency.

Consider an ideal transformer as shown in Figure 2.11.
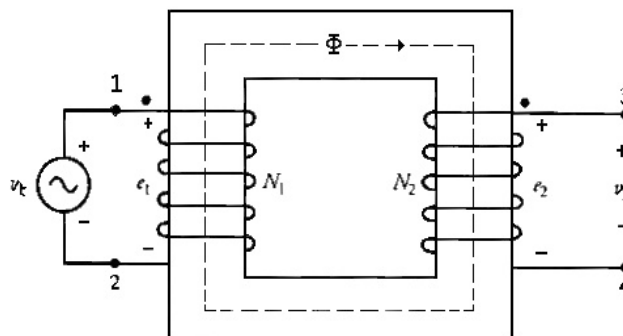
Figure 2.11: Ideal transformer

The ratio of primary and secondary voltage can be obtained from equation (2.11) as:

$$\frac{v_1}{v_2} = \frac{N_1}{N_2} = \frac{i_2}{i_1} \qquad (2.11)$$

As it is mentioned, AVR ATmega32 microcontroller is the component, used in this achievement and the maximum voltage can be sensed by microcontroller is 5.00 V AC or DC[1].

The resistor values *R1, R2* in Figure 2.10 are chosen in a manner to give us a voltage gain of ($\frac{1}{4}$) and transformer turns ratio ($\frac{1}{12}$). These values are chosen specifically to satisfy the circuit design requirements.

2.2.8 Zero Cross Detection

As the name implies, zero cross detector is an appliance for detecting the point where the voltage crosses zero in either direction. A comparator can be used as a zero cross detector.

If reference voltage of comparator is selected as zero (V_{ref}=0), slightest input voltage will saturate the comparator and consequently Op-Amp will operate as a Zero Cross Detector. The zero cross detector used in this project is shown in Figure 2.12.

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[1] In this study DC voltage is used in order to acquire accurate results.
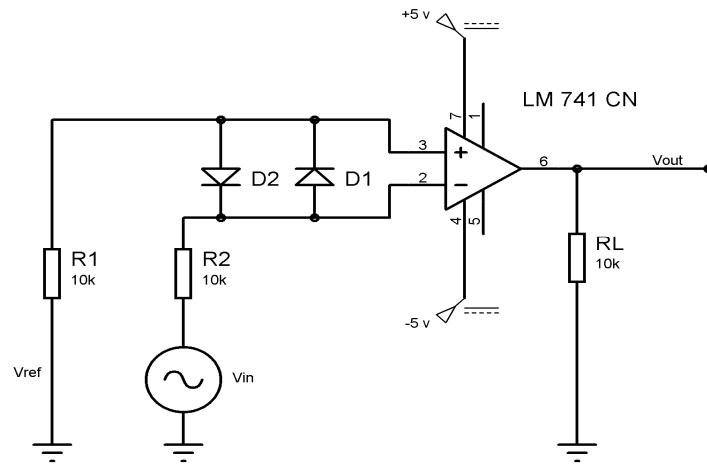
Figure 2.12: Zero Cross Detector, used in this project

Figure 2.13 shows the sinusoidal input signal and zero cross detected output wave, simulated in Proteus ISIS Professional ver. 7.6

Channel A: Input Signal

Channel B: Output Signal
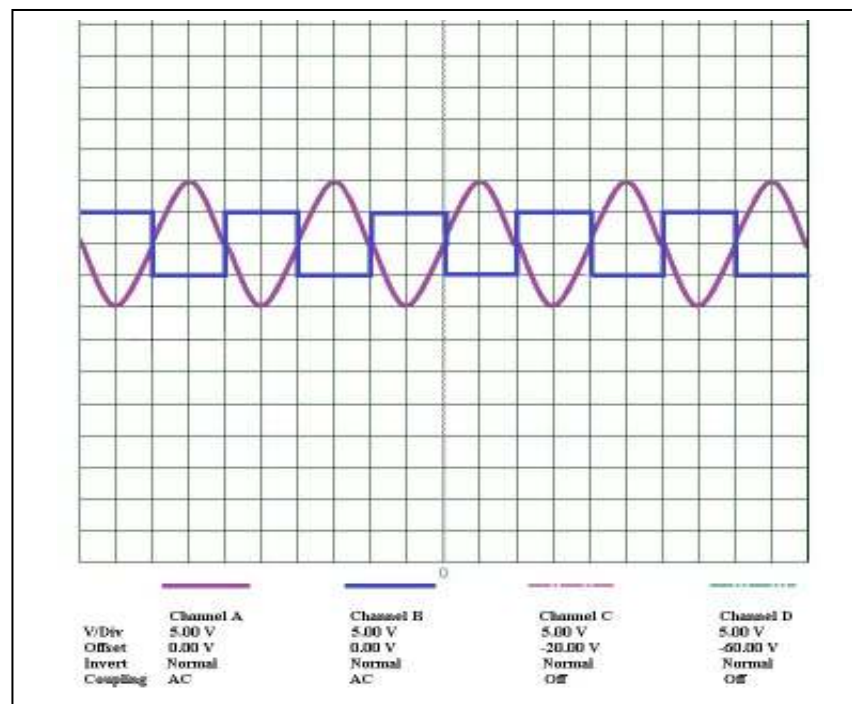
Figure 2.13: The sinusoidal input signal and zero cross detected output wave

2.2.9 Data Transmission

Data Transmission is physical sending and/or receiving an electromagnetic signal. Since appearance of communication, informational data has mostly been sent via non-electronic approaches such as optical, acoustic or mechanical methods. Electronic method of analog signal sending has been launched since the invention of telephone.

However, the first data electromagnetic transmission applications in modern time were telegraphy (1809) and teletypewriters (1906), which are both digital signals. Harry Nyquist, Ralph Hartley, Claude Shannon and other scientist in the early 20th century, used these applications in their basic theoretical works in data transmission and information theory [16].

Data transmission is used in computers, in computer buses and for communication with peripheral equipment via parallel ports and serial ports such as RS-232 (1969), Firewire (1995) and USB (1996). The principles of data transmission are also utilized in storage media for Error detection and correction since 1951 [17].

Nowadays there is an intense need to send computer data in remote measurement applications. Owing to the ability of digital communication systems, fast wideband communication channels have emerged and solid-state electronics have been enhanced too therefore these developments helped scientists to exploit advantages of digital communications.

The most preferred methods for transmitting the data are:

- Twisted-Pair Wire

- Coaxial Cable

- Fiber Optic Cable: Light Pulse

- High-Speed Wireless Communication [18]

2.2.10 Chosen method for transmitting the data

The aim of this project is to construct a device to monitor the data; measured by an Energy Meter functioned on the desired system. It is possible to achieve this issue by using simple Energy Meters. But sometimes the limited functionality of these meters also restricts their area of application, in inaccessible positions or in the situations that there is no enough vision etc, it is not possible to use such an appliance. A possible solution is a Wireless Energy Meter (WEM) which is able to send its data via wireless communication to a PC. Therefore monitoring and analysis of the data will be easily done through this method. On the other hand considering the possibility of wireless transceiver to be hooked into a serial port and since sending data on serial port is one of the most common methods for AVR so the only necessity is to use a wireless serial adaptor.

2.2.11 Wireless Transmission

Nowadays wireless communication has become one of the most active fields of technology advancement. This advancement is evident in what has been implemented to voice telephony or other services such as the transmission of video, images, text and data. The need for new wireless capacity started to grow in the 1990's rapidly. In spite of technical problems that still exist in wireline communications, needs for extra wireline capacity can be satisfied immensely with

the addition of new private infrastructure, such as additional optical fiber, routers, switches, and so forth [19].

2.2.11 Data Monitoring and Analysis

After transmission procedure, next step is data monitoring and analysis. Graphical User Interface (GUI) for showing the transferred data or doing more processes on them is necessary.

Microsoft Visual Studio C# is a programming language that is designed for building a variety of applications that run on the .NET Framework. C# is simple, powerful, type-safe, and object-oriented. GUI is written under Visual C# software for data monitoring and even analyzing them.

Chapter 3

DESIGN OF MEASUREMENT SYSTEM AND DATA TRANSMISSION

3.1 General Design Procedure

As it is mentioned in 2.2.3 and 2.2.4 sections; Current Transformer or Hall Effect Sensor are the elements that can be used for current sensing whereas Voltage Transformer and a Resistive Voltage Divider circuit are utilized for voltage sensing. Two voltage comparators are used as Zero Cross Detectors for the current and voltage signals[2].

In Figure 3.1 detailed Block Diagram of the desired digital wireless energy meter is shown. This system is designed based on an ATmega32 AVR microcontroller which acts as a data acquisition processing and transmission system. A current and a voltage signal are connected to its analog inputs and converted into digital form. The zero cross detected signals of the current and voltage are applied to the interrupt inputs of the microcontroller to measure the phase difference between two signals. The microcontroller can therefore evaluate the rms values of measured signals together with the power factor at the measurement terminals.

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[2] More descriptions can be found in section 2.2.8

In the last stage Data transmission is conducted using wireless transceiver. Since the standard of RS-232 does not conform to TTL therefore in order to convert the RS-232 voltage level to TTL voltage level MAX232 Integrated Circuit (IC) is used.
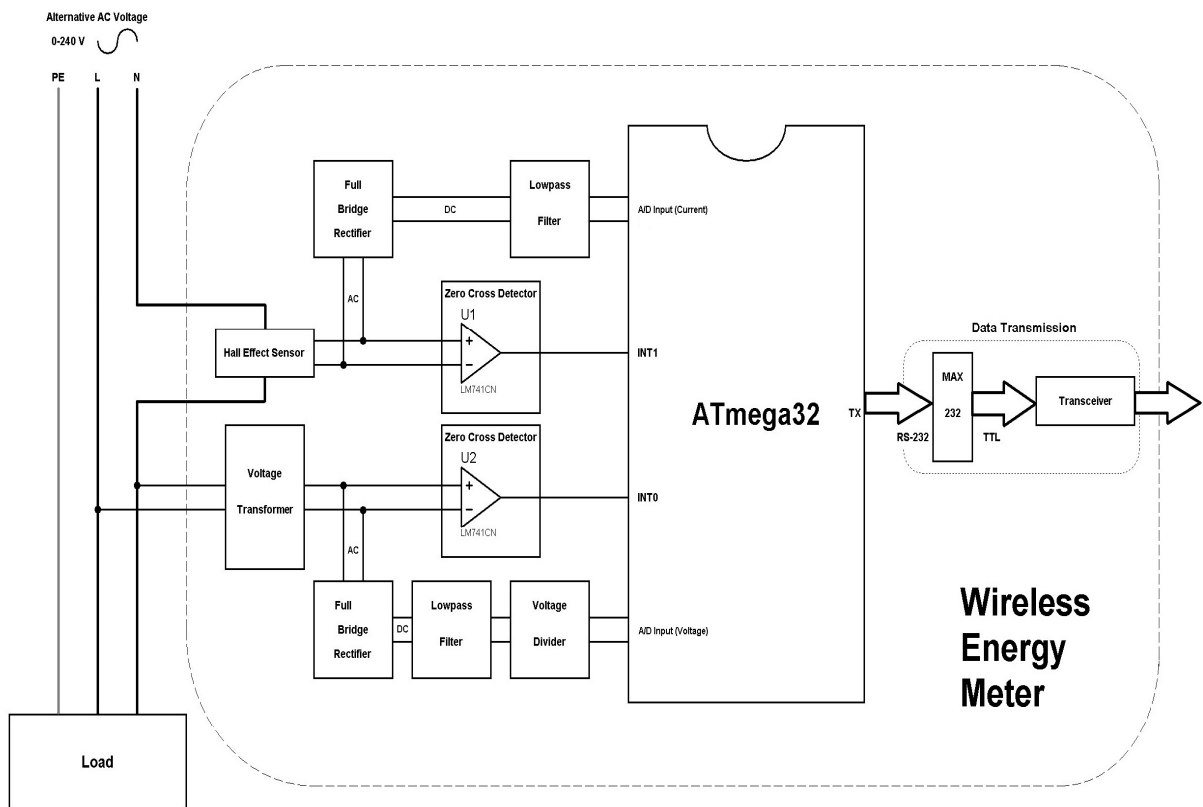
Figure 3.1: Detailed Block Diagram of WEM

3.2 Hardware Design

Regarding to the mentioned considerations, first of all, circuit demonstrated in Figure 3.2 is simulated in Proteus ISIS Professional 7.6 simulation software.
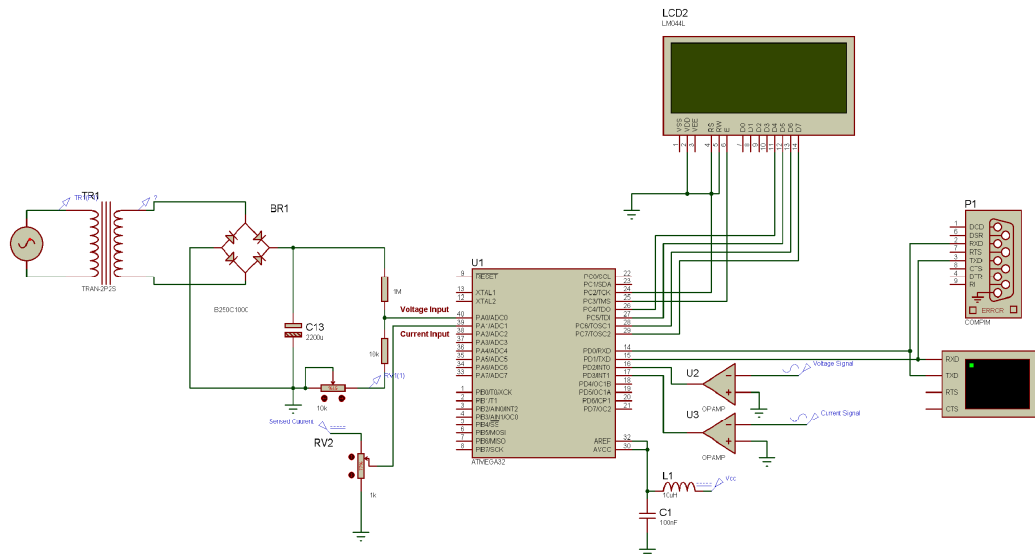
Figure 3.2: WEM simulated in Proteus ISIS Professional

After explaining the general principles of the design procedure, the next step is to simulate the hardware using the Proteus software; part by part, since not everything can be simulated; some results are acquired by relying on experiments. Initially the zero cross detector circuits using comparators are designed and simulated in the Proteus environment where several different components were tried and eventually LM741CN was selected to yield the best performance both in simulations and also in real hardware. In the second stage the ATmega32 microcontroller based processing and calculation unit was simulated, finally the wireless transmission system based on LM058 Bluetooth serial Adopter was simulated successfully.

The desired Wireless Energy Meter (WEM) is successfully implemented based on AVR microcontroller, which is illustrated in Figure 3.3.
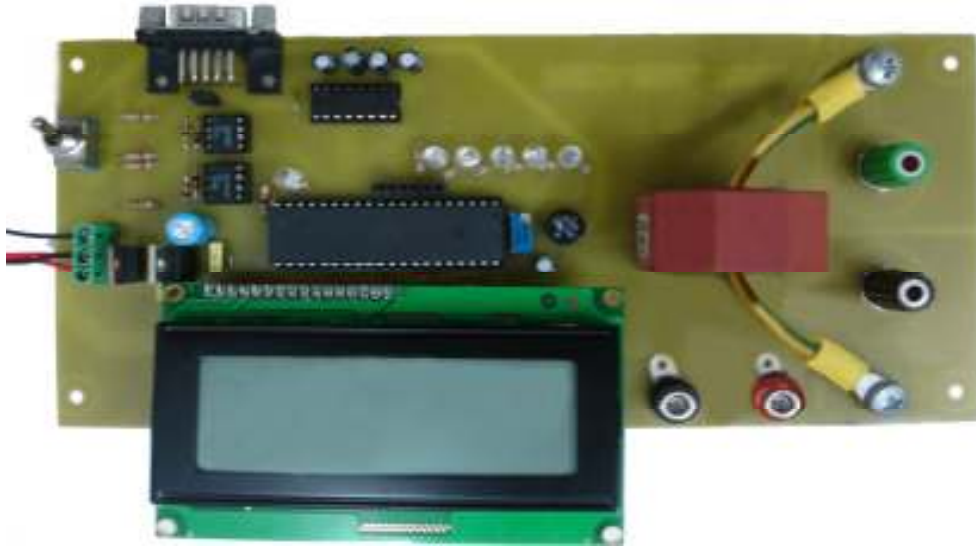
Figure 3.3: Implemented WEM

The details for the main parts of WEM are presented in the following sections.

3.2.1 AVR microcontroller Atmega32

The ATmega32 is a low-power Complementary metal–oxide–semiconductor (CMOS) 8-bit microcontroller based on the AVR enhanced RISC architecture which is used as the main part of this project. By executing powerful instructions in a single clock cycle, the ATmega32 achieves throughputs approaching 1 MIPS per MHz allowing the system designer to optimize power consumption versus processing speed, operating Voltage range for this microcontroller is – *4.5V - 5.5V* [20].

Important Features of ATmega32[3]:

  – Two 8-bit Timer/Counters with Separate Prescalers and Compare Modes

  – One 16-bit Timer/Counter with Separate Prescaler, Compare Mode, and Capture

Mode

  – Real Time Counter with Separate Oscillator

  – 8-channel, 10-bit ADC

  – Byte-oriented Two-wire Serial Interface

  – Master/Slave SPI Serial Interface

Figure 3.4 is shown the Pinout of ATmega32:

PDIP

```
         (XCK/T0) PB0 □ 1        40 □ PA0 (ADC0)
             (T1) PB1 □ 2        39 □ PA1 (ADC1)
      (INT2/AIN0) PB2 □ 3        38 □ PA2 (ADC2)
       (OC0/AIN1) PB3 □ 4        37 □ PA3 (ADC3)
             (SS) PB4 □ 5        36 □ PA4 (ADC4)
           (MOSI) PB5 □ 6        35 □ PA5 (ADC5)
           (MISO) PB6 □ 7        34 □ PA6 (ADC6)
            (SCK) PB7 □ 8        33 □ PA7 (ADC7)
               RESET □ 9        32 □ AREF
                 VCC □ 10       31 □ GND
                 GND □ 11       30 □ AVCC
               XTAL2 □ 12       29 □ PC7 (TOSC2)
               XTAL1 □ 13       28 □ PC6 (TOSC1)
            (RXD) PD0 □ 14       27 □ PC5 (TDI)
            (TXD) PD1 □ 15       26 □ PC4 (TDO)
           (INT0) PD2 □ 16       25 □ PC3 (TMS)
           (INT1) PD3 □ 17       24 □ PC2 (TCK)
          (OC1B) PD4 □ 18       23 □ PC1 (SDA)
          (OC1A) PD5 □ 19       22 □ PC0 (SCL)
           (ICP1) PD6 □ 20       21 □ PD7 (OC2)
```

Figure 3.4: Pinout ATmega32

As it is illustrated in Figure3.3 Port A serves as the analog inputs to the A/D

converter so Pins 40 and 39 are used as inputs for the current and voltage values.

[3] For more details refer to [20]

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This ability of ATmega32 allows to use Port A as A/D converter and lets the users measure the values which are needed therefore these two inputs should be in the sensible range of at most *5.00 V* for microcontroller.

3.2.2 Hall Effect Sensor

The Hall Effect Sensor; used in this project is the NNC series of LEM Co. NNC – 30 GFP is the element which senses the current with the methods that were subjected in the previous chapter and helps to get accurate results.

The Hall Effect Sensor is also called the Current Transducer since it converts the current into voltage which can be applied directly to the microcontroller analog input after amplification. NNC – 30 GFP is the device used for the electronic measurement of current: DC, AC, pulsed, mixed, with the galvanic isolation between the primary circuit (high power) and the secondary circuit (electronic circuit) [21]
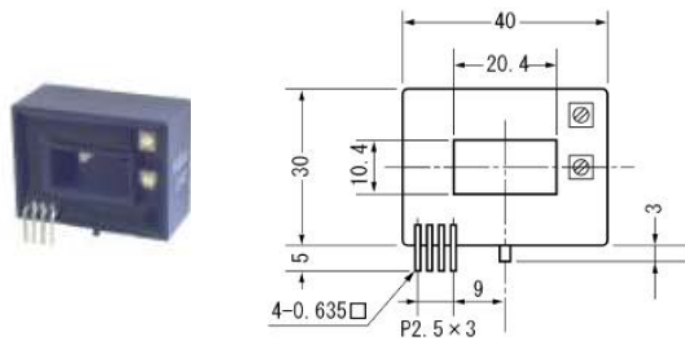
Figure 3.5: NNC – 30GFP Current Transducer

Features of this device are as below:

This Hall Effect Sensor with galvanic isolation between primary and secondary circuit can be used for measurement purposes as this sensor has isolation voltage up to 2500V and consumes very low power. This sensor may be used in AC variable speed drives, Uninterruptible Power Supplies (UPS), DC motor drives, Switched Mode Power Supplies (SMPS)

3.2.3 Current Transformer (CT)

As it is mentioned for current sensing, both Hall Effect Sensor and Current Transformer devices are feasible solutions, both appliances are tested and both of them are working flawlessly in the circuit. Considering simpler usage of CT, it is used in this project to satisfy PCB designing requirements but Hall Effect Sensor is also tested and it is totally compatible with design needs. It is worth mentioning that Hall Effect Sensor needs two +15 and -15 volt extra power supply therefore the design will slightly be complicated.

As Current Sense Transformer, Cogema 949334 is used. These types of CTs can be used for sensing the current of measurement instruments or electronic control and protection circuits of equipments such as rectifier bridges, motors, UPS'.
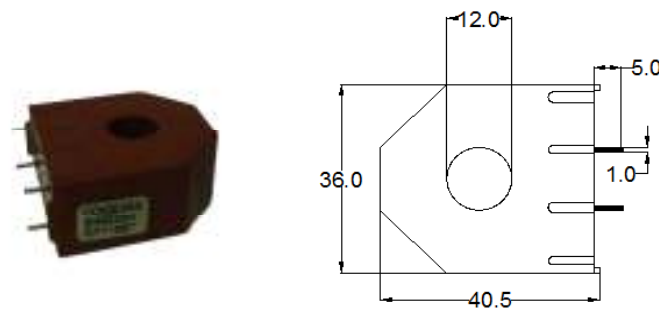
Figure 3.6: Cogema 949334 Current Sense Transformer

3.2.4 LM741CN Amplifier

The LM741 series are general purpose operational amplifiers whose performance is improved according to requirements of industrial standards. The amplifiers offer many features which make their application nearly foolproof: overload protection on the input and output, no latch-up when the common mode range is exceeded, and the oscillations are prevented. Their performance is guaranteed over a 0°C to +70°C temperature range. [22]

This amplifier is one of the most important part which is used as a zero cross detector the output of which is applied to the microcontroller to enable the calculation of the phase difference between current and voltage as mentioned in section 2.2.8.

Connection diagram of LM741 is as shown below:
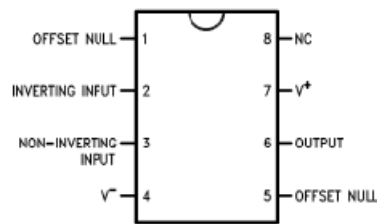
Figure 3.7: Connection Diagram of LM741

3.2.5 LM7805 and LM7905 voltage regulators

LM7805 and 7905 are used to regulate the voltage applied to the comparators and also the microcontroller to protect the components and to get accurate results from comparators.

The LM78MXX series of three-terminal positive voltage regulators employ built-in current limiting, thermal shutdown, and safe-operating area protection which make them virtually immune to damage from output overloads. With adequate heat sinking, they can deliver in excess of 0.5A output current. Typical applications would include local (on-card) regulators which can eliminate the noise and degraded performance associated with single-point regulation [23].

This device is usually used for safety in most of the circuits with need of a constant value of the voltage. In this project the supply voltage of microcontroller is *5.00* V, so using 7805 in order to reach the pure *5.00* V is recommended.

7905 is also voltage regulator with this difference that it is useful for negative voltages. It has the same duty as 7805.Amplifiers which are used for zero cross detection need *+5* and *-5* V DC supply therefore both elements are used. Figure 3.8(a) is illustrated connection diagram and Figure 3.8(b) is shown typical application of LM7805
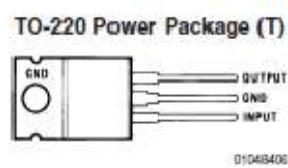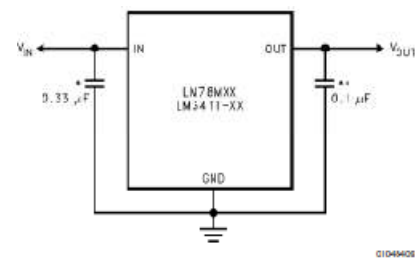
(a)   (b)

Figure 3.8: (a) Connection diagram, (b) Typical Connection of LM7805

And Figure 3.9(a) and (b) are shown same properties for LM7905 [24].
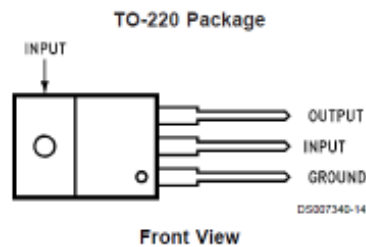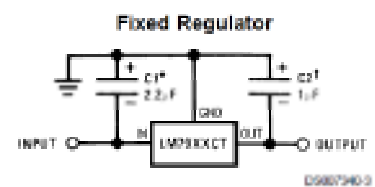
(a)   (b)

Figure 3.9: (a) Connection diagram, (b) Typical Connection of LM7905

3.2.6 Important Points

1. Noise can be produced by digital circuits; inside and/or outside of microcontroller and may affect the accuracy of the A/D measurement therefore the techniques below are used to suppress the effect of noise.

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- o Whole analog section of the chip should contain an isolated Ground from each other and these grounds must be connected to the digital one by a single path.

- o All analog connections should be as close as possible to chip and be far from the digital connections with high frequency.

- o Analog V_{cc} (AV_{cc}) should be connected to digital V_{cc} by a low pass filter.

Because AV_{cc} is chosen as reference voltage, thus the connection shown in Figure 3.10 is applied.
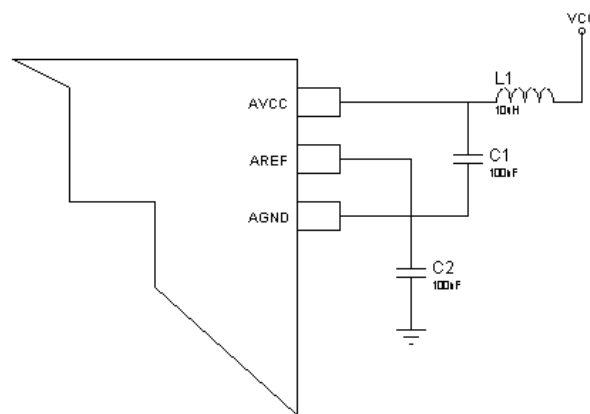
Figure 3.10: Connection for AV_{cc} as a reference voltage

2. As it is mentioned to get more accurate A/D measurement; DC voltage is applied to microcontroller. In order to fulfill this demand, RB165 full bridge rectifier is used. Connection is illustrated in Figure 3.1.

3. Voltage range 0-240 volt is selected, so conversion and reduction of the voltage is inevitable and to achieve this demand, voltage transformer and voltage division technique are used.

3.2.6 Printed Circuit Board (PCB) Layout and Design

Last step of design is taken with the PCB design of circuit shown in Figure 3.11, Circuit Layout is drawn by using Proteus ARES Professional 7.6 and the PCB of the circuit is printed with a PCB machine located at the Mechatronix Laboratory of the GMTGB Technopark. Figure 3.12 illustrates 3D picture of the printed circuit.
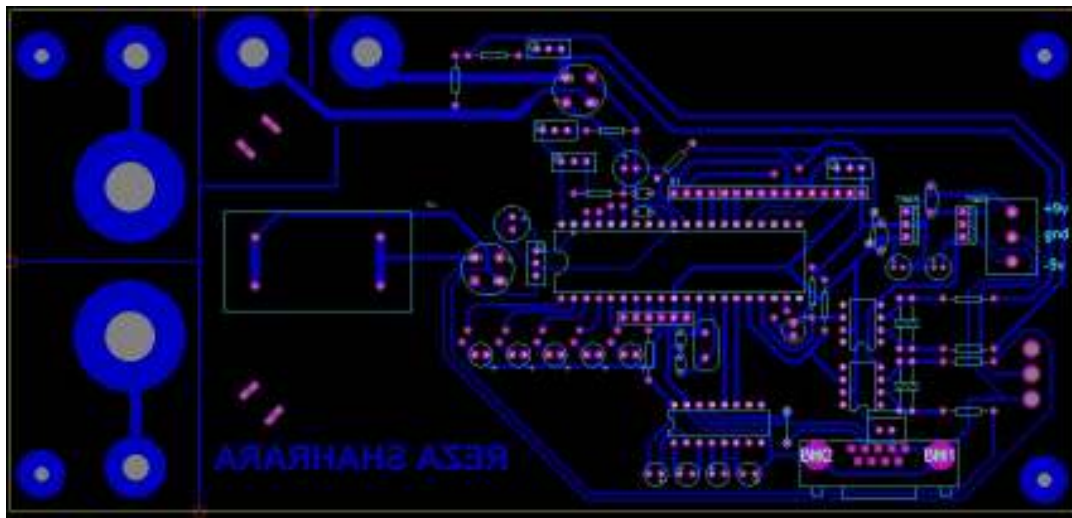
Figure 3.11: PCB layout of WEM
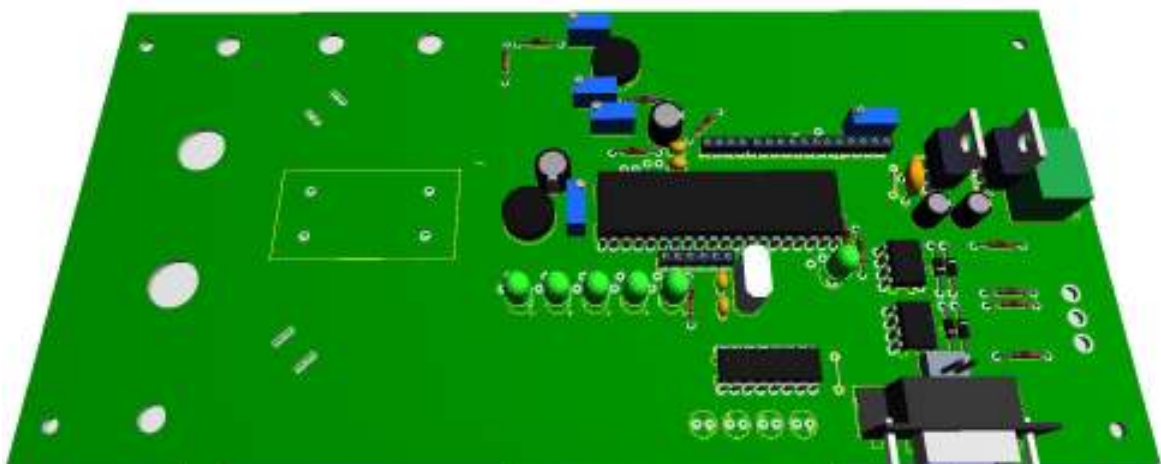
Figure 3.12: 3D Visualization of designed WEM

3.3 Software Development

3.3.1 Microcontroller Programming

After testing and simulation of every single part, the operational program for microcontroller is written under BASCOM-AVR in conformance with the designed circuit.

Drawn Flowchart for this purpose is shown in Figure 3.13; same procedure is illustrated in the Timing Diagram sketched in Figure 3.14.

Program starts with the part related to the calculation of phase difference and hence the Power Factor. The zero cross detected voltage and current signals are applied to the interrupt pins of the microcontroller. As the interrupt pins of Atmega32 are sensible to falling or rising edges, it depends on the selected configuration in the written programming codes for interrupt pins, there should be a decision making option to control whether a falling edge exists on INT0[4] or not. Timer1 will start when falling edge of first signal is sensed and timer will stop when falling edge of second signal is sensed therefore calculation of phase difference and power factor will be possible according to the frequency of the signals and selected prescale factor of the microcontroller. In order to define whether the system has a lagging or a leading power factor or whether it is a resistive circuit; other decision boxes are used after power factor calculation.

---

[4] INT0 is used to start the timer1 and INT1 is used to stop it.

Current and Voltage signals after being rectified are applied to analog input of microcontroller therefore their values will be measured by using the "Getadc" command. All desired values are obtained by using some simple calculations.

A

V = Get ADC (0)
For Voltage value

V > 5

NO → Voltage LED Off

YES

Voltage LED On

I = Get ADC (1)
For Current Value

I > 0.1

NO → Current LED Off

YES

Current LED On

S = V * I
P = S * Cos(Fi)
Q = S * Sin(Fi)

Show Fi, PF, S ,P ,Q ,V
I ,L on LCD

Send Fi, PF,S,P, Q, V
I, L, to Serial Port

Goto Start
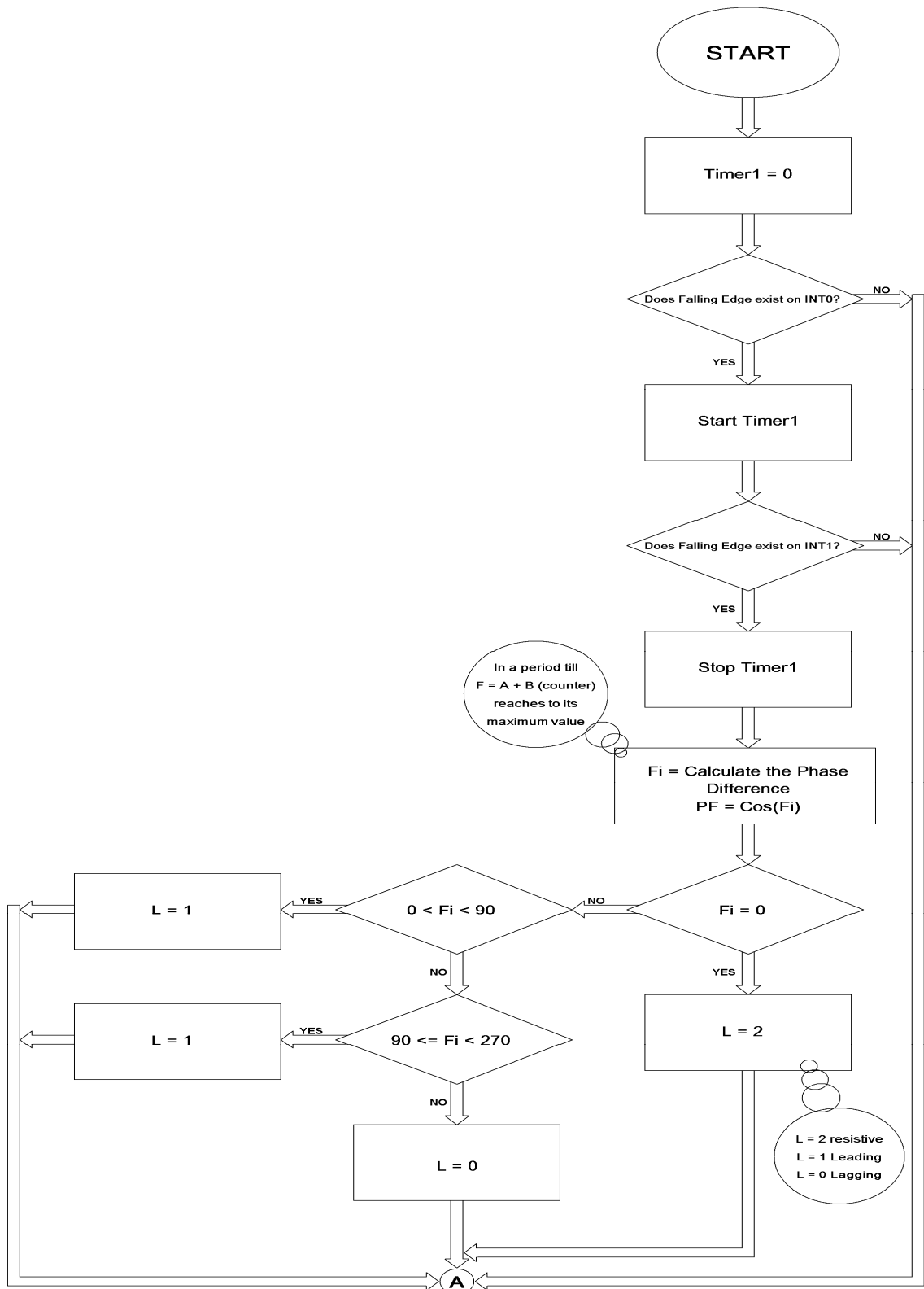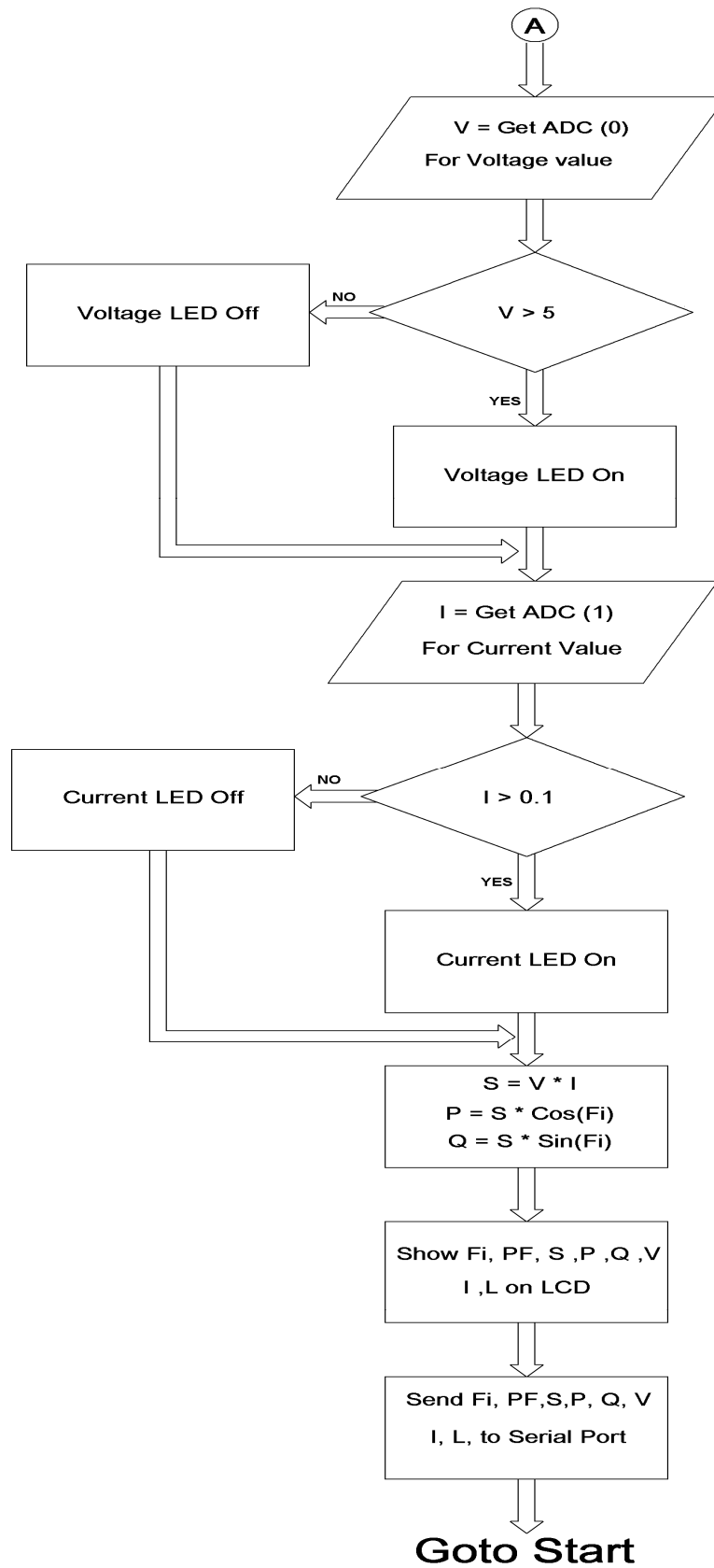
Figure 3.13: General Flowchart of main operation

34
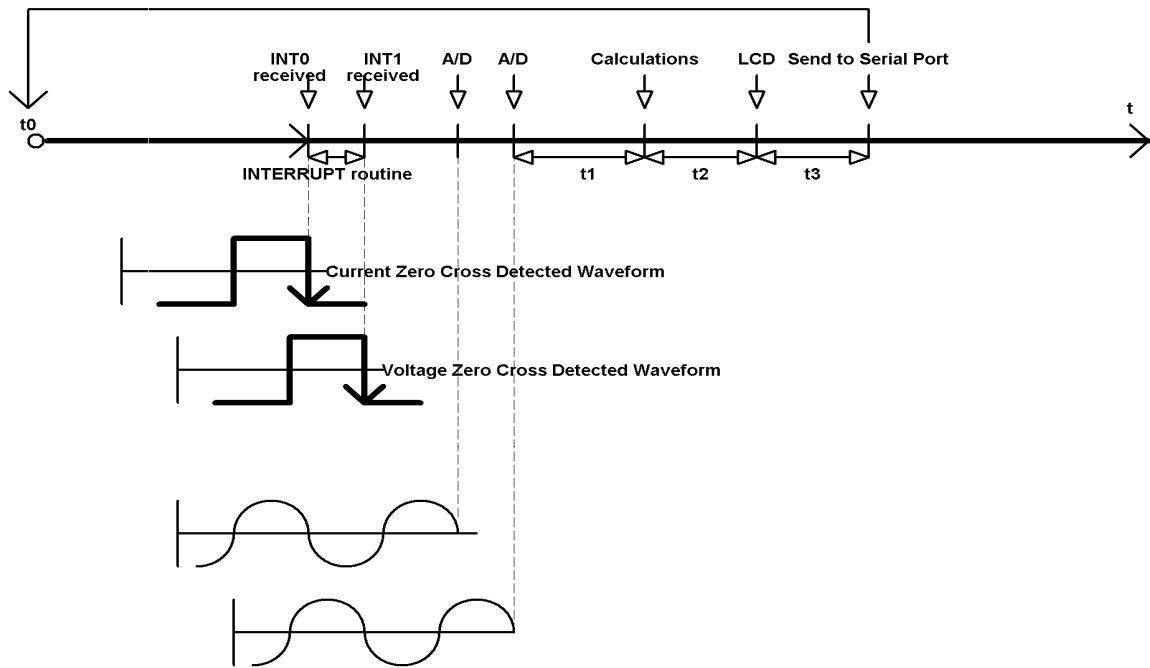
Figure 3.14: Timing Diagram of main operation

3.3.2 BASCOM-AVR

The measurement, transmission and LCD monitoring software is written ender BASCOM-AVR environment using the flowchart of Figure 3.13.

BASCOM-AVR is the original Windows BASIC COMPILER for the AVR family. All the codes are written under BASCOM-AVR and transferred via PROGISP (ver 1.6.7) programmer to microcontroller after being complied to the HEX file.

Calculating Current, Voltage and Phase difference between these two and sending them on Serial Port are major issues in writing the codes[5] for AVR under BASCOM-AVR compiler.

---

[5] All codes can be found in appendix section.

3.3.3 GUI Programming

According to data monitoring; Graphical User Interface (GUI) is written under Microsoft Visual C#. This software is preferred because of its simple object oriented programming features; instead of writing codes, the library tools are used to construct the user interface.

It is worth mentioning that "ReadExisting" command is used to read the incoming values from the serial port, after the maximum value for current and voltage are set with String "Var" command; to make the program understand which value is related to which box and by using of some simple codes; possible errors are minimized.

3.3.4 Microsoft Visual Studio C#

Microsoft Visual C# is used to build GUI. As it is shown in Figure 3.15 and 3.16, written GUI software has two main measurement and graph drawing parts. In measurement part as shown in Figure 3.15 all measurement values exist, besides, for each of them one progress bar is set to show the percentage of value. This percentage is being calculated based on the maximum value of the current and voltage which can be set from the left side track bars. There is a combo box for selecting the related COM port; the program finds all open COM ports and brings them to this combo bar so user can select related COM port and then push the Start button in order to start the software. Stop button is present next to the Start button to end the program.

Software starts to show all measured and transferred data one by one in the related boxes. For the Phase Difference, there is an option which is distinct with the different colors next to Phase Shift's text box that shows if the circuit is resistive or has a Lagging or Leading power factor.
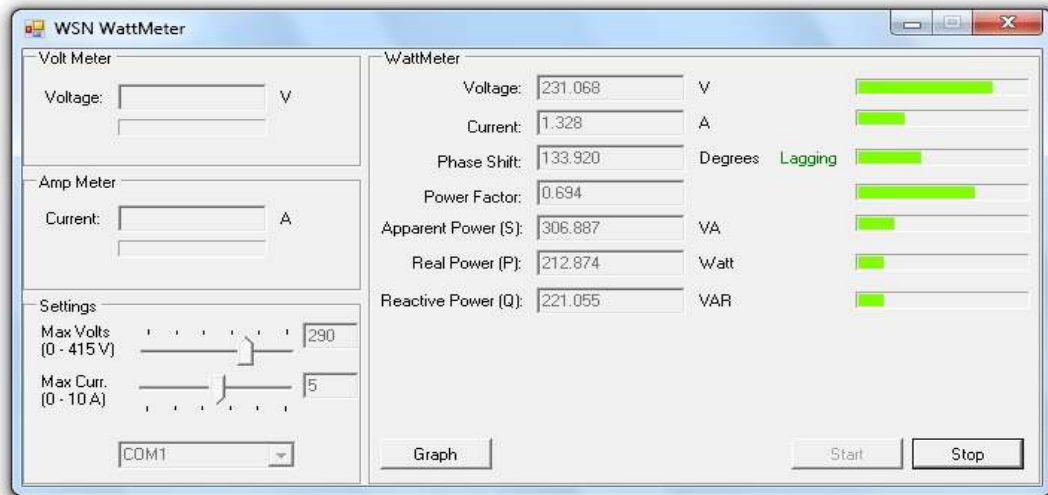
Figure 3.15: GUI Software written under the Visual Studio C#

There is another button for Graph which will be opened by clicking on it. In the new opened window, there is a possibility of showing all measured data on one graph. On the right side of this page which is shown in figure 3.16, there is an option to select the desired graph to be depicted by clicking the check boxes in this window.
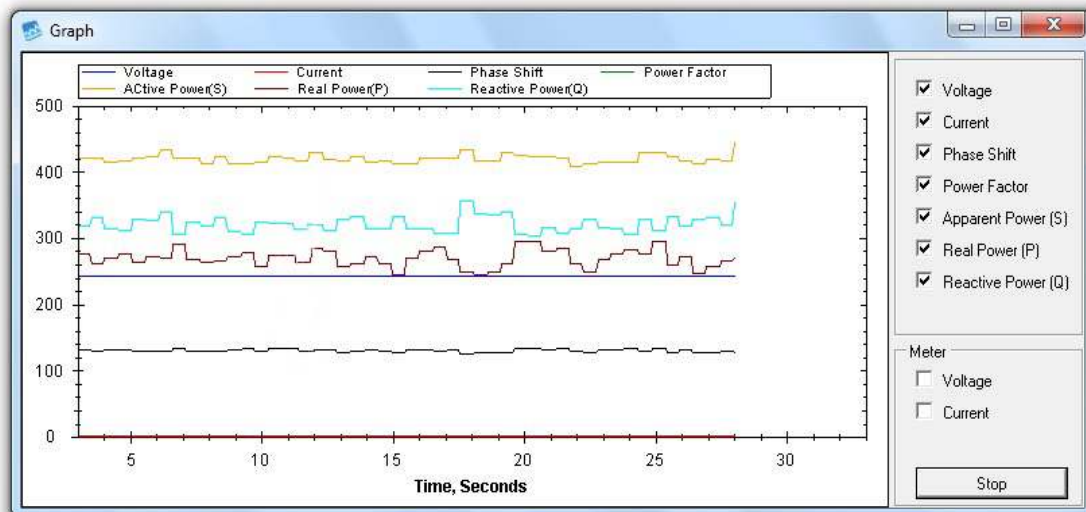
Figure 3.16: Graph Partition of GUI software

The scale of vertical axis changes automatically when a specific measured quantity is selected from the check boxes located in the right side of the Graph window.

3.4 Wireless Transmission

The measured and calculated values are transmitted to a base station via the LM058 wireless module connected to the serial port of the microcontroller.

PC serial port follows specific packet transmission with one stop/start bit and 5-8 bits of data. In this thesis same standard is used for compatibility. 8 bits (one byte) with one start bit and one stop bit are used for data bits. The baud rate 9.6 Kbps with neither parity bit nor flow control bit is selected.

LM-058 wireless serial adaptor which works under the Bluetooth communication properties is used. This adaptor helps us to eliminate the conventional RS232 serial cables; LM-058 can communicate with another Bluetooth serial adaptor or other Bluetooth-enabled devices such as a laptop computer, personal digital assistant (PDA) or mobile phone. [25]

In this project same device is used as a receiver. In Figure 3.17, LM-058 Bluetooth Serial Adaptor is illustrated.

Figure 3.17 LM-058 Bluetooth Serial Adaptor

Chapter 4

TEST RESULTS

Some measurements with the implemented WEM are conducted regarding the accuracy of the system for evaluation purposes.

4.1 Testing Zero Cross Detectors

In order to see that Zero Cross Detectors are correctly doing their duties, input signal and its related output is controlled by a digital real time oscilloscope.

Results are shown in the Figure 4.1 (a) Input Current signal (b) Zero Cross Detected Output Current Signal (c) Input Voltage signal (d) Zero Cross Detected Output Voltage Signal.
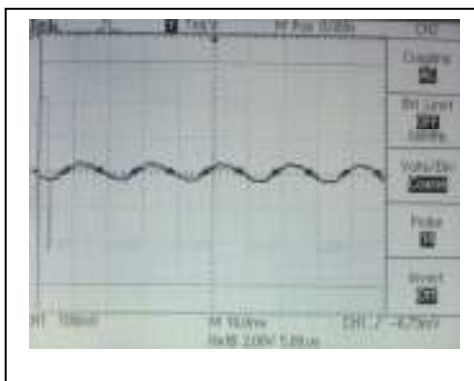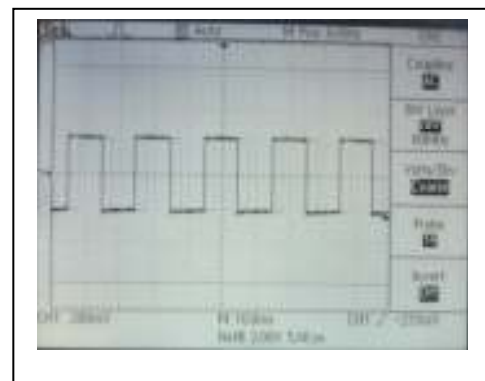
(a)   (b)

Figure 4.1 (a): Input Current signal

Figure 4.1 (b): Zero Cross Detected Output Current Signal
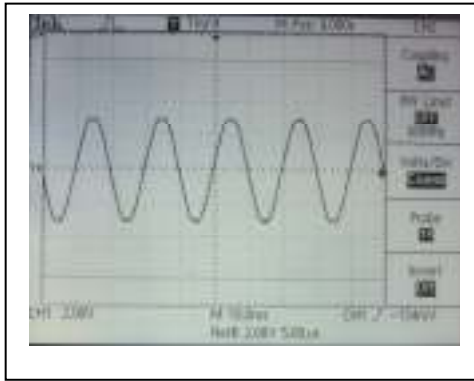
<center>(c)</center>
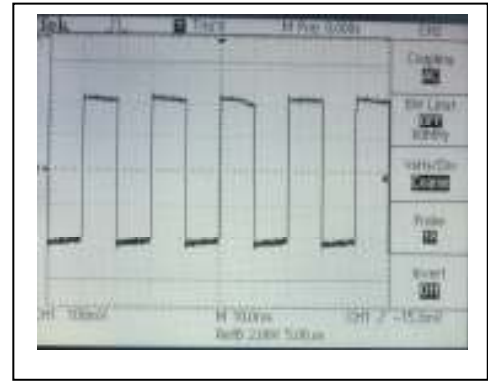
<center>(d)</center>

Figure 4.1 (c): Input Voltage signal

Figure 4.1 (d): Zero Cross Detected Output Voltage Signal

It is clearly observed on Figure 4.1 (a), (b) and Figure 4.1 (c), (d) that the square-wave outputs of the comparators follow the zero cross points of the sinusoidal input signals faithfully with almost no phase shift.

4.2 Tests on AC Induction Motor

In this test single phase AC induction motor made by Brook Crompton Parkinson Motors [26] is used. Tests are made on no-load, 0.5-load and full-load.

Table 4.1 (a), (b), (c) shows respectively the test results of WEM and reference meter on no-load, 0.5-load and full-load.

YL-195 Motor, Electric Traction & Electrical Control Trainer device is used as a reference meter[6].

6 All experiments and tests are done in the EENG350 Electromechanical Conversion Energy Laboratory.

NO-LOAD			
Test Device	WEM	YL-195	% Error
Terminal Voltage V_t (V)	242.693	242	0.286
Line Current I_l (A)	1.411	1.39	1.510
Power Factor	0.128	0.121	5.785
Real Power P (W)	43.837	40.701	7.704

Table 4.1 (a): AC Induction motor test results on no-load

0.5-LOAD			
Test Device	WEM	YL-195	% Error
Terminal Voltage V_t (V)	242.693	242	0.286
Line Current I_l (A)	2.188	2.17	0.829
Power Factor	0.088	0.090	2.222
Real Power P (W)	46.72	47.26	1.142

Table 4.1 (b): AC Induction motor test results on 0.5-load

FULL-LOAD			
Test Device	WEM	YL-195	% Error
Terminal Voltage V_t (V)	242.812	242	0.335
Line Current I_l (A)	3.7	3.73	0.804
Power Factor	0.187	0.19	1.578
Real Power P (W)	168.344	171.505	1.843

Table 4.1 (c): AC Induction motor test results on full-load

4.3 Single Phase Transformer Open-Circuit and Short-Circuit Test

These tests are applied on the transformer to determine the equivalent circuit parameters and the losses of the transformer.

These test were done with both WEM and reference meter.

4.3.1 Open-Circuit Test

Table 4.2 shows the Open-Circuit test results. Primary voltage is 120 V AC.

Open-Circuit Test			
Test Device	**WEM**	**YL-195**	**% Error**
Primary Voltage V_1 (V)	120.051	120	0.042
Primary Current I_1 (A)	2.01	2.1	4.285
Power Factor	0.058	0.06	3.333
Power P(W)	13.995	15.12	7.440
Secondary Voltage V_2(V)	55.121	55	0.22

Table 4.2: Transformer Open-Circuit test results

4.3.2 Short-Circuit Test

In this test; results are recorded by increasing secondary current I_2 from 0.5 A to 2 A. The results of Short-Circuit Test with both WEM and YL-195 are shown in Table 4.3.

Short-Circuit Test			
Test Device	**WEM**	**YL-195**	**% Error**
Secondary Current I_2(A)	**Power P_1(W)**		
0.5	2.2	2.12	3.773
1	6.211	6.02	3.172
1.5	14.366	14.11	1.814
2	29.151	28.7	1.571

Table 4.3: Transformer Short-Circuit test results

4.3.2 Equivalent Circuit Parameters of Tested Transformer

The equivalent impedance of transformer shown in Figure 4.2 can be obtained from the measured voltage and current as follows.

$$Z_{eq} = Z_{sc} = V_{sc} / I_{sc} \tag{4.1}$$

$$R_{eq} = R_{sc} = P_{sc} / I_{sc}^2 \tag{4.2}$$

Therefore X_{eq} can be obtained using Z_{eq} and R_{eq} as follows.

$$X_{eq} = \sqrt{Z_{eq}^2 - R_{eq}^2} \tag{4.3}$$

Consequently

$R_{eq}(WEM) = 29.151 / 2^2 = 7.287\Omega$
$Z_{eq}(WEM) = 120 / 2 = 60\Omega$
$X_{eq}(WEM) = \sqrt{60^2 + 7.287^2} = 60.44\Omega$

And For YL-195

$R_{eq}(YL-195) = 28.7 / 2^2 = 7.175\Omega$
$Z_{eq}(YL-195) = 120 / 2 = 60\Omega$
$X_{eq}(YL-195) = \sqrt{60^2 + 7.175^2} = 59.56\Omega$

Percentage Error in this situation is 1.477 percent.
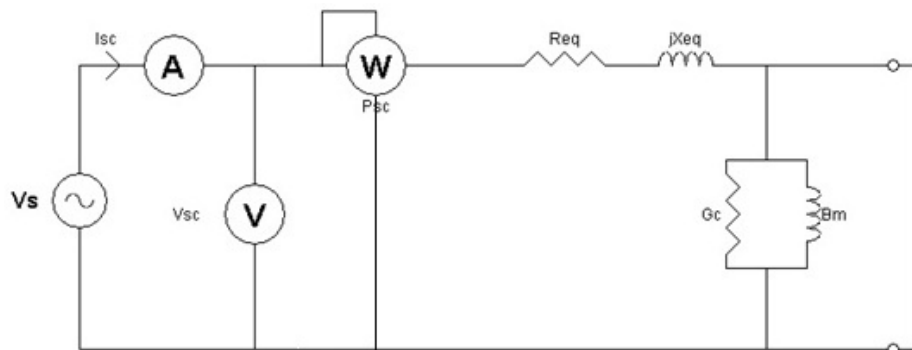
Figure 4.2: Transformer equivalent circuit under short-circuit test

And exiting branch parameters of transformer shown in Figure 4.3 can obtain using open-circuit test results as follow

$$Y\phi = Y_{oc} = I_{oc} / V_{oc} \tag{4.4}$$

$$G_c = G_{oc} = P_{oc} / V_{oc}^2 \tag{4.5}$$

$$B_m = B_{oc} = \sqrt{Y_{oc}^2 - G_{oc}^2} \tag{4.6}$$

$\rightarrow \quad Y\phi(YL-195) = Y_{oc} = 0.016\Omega$

$\quad G_c(WEM) = 9.71 \times 10^{\wedge} -4\Omega$

$\quad B_m(WEM) = 0.016\Omega$

And with YL-195

$Y\phi(YL-195) = Y_{oc} = 0.0175\Omega$

$G_c(YL-195) = 1.05 \times 10^{\wedge} -3\Omega$

$B_m(YL-195) = 0.0174\Omega$

Percentage Error is 8.04 percent.
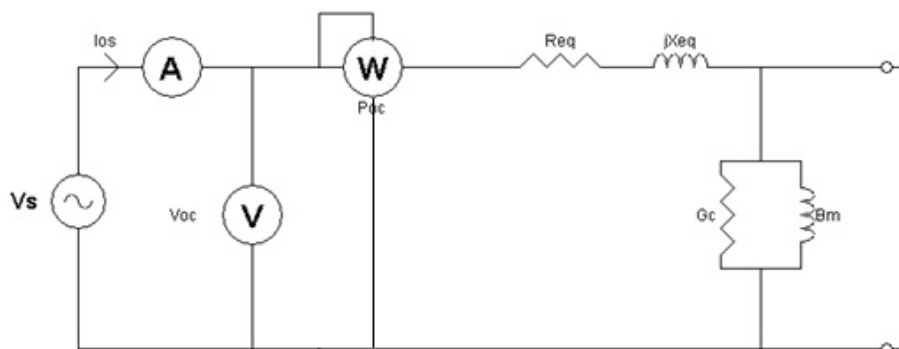
Figure 4.3: Transformer equivalent circuit under open-circuit test

Chapter 5

CONCLUSION

In this thesis design and implementation of an inexpensive and reliable digital Wireless Energy Meter based on AVR microcontroller is described. With the designed new energy meter; measurement and wirelessly transmission of the desired data are possible. The program written under Microsoft Visual Studio C# as a Graphical User Interface (GUI) enables monitoring and even comparison of the measured data with the data which may be received from other wireless energy meter.

In this achievement, different methods for sensing the current and voltage and phase difference between them are proposed and implemented. This system is designed based on an ATmega32 AVR microcontroller which acts as a data acquisition processing and transmission system. A current and a voltage signals are connected to their analog inputs and converted into digital form. The zero cross detected signals of the current and voltage are applied to the interrupt inputs of the microcontroller to measure the phase difference between two signals. The microcontroller can therefore evaluate the rms values of measured signals together with the power factor at the measurement terminals which enable the calculation of all other energy related quantities. Data transmission is one of the important issues in remote sensing applications. In this case study we proposed a simple and versatile wireless

communication method where the transferred data can be easily monitored on a PC screen using the user interface.

The new measurement system will certainly help to decrease the cost and efficient usage of time as compared to conventional method of getting the same results.

Future work may include the calculation of total harmonic distortion. By incorporating the calculated harmonic distortion values; a method to improve the power factor using a microcontroller will be proposed.

Nowadays Wireless Sensor Network (WSN) is one of the active fields because of its capability and compatibility to the implemented device so we would like to use this device as a measurement sensor in the wireless sensor network based on IEEE 802.15.4 [27] technology. In this manner measurement and control of the network will be possible.

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APPENDICES

Appendix A: ATmega32 Main Codes

```
'*********************************************************************
'* BASCOM AVR for Atmel ATMEGA32                                    *
'* to calculate Volatge, Cuurent, Phase Differnce,                  *
'*  Power Factor, Apparent Power, Reactive Power and Real Power      *
'* Copyright 2010, Eastern Mediterranean University                  *
'*                                                                  *
'*                                                                  *
'* ©Reza Shahrara                                                    *
'*                                                                  *
'*********************************************************************




$regfile "m32def.dat"
$crystal = 8000000
$baud = 19200

'============================

Dim Volt1 As Word , Volt As Single
Dim Vrms As Single , Irms As Single , S As Single
Dim Pf As Single , Q As Single
Dim Frad As Single , P As Single
Dim Curr1 As Word , Curr As Single
Dim Chan1 As Byte , Chan2 As Byte
Dim L As Word
Dim I As Byte
Dim A As Integer
Dim B As Word
Dim F As Single
Dim Fmin(250) As Single
Dim Ph As String * 6

'=========================================


Config Lcd = 16 * 2
Config Lcdpin = Pin , Db4 = Portc.4 , Db5 = Portc.5 , Db6 = Portc.6 , Db7 -
   = Portc.7 , E = Portc.3 , Rs = Portc.2
Deflcdchar 1 , 2 , 5 , 5 , 2 , 32 , 32 , 32 , 32
```

```
                              ' replace ? with number (0-7)
Config Portb = Output
Portb = &B01111000


'=======================================


Config Adc = Single , Prescaler = Auto , Reference = Avcc
Stop Adc
Start Adc

Stop Timer1
'===============================================================
Config Timer1 = Timer , Prescale = 8
Enable Interrupts
Enable Timer1
Enable Ovf1

Config Int0 = Falling
Enable Int0
Config Int1 = Falling
Enable Int1
On Ovf1 Tim
On Int1 Stp
On Int0 Sta



'=============================================================
Start Timer1

Main:

  Do
      Goto Calc
  Loop

End                                    'end program



'-------------------------


Tim:

A = A + 1


Return
'-------------------------
```

'phase Shift "degree" = 360 * Delta(t) / T "20ms=.02

Stp:
B = Timer1

Stop Timer1

Disable Int0
Disable Int1
Disable Interrupts
Stop Timer1

F = A * 65535
        '2^16 =one A full cycle"bite"
F = F + B

F = F / 1000000
        'F/(crystal"MHz"/prescale)=f/(8MHz/8)
F = F * 360

F = F / .02
        'T=1/(F=50 Hz)

A = 0
B = 0

Start Timer1

Enable Int0
Enable Int1

Return

'-------------------------
Sta:

A = 0
B = 0
Timer1 = 0
Start Timer1

Return

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```
'===============================

 Calc:
Cls


 Select Case F
 Case 0 : L = 2
   Case 0 To 90 : L = 1                    ' Print " Lead "
    Case 91 To 270 : L = 0                  ' Print " lag "
      Case 271 To 359 : L = 1                ' Print " Lead "
       'Case 360 : L = 2
End Select

 Volt1 = Getadc(0)
 Volt = Volt1 / 204.8
 Volt = Volt * 48.586

 If Volt > 10 Then
   Reset Portb.1
Else
   Set Portb.1
 End If


'-------------------

 Curr1 = Getadc(1)
 Curr = Curr1 / 204.8



 If Curr > 0.1 Then
   Reset Portb.2
Else
   Set Portb.2
 End If
'--------------------

 'Vrms = Volt * 0.707
 'Irms = Curr * 0.707

'S = Vrms * Irms
 S = Volt * Curr                         'Apparent Power(VA)

 Frad = Deg2rad(f)
                          'degree to radian converter
 Pf = Cos(frad)
                           'Power Factor
 Q = Sin(frad)
 Pf = Abs(pf)
```

```
Q = Abs(q)

'P = S * Pf

Q = Q * S                              'Reactive Power(VAR)

P = S * Pf                             'Real Power(WATT)

Set Portb.3

 Print " F " ; Fusing(f , "###.###") ;

 Print " Pf " ; Fusing(pf , "###.###") ;

 Print " S " ; Fusing(s , "###.###") ;

 Print " Q " ; Fusing(q , "###.###") ;

 Print " Pw " ; Fusing(p , "###.###") ;

 Print " Volt " ; Fusing(volt , "###.###") ;

 Print " Curr " ; Fusing(curr , "###.###") ;

 Print " L " ; L

    Cls

Locate 1 , 1

  Lcd Fusing(f , "#.#") ; Chr(1)

Locate 1 , 9

Lcd Fusing(curr , "###.###")

Locate 2 , 1

  Lcd Fusing(volt , "###.###")

Locate 2 , 9
  Lcd Fusing(pf , "###.###")

  Waitms 100

 Reset Portb.3

 Return
```

Appendix B: Microsoft Visual Studio C# Codes

Appendix B.1: Monitoring Window Codes

```csharp
using System;
using System.Collections;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Drawing;
using System.Linq;
using System.Text;
using System.Windows.Forms;
using System.Threading;
using Excel = Microsoft.Office.Interop.Excel;
using System.Runtime.InteropServices;


namespace Reza_Shahrara_Project
{
    public partial class Form1 : Form
    {
        /// <summary>
        /// Public Variables
        /// </summary>
        int maxvolt;
        int maxamp;
        string hold;

        public Form1()
        {
            InitializeComponent();
        }

        /// <summary>
        /// Serial Port Enumeration During Load
        /// </summary>

        private void Form1_Load(object sender, EventArgs e)
        {
            string[] ports = System.IO.Ports.SerialPort.GetPortNames();
            int k = ports.Length;
            for (int j = 0; j < k; j++)
                comBox.Items.Add(ports[j]);
            textBox1.Text = Convert.ToString(trackBar1.Value);
            textBox2.Text = Convert.ToString(trackBar2.Value);
        }

        /// <summary>
        /// BackgroundWorker gets the data from serial port and shows on GUI
        /// </summary>

        private void backgroundWorker1_DoWork(object sender, DoWorkEventArgs
e)
        {
            if(button1.Enabled==true)
            {
                BackgroundWorker worker = sender as BackgroundWorker;
                if (serialPort1.IsOpen == true)
                    e.Result = readdata(worker, e);
            }
```

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```csharp
        }

        private void backgroundWorker1_RunWorkerCompleted(object sender,
RunWorkerCompletedEventArgs e)
        {
            if (!(e.Result == null))
            {
                hold = e.Result.ToString();
                hold = hold.Trim();
                setdata();
                if (button1.Enabled==true)
                    backgroundWorker1.RunWorkerAsync();
                if (serialPort1.IsOpen == true && button1.Enabled==false)
                    serialPort1.Close();

            }
        }

        private void backgroundWorker1_ProgressChanged(object sender,
ProgressChangedEventArgs e)
        { }

        /// <summary>
        /// Start Button
        /// </summary>

        private void S_Click_1(object sender, EventArgs e)
        {
            if (comBox.SelectedItem != null)
            {
                serialPort1.PortName = comBox.SelectedItem.ToString();
                if (serialPort1.IsOpen != true)
                {
                    try
                    {
                        serialPort1.Open();
                    }
                    catch (Exception ex)
                    {
                        MessageBox.Show(ex.Message, "Error!",
MessageBoxButtons.OK, MessageBoxIcon.Error);
                        return;
                    }
                }
                if (serialPort1.IsOpen == true)
                {
                    button1.Enabled = true;
                    S.Enabled = false;
                    trackBar2.Enabled = false;
                    trackBar1.Enabled = false;
                    comBox.Enabled = false;
                    try
                    {
                        backgroundWorker1.RunWorkerAsync();
                    }
                    catch (Exception ex)
                    {
                        MessageBox.Show(ex.Message);
                    }
                }
```

```csharp
        }
        else
        {
            MessageBox.Show("Select a proper COM port!", "Error!",
MessageBoxButtons.OK, MessageBoxIcon.Error);
        }
    }

    /// <summary>
    /// Stop Button
    /// </summary>

    private void button1_Click(object sender, EventArgs e)
    {
        backgroundWorker1.CancelAsync();
        S.Enabled = true;
        button1.Enabled = false;
        trackBar1.Enabled = true;
        trackBar2.Enabled = true;
        comBox.Enabled = true;
     //    serialPort1.Close();
    }

    /// <summary>
    /// Graph Button
    /// </summary>

    private void button2_Click(object sender, EventArgs e)
    {
        Graph g = new Graph();
        g.frm1 = this;
        g.Show();
    }

    /// <summary>
    /// Function to set the data in the specific fields
    /// </summary>
    ///
    void setdata(){
        maxvolt = trackBar1.Value;
        maxamp = trackBar2.Value;
        string ps = hold.Substring(hold.IndexOf("F") + 2,
hold.IndexOf("Pf") - 2).Trim();
        string pf = hold.Substring(hold.IndexOf("Pf") + 3,
hold.IndexOf("S") - hold.IndexOf("Pf") - 3).Trim();
        string s = hold.Substring(hold.IndexOf("S") + 2, hold.IndexOf("Q")
- hold.IndexOf("S") - 2).Trim();
        string p = hold.Substring(hold.IndexOf("Pw") + 3,
hold.IndexOf("Volt") - hold.IndexOf("Pw") - 3).Trim();
        string wvolt = hold.Substring(hold.IndexOf("Volt") + 5,
hold.IndexOf("Curr") - hold.IndexOf("Volt") - 5).Trim();
        string wamp = hold.Substring(hold.IndexOf("Curr") + 5,
hold.IndexOf("L") - hold.IndexOf("Curr") - 5).Trim();
        string L = hold.Substring(hold.IndexOf("L") + 2, hold.Length -
hold.IndexOf("L") - 2).Trim();
        string q = hold.Substring(hold.IndexOf("Q") + 2,
hold.IndexOf("Pw") - hold.IndexOf("Q") - 2).Trim();

        //string volt = hold.Substring(hold.LastIndexOf(" "), hold.Length
- 1).Trim();
        //string amp = hold.Substring(hold.LastIndexOf(" "), hold.Length -
1).Trim();
```

```csharp
            if (q.Length < 8 && q != "NAN" &&
!(Convert.ToInt32(Convert.ToDecimal(q)) >(maxamp * maxvolt)))
            {
                QBox.Text = q;
                QBar.Value = Convert.ToInt32(Convert.ToDecimal(q) / (maxamp *
maxvolt) * 100);
            }
            if (s.Length < 8 && s != "NAN" &&
!(Convert.ToInt32(Convert.ToDecimal(s)) > (maxamp * maxvolt)))
            {
                SBox.Text = s;
                SBar.Value = Convert.ToInt32(Convert.ToDecimal(s) / (maxamp *
maxvolt) * 100);
            }
            if (ps.Length < 8 && ps != "NAN" &&
!(Convert.ToInt32(Convert.ToDecimal(ps)) > 360))
            {
                psBox.Text = ps;
                PsBar.Value = Convert.ToInt32(Convert.ToDecimal(ps) / 360 *
100);
            }
            if (pf.Length < 8 && pf != "NAN" && !(Convert.ToDecimal(pf) > 1))
            {
                pfBox.Text = pf;
                PfBar.Value = Convert.ToInt32(Convert.ToDecimal(pf) / 1 *
100);
            }
            if (p.Length < 8 && p != "NAN" &&
!(Convert.ToInt32(Convert.ToDecimal(p)) > (maxamp * maxvolt)))
            {
                PBox.Text = p;
                PBar.Value = Convert.ToInt32(Convert.ToDecimal(p) / (maxamp *
maxvolt) * 100);
            }
            if (wvolt.Length < 8 && wvolt != "NAN" &&
!(Convert.ToDecimal(wvolt) > maxvolt))
            {
                VoltBox.Text = wvolt;
                VoltBar.Value = Convert.ToInt32(Convert.ToDecimal(wvolt) /
maxvolt * 100);
            }
            if (wamp.Length < 8 && wamp != "NAN" && !(Convert.ToDecimal(wamp)
> maxamp))
            {
                AmpBox.Text = wamp;
                AmpBar.Value = Convert.ToInt32(Convert.ToDecimal(wamp) /
maxamp * 100);
            }
            if (L.Length < 2 && L != "NAN")
            {
                if (Convert.ToInt16(L) == 1)
                {
                    PS.Text = "Leading";
                    PS.ForeColor = Color.Purple;
                }
                if (Convert.ToInt16(L) == 0)
                {
                    PS.Text = "Lagging";
                    PS.ForeColor = Color.Green;
                }
                if (Convert.ToInt16(L) == 2)
```

```csharp
            {
                PS.Text = "Resistive";
                PS.ForeColor = Color.Blue;
            }

        }

        //vvoltBox.Text = volt;
        //aaBox.Text = amp;


    }

    /// <summary>
    /// Function to read the data from Serial port
    /// </summary>

    string readdata(BackgroundWorker bw, DoWorkEventArgs e)
    {
        try
        {
            serialPort1.ReadExisting();
            hold = serialPort1.ReadLine();
        }
        catch (Exception ex)
        {
            MessageBox.Show(ex.Message, "Error!", MessageBoxButtons.OK,
MessageBoxIcon.Error);
            hold = "Err";
        }
        return hold;
    }

    private void trackBar1_ValueChanged(object sender, EventArgs e)
    {
        textBox1.Text = Convert.ToString(trackBar1.Value);
    }

    private void trackBar2_ValueChanged(object sender, EventArgs e)
    {
        textBox2.Text = Convert.ToString(trackBar2.Value);
    }

    private void button3_Click(object sender, EventArgs e)
    {

    }
```

Appendix B.2: Graph Window Codes

```csharp
using System;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Drawing;
using System.Linq;
using System.Text;
using System.Windows.Forms;
using System.Threading;
using ZedGraph;

namespace Reza_Shahrara_Project
{
    public partial class Graph : Form
    {
        public Form1 frm1;
        int tickStart = 0;

        public Graph()
        {
            InitializeComponent();

        }

        private void Graph_Load(object sender, EventArgs e)
        {
            GraphPane myPane = zedGraphControl1.GraphPane;
            myPane.XAxis.Title.Text = "Time, Seconds";
            myPane.YAxis.Title.Text = "";
            myPane.Title.Text = "";

        }

        private void timer1_Tick(object sender, EventArgs e)
        {
            if (zedGraphControl1.GraphPane.CurveList.Count <= 0)
                return;

            LineItem curve = zedGraphControl1.GraphPane.CurveList[0] as
LineItem;
            if (curve == null)
                return;
            LineItem acurve = zedGraphControl1.GraphPane.CurveList[1] as
LineItem;
            if (acurve == null)
                return;
            LineItem pscurve = zedGraphControl1.GraphPane.CurveList[2] as
LineItem;
            if (pscurve == null)
                return;
            LineItem pfcurve = zedGraphControl1.GraphPane.CurveList[3] as
LineItem;
            if (pfcurve == null)
                return;
            LineItem scurve = zedGraphControl1.GraphPane.CurveList[4] as
LineItem;
            if (scurve == null)
                return;
            LineItem pcurve = zedGraphControl1.GraphPane.CurveList[5] as
LineItem;
```

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```csharp
            if (pcurve == null)
                return;
            LineItem qcurve = zedGraphControl1.GraphPane.CurveList[6] as
LineItem;
            if (qcurve == null)
                return;

            IPointListEdit vlist = curve.Points as IPointListEdit;
            if (vlist == null)
                return;
            IPointListEdit alist = acurve.Points as IPointListEdit;
            if (alist == null)
                return;
            IPointListEdit pslist = pscurve.Points as IPointListEdit;
            if (pslist == null)
                return;
            IPointListEdit pflist = pfcurve.Points as IPointListEdit;
            if (pflist == null)
                return;
            IPointListEdit slist = scurve.Points as IPointListEdit;
            if (slist == null)
                return;
            IPointListEdit plist = pcurve.Points as IPointListEdit;
            if (plist == null)
                return;
            IPointListEdit qlist = qcurve.Points as IPointListEdit;
            if (qlist == null)
                return;

            double time = (Environment.TickCount - tickStart) / 1000.0;

            if (VCB.Checked==true)
            {
                vlist.Add(time,
Convert.ToDouble(Convert.ToDecimal(((Form1)frm1).VoltBox.Text)));
            }
            if (ACB.Checked==true)
            {
                alist.Add(time,
Convert.ToDouble(Convert.ToDecimal(((Form1)frm1).AmpBox.Text)));
            }
            if (PSCB.Checked==true)
            {
                pslist.Add(time,
Convert.ToDouble(Convert.ToDecimal(((Form1)frm1).psBox.Text)));
            }
            if (PFCB.Checked==true)
            {
                pflist.Add(time,
Convert.ToDouble(Convert.ToDecimal(((Form1)frm1).pfBox.Text)));
            }
            if (SCB.Checked==true)
            {
                slist.Add(time,
Convert.ToDouble(Convert.ToDecimal(((Form1)frm1).SBox.Text)));
            }
            if (PCB.Checked==true)
            {
                plist.Add(time,
Convert.ToDouble(Convert.ToDecimal(((Form1)frm1).PBox.Text)));
            }
            if (QCB.Checked==true)
```

```csharp
            {
                qlist.Add(time,
Convert.ToDouble(Convert.ToDecimal(((Form1)frm1).QBox.Text)));
            }



            Scale xScale = zedGraphControl1.GraphPane.XAxis.Scale;
            if (time > xScale.Max - xScale.MajorStep)
            {
                xScale.Max = time + xScale.MajorStep;
                xScale.Min = xScale.Max - 30.0;
            }

            zedGraphControl1.AxisChange();
            zedGraphControl1.Invalidate();
        }

        void graph()
        {
            GraphPane myPane = zedGraphControl1.GraphPane;

          // myPane.XAxis.Title.Text = "Time, Seconds";


            // Save 1200 points.  At 50 ms sample rate, this is one minute
            // The RollingPointPairList is an efficient storage class that
always
            // keeps a rolling set of point data without needing to shift any
data values
            RollingPointPairList vlist = new RollingPointPairList(1200);
            RollingPointPairList alist = new RollingPointPairList(1200);
            RollingPointPairList pslist = new RollingPointPairList(1200);
            RollingPointPairList pflist = new RollingPointPairList(1200);
            RollingPointPairList slist = new RollingPointPairList(1200);
            RollingPointPairList plist = new RollingPointPairList(1200);
            RollingPointPairList qlist = new RollingPointPairList(1200);


            // Initially, a curve is added with no data points (list is empty)
            // Color is blue, and there will be no symbols
            //LineItem curve =
                myPane.AddCurve("Voltage", vlist, Color.Blue,
SymbolType.None);
                myPane.AddCurve("Current", alist, Color.Red, SymbolType.None);
                myPane.AddCurve("Phase Shift", pslist , Color.Black,
SymbolType.None);
                myPane.AddCurve("Power Factor", pflist, Color.Green,
SymbolType.None);
                myPane.AddCurve("ACtive Power(S)", slist, Color.Orange,
SymbolType.None);
                myPane.AddCurve("Real Power(P)", plist, Color.DarkRed,
SymbolType.None);
                myPane.AddCurve("Reactive Power(Q)", qlist, Color.Cyan,
SymbolType.None);

            // Sample at 50ms intervals
            timer1.Interval = 50;
            timer1.Enabled = true;
            timer1.Start();
```

```csharp
            // Just manually control the X axis range so it scrolls
continuously
            // instead of discrete step-sized jumps
            myPane.XAxis.Scale.Min = 0;
            myPane.XAxis.Scale.Max = 30;
            myPane.XAxis.Scale.MinorStep = 1;
            myPane.XAxis.Scale.MajorStep = 5;

            // Scale the axes
            zedGraphControl1.AxisChange();

            // Save the beginning time for reference
            tickStart = Environment.TickCount;


        }

        private void button1_Click(object sender, EventArgs e)
        {
            if (button1.Text == "Start")
            {
                graph();
                button1.Text = "Stop";
            }
            else
            {
                timer1.Stop();
                zedGraphControl1.GraphPane.CurveList.Clear();
                button1.Text = "Start";
            }
        }

    }
}
```

Appendix C: Essential Data Sheets

Appendix C.1: Current Transducer NNC-10..40 GFP

LEM

Current Transducer NNC-10..40GFP

I_{PN} = 50 .. 600 A

For the electronic measurement of currents: DC, AC, pulsed, mixed, with a galvanic isolation between the primary circuit (high power) and the secondary circuit (electronic circuit).

Electrical data

Primary nominal DC current I_{PN} (A)	Primary current measuring range I_P (A)		Type
100	± 300		NNC-10GFP
200	± 600		NNC-20GFP
300	± 900		NNC-30GFP
400	± 1000		NNC-40GFP
V_c	Supply voltage (±5 %)	±15	V
I_c	Current consumption	<±18	mA
V_d	R.m.s. voltage for AC isolation test, 50/60 Hz, 1 mn	2.5	kV
R_{is}	Isolation resistance @ 500 VDC	> 1000	MΩ
V_{OUT}	Output voltage @ ± I_{PN}, R_L = 10 kΩ, T_A = 25°C	±4	V
R_{OUT}	Output internal resistance	< 100	Ω
R_L	Load resistance	10	kΩ

Accuracy - Dynamic performance data

X	Accuracy @ T_A = 25°C (without offset)	<±1	% of I_{PN}
ε_L	Linearity [5] (0 .. ± I_{PN})	<±1	% of I_{PN}
V_{OE}	Electrical offset voltage, T_A = 25°C	<±30	mV
V_{OH}	Hysteresis offset voltage @ I_P = 0; after an excursion of 1 x I_{PN}	<±35	mV
V_{OT}	Thermal drift of V_{OE} NNC-10GFP	<±2	mV/K
	NNC-20..40GFP	<±1	mV/K
TCE_G	Thermal drift of the gain (% of reading)	<±0.1	%/K
t_r	Response time @ 90% of I_P	< 7	µs

General data

T_A	Ambient operating temperature	-10 .. +80	°C
T_0	Ambient storage temperature	-15 .. +85	°C
m	Mass	50	g

Features

- Hall effect measuring principle
- Galvanic isolation between primary and secondary circuit
- Isolation voltage 2500V
- Low power consumption
- Extended measuring range (3 x I_{PN})

Advantages

- Small size and space saving
- Only one design for wide current ratings range
- High immunity to external interference

Applications

- AC variable speed drives
- Battery supplied applications
- Uninterruptible Power Supplies (UPS)
- DC motor drives
- Switched Mode Power Supplies(SMPS)
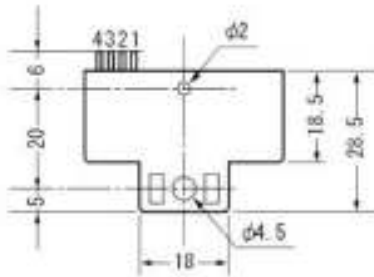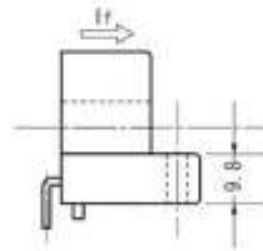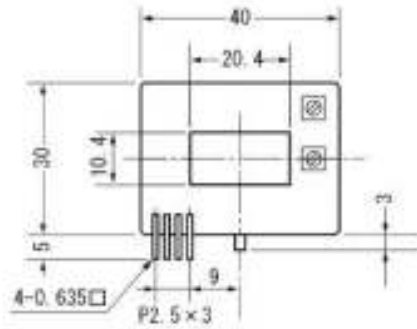- Power supplies for welding applications

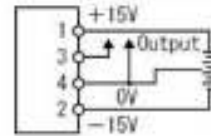Notes : [5] Linearity data exclude the electrical offset.

050113/1

LEM Components

www.lem.com

NNC-10..40GFP
Dimensions (in mm)

Terminal Pin Identification

Appendix C.2: LM741 Operational Amplifier

National Semiconductor

August 2000

LM741
Operational Amplifier

General Description

The LM741 series are general purpose operational amplifiers which feature improved performance over industry standards like the LM709. They are direct, plug-in replacements for the 709C, LM201, MC1439 and 748 in most applications.

The amplifiers offer many features which make their application nearly foolproof: overload protection on the input and output, no latch-up when the common mode range is exceeded, as well as freedom from oscillations.

The LM741C is identical to the LM741/LM741A except that the LM741C has their performance guaranteed over a 0°C to +70°C temperature range, instead of −55°C to +125°C.

Features

Connection Diagrams

Metal Can Package
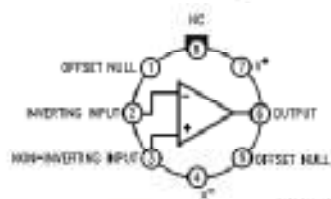
Note 1: LM741H is available per JM38510/10101

Order Number LM741H, LM741H/883 (Note 1), LM741AH/883 or LM741CH
See NS Package Number H08C

Dual-In-Line or S.O. Package
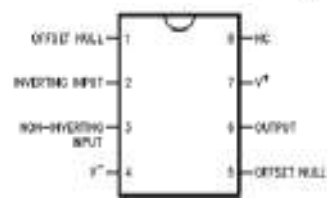
Order Number LM741J, LM741J/883, LM741CN
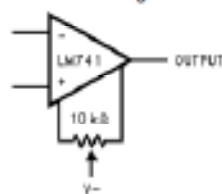See NS Package Number J08A, M08A or N08E

Ceramic Flatpak
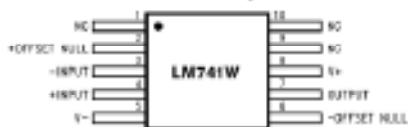
LM741W

Order Number LM741W/883
See NS Package Number W10A

Typical Application

Offset Nulling Circuit

LM741

OUTPUT

10 kΩ

V−

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Absolute Maximum Ratings (Note 2)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/ Distributors for availability and specifications.

(Note 7)

	LM741A	LM741	LM741C
Supply Voltage	±22V	±22V	±18V
Power Dissipation (Note 3)	500 mW	500 mW	500 mW
Differential Input Voltage	±30V	±30V	±30V
Input Voltage (Note 4)	±15V	±15V	±15V
Output Short Circuit Duration	Continuous	Continuous	Continuous
Operating Temperature Range	−55°C to +125°C	−55°C to +125°C	0°C to +70°C
Storage Temperature Range	−65°C to +150°C	−65°C to +150°C	−65°C to +150°C
Junction Temperature	150°C	150°C	100°C
Soldering Information			
N-Package (10 seconds)	260°C	260°C	260°C
J- or H-Package (10 seconds)	300°C	300°C	300°C
M-Package			
Vapor Phase (60 seconds)	215°C	215°C	215°C
Infrared (15 seconds)	215°C	215°C	215°C

See AN-450 "Surface Mounting Methods and Their Effect on Product Reliability" for other methods of soldering

surface mount devices.

ESD Tolerance (Note 8)	400V	400V	400V

Electrical Characteristics (Note 5)

Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage	$T_A = 25°C$										
	$R_S \leq 10\ k\Omega$					1.0	5.0		2.0	6.0	mV
	$R_S \leq 50\Omega$		0.8	3.0							mV
	$T_{AMIN} < T_A < T_{AMAX}$										
	$R_S \leq 50\Omega$			4.0							mV
	$R_S \leq 10\ k\Omega$						6.0			7.5	mV
Average Input Offset Voltage Drift				15							μV/°C
Input Offset Voltage Adjustment Range	$T_A = 25°C$, $V_S = ±20V$	±10				±15			±15		mV
Input Offset Current	$T_A = 25°C$		3.0	30		20	200		20	200	nA
	$T_{AMIN} \leq T_A \leq T_{AMAX}$			70		85	500			300	nA
Average Input Offset Current Drift				0.5							nA/°C
Input Bias Current	$T_A = 25°C$		30	80		80	500		80	500	nA
	$T_{AMIN} \leq T_A \leq T_{AMAX}$			0.210			1.5			0.8	μA
Input Resistance	$T_A = 25°C$, $V_S = ±20V$	1.0	6.0		0.3	2.0		0.3	2.0		MΩ
	$T_{AMIN} \leq T_A \leq T_{AMAX}$, $V_S = ±20V$	0.5									MΩ
Input Voltage Range	$T_A = 25°C$							±12	±13		V
	$T_{AMIN} \leq T_A \leq T_{AMAX}$				±12	±13					V

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Electrical Characteristics (Note 5) (Continued)

Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Large Signal Voltage Gain	$T_A = 25°C$, $R_L ≥ 2$ kΩ										
	$V_S = ±20V$, $V_O = ±15V$	50									V/mV
	$V_S = ±15V$, $V_O = ±10V$				50	200		20	200		V/mV
	$T_{AMIN} ≤ T_A ≤ T_{AMAX}$, $R_L ≥ 2$ kΩ,										
	$V_S = ±20V$, $V_O = ±15V$	32									V/mV
	$V_S = ±15V$, $V_O = ±10V$				25			15			V/mV
	$V_S = ±5V$, $V_O = ±2V$	10									V/mV
Output Voltage Swing	$V_S = ±20V$										
	$R_L ≥ 10$ kΩ	±16									V
	$R_L ≥ 2$ kΩ	±15									V
	$V_S = ±15V$										
	$R_L ≥ 10$ kΩ				±12	±14		±12	±14		V
	$R_L ≥ 2$ kΩ				±10	±13		±10	±13		V
Output Short Circuit Current	$T_A = 25°C$	10	25	35		25			25		mA
	$T_{AMIN} ≤ T_A ≤ T_{AMAX}$	10		40							mA
Common-Mode Rejection Ratio	$T_{AMIN} ≤ T_A ≤ T_{AMAX}$										
	$R_S ≤ 10$ kΩ, $V_{CM} = ±12V$				70	90		70	90		dB
	$R_S ≤ 50\Omega$, $V_{CM} = ±12V$	80	95								dB
Supply Voltage Rejection Ratio	$T_{AMIN} ≤ T_A ≤ T_{AMAX}$, $V_S = ±20V$ to $V_S = ±5V$										
	$R_S ≤ 50\Omega$	86	96								dB
	$R_S ≤ 10$ kΩ				77	96		77	96		dB
Transient Response	$T_A = 25°C$, Unity Gain										
Rise Time			0.25	0.8		0.3			0.3		μs
Overshoot			6.0	20		5			5		%
Bandwidth (Note 6)	$T_A = 25°C$	0.437	1.5								MHz
Slew Rate	$T_A = 25°C$, Unity Gain	0.3	0.7			0.5			0.5		V/μs
Supply Current	$T_A = 25°C$					1.7	2.8		1.7	2.8	mA
Power Consumption	$T_A = 25°C$										
	$V_S = ±20V$		80	150							mW
	$V_S = ±15V$					50	85		50	85	mW
LM741A	$V_S = ±20V$										
	$T_A = T_{AMIN}$			165							mW
	$T_A = T_{AMAX}$			135							mW
LM741	$V_S = ±15V$										
	$T_A = T_{AMIN}$					60	100				mW
	$T_A = T_{AMAX}$					45	75				mW

Note 2: "Absolute Maximum Ratings" indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is functional, but do not guarantee specific performance limits.

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Electrical Characteristics (Note 5) (Continued)

Note 3: For operation at elevated temperatures, these devices must be derated based on thermal resistance, and T_j max. (listed under 'Absolute Maximum Ratings'). $T_j = T_A + (\theta_{jA} P_D)$.

Thermal Resistance	Cerdip (J)	DIP (N)	HO8 (H)	SO-8 (M)
θ_{jA} (Junction to Ambient)	100°C/W	100°C/W	170°C/W	195°C/W
θ_{jC} (Junction to Case)	N/A	N/A	25°C/W	N/A

Note 4: For supply voltages less than ±15V, the absolute maximum input voltage is equal to the supply voltage.

Note 5: Unless otherwise specified, these specifications apply for V_S = ±15V, −55°C ≤ T_A ≤ +125°C (LM741/LM741A). For the LM741C/LM741E, these specifications are limited to 0°C ≤ T_A ≤ +70°C.

Note 6: Calculated value from: BW (MHz) = 0.35/Rise Time(µs).

Note 7: For military specifications see RETS741X for LM741 and RETS741AX for LM741A.

Note 8: Human body model, 1.5 kΩ in series with 100 pF.

Schematic Diagram

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Physical Dimensions inches (millimeters)
unless otherwise noted

0.350 − 0.370
(8.890 − 9.398)
DIA

0.315 − 0.335
(8.001 − 8.509) DIA

0.025 MAX
(0.635) UNCONTROLLED
LEAD DIA

0.165 − 0.185
(4.191 − 4.699)

REFERENCE PLANE

SEATING PLANE

0.500
(12.70)
MIN

0.035
(0.889)
MAX

0.015 − 0.040
(0.381 − 1.016)

0.016 − 0.019
(0.406 − 0.483) DIA TYP

0.100
(2.540) TYP

0.195 − 0.205 DIA
(4.953 − 5.207) P.C.

0.029 − 0.045
(0.737 − 1.143)

0.028 − 0.034
(0.711 − 0.864)

0.115 − 0.145
(2.921 − 3.683)
DIA

45° EQUALLY
SPACED
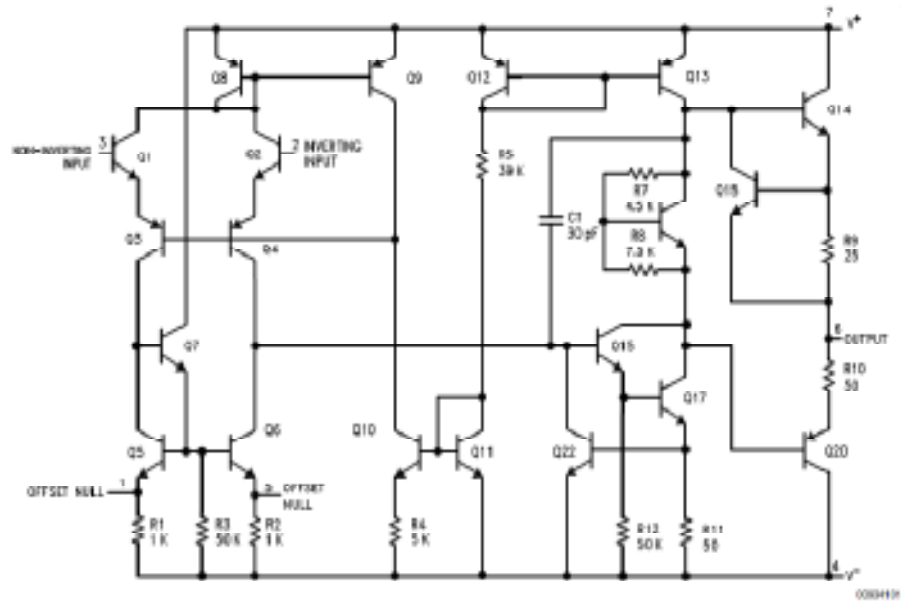
H08C (REV D)
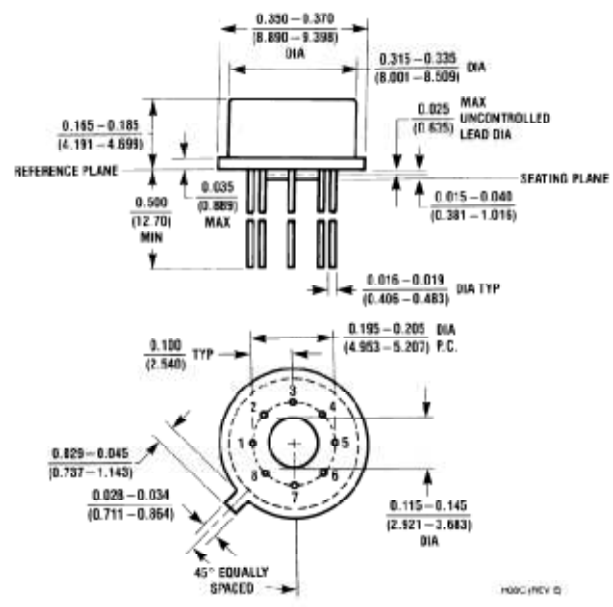
Metal Can Package (H)
Order Number LM741H, LM741H/883, LM741AH/883, LM741AH-MIL or LM741CH
NS Package Number H08C

Physical Dimensions inches (millimeters) unless otherwise noted (Continued)
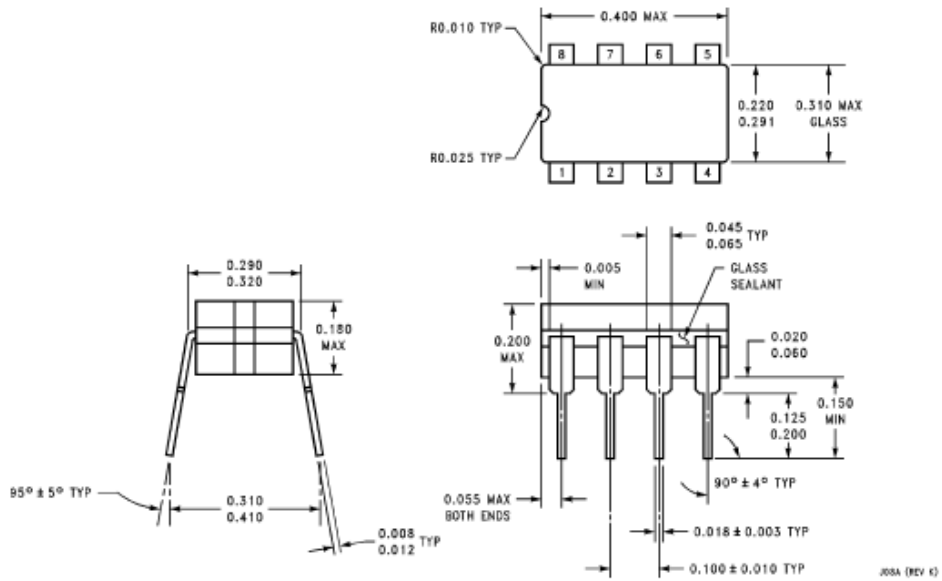
Ceramic Dual-In-Line Package (J)
Order Number LM741J/883
NS Package Number J08A
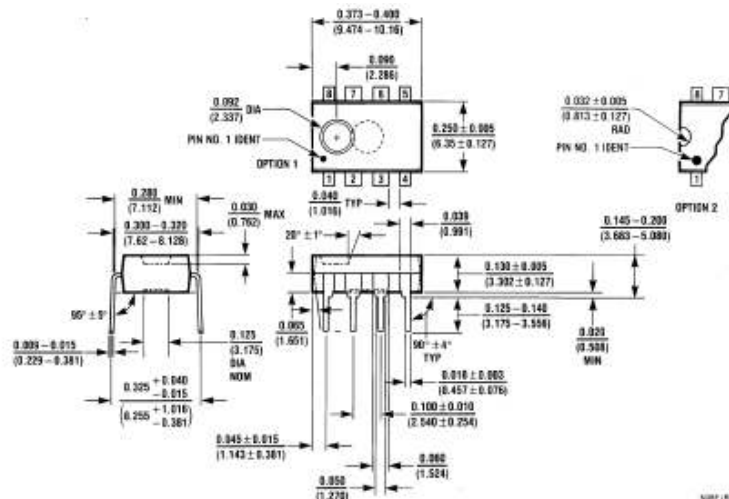
Dual-In-Line Package (N)
Order Number LM741CN
NS Package Number N08E

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Physical Dimensions inches (millimeters) unless otherwise noted (Continued)
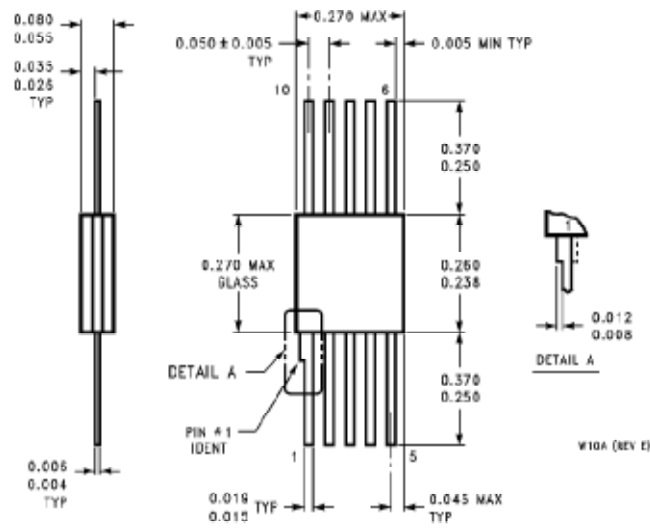
10-Lead Ceramic Flatpak (W)
Order Number LM741W/883, LM741WG-MPR or LM741WG/883
NS Package Number W10A

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For the most current product information visit us at www.national.com.

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1. Life support devices or systems are devices or systems which, (a) are intended for surgical implant into the body, or (b) support or sustain life, and whose failure to perform when properly used in accordance with instructions for use provided in the labeling, can be reasonably expected to result in a significant injury to the user.

2. A critical component is any component of a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system, or to affect its safety or effectiveness.

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National Semiconductor certifies that the products and packing materials meet the provisions of the Customer Products Stewardship Specification (CSP-9-111C2) and the Banned Substances and Materials of Interest Specification (CSP-9-111S2) and contain no "Banned Substances" as defined in CSP-9-111S2.

Absolute Maximum Ratings (Note 1)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/ Distributors for availability and specifications.

Lead Temperature (Soldering, 10 seconds)

TO-39 Package (H)	300°C
TO-220 Package (T)	260°C
Storage Temperature Range	−65°C to +150°C

Operating Junction Temperature

Range	−40°C to +125°C
Power Dissipation (Note 2)	Internally Limited
Input Voltage	
5V ≤ V_O ≤ 15V	35V
ESD Susceptibility	TBD

Electrical Characteristics

Limits in standard typeface are for T_J = 25°C, and limits in **boldface type** apply over the −40°C to +125°C operating temperature range. Limits are guaranteed by production testing or correlation techniques using standard Statistical Quality Control (SQC) methods.

LM341-5.0, LM78M05C

Unless otherwise specified: V_{IN} = 10V, C_{IN} = 0.33 µF, C_O = 0.1 µF

Symbol	Parameter	Conditions		Min	Typ	Max	Units
V_O	Output Voltage	I_L = 500 mA		4.8	5.0	5.2	V
		5 mA ≤ I_L ≤ 500 mA P_D ≤ 7.5W, 7.5V ≤ V_{IN} ≤ 20V		**4.75**	5.0	**5.25**	
$V_{R LINE}$	Line Regulation	7.2V ≤ V_{IN} ≤ 25V	I_L = 100 mA			50	mV
			I_L = 500 mA			100	
$V_{R LOAD}$	Load Regulation	5 mA ≤ I_L ≤ 500 mA				100	
I_Q	Quiescent Current	I_L = 500 mA			4	10.0	mA
ΔI_Q	Quiescent Current Change	5 mA ≤ I_L ≤ 500 mA				0.5	
		7.5V ≤ V_{IN} ≤ 25V, I_L = 500 mA				1.0	
V_n	Output Noise Voltage	f = 10 Hz to 100 kHz			40		µV
$\dfrac{\Delta V_{IN}}{\Delta V_O}$	Ripple Rejection	f = 120 Hz, I_L = 500 mA			78		dB
V_{IN}	Input Voltage Required to Maintain Line Regulation	I_L = 500 mA		7.2			V
ΔV_O	Long Term Stability	I_L = 500 mA				20	mV/khrs

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Electrical Characteristics

Limits in standard typeface are for $T_J = 25°C$, and limits in **boldface type** apply over the −40°C to +125°C operating temperature range. Limits are guaranteed by production testing or correlation techniques using standard Statistical Quality Control (SQC) methods. (Continued)

LM341-12, LM78M12C

Unless otherwise specified: $V_{IN} = 19V$, $C_{IN} = 0.33 \mu F$, $C_O = 0.1 \mu F$

Symbol	Parameter	Conditions		Min	Typ	Max	Units
V_O	Output Voltage	$I_L = 500$ mA		11.5	12	12.5	V
		5 mA ≤ I_L ≤ 500 mA		**11.4**	**12**	**12.6**	
		P_D ≤ 7.5W, 14.8V ≤ V_{IN} ≤ 27V					
$V_{R\ LINE}$	Line Regulation	14.5V ≤ V_{IN} ≤ 30V	$I_L = 100$ mA			120	mV
			$I_L = 500$ mA			240	
$V_{R\ LOAD}$	Load Regulation	5 mA < I_L < 500 mA				240	
I_Q	Quiescent Current	$I_L = 500$ mA			4	10.0	mA
ΔI_Q	Quiescent Current Change	5 mA ≤ I_L ≤ 500 mA				0.5	
		14.8V ≤ V_{IN} ≤ 30V, $I_L = 500$ mA				1.0	
V_n	Output Noise Voltage	f = 10 Hz to 100 kHz			75		μV
$\frac{\Delta V_{IN}}{\Delta V_O}$	Ripple Rejection	f = 120 Hz, $I_L = 500$ mA			71		dB
V_{IN}	Input Voltage Required to Maintain Line Regulation	$I_L = 500$ mA		14.5			V
ΔV_O	Long Term Stability	$I_L = 500$ mA				48	mV/khrs

LM341-15, LM78M15C

Unless otherwise specified: $V_{IN} = 23V$, $C_{IN} = 0.33 \mu F$, $C_O = 0.1 \mu F$

Symbol	Parameter	Conditions		Min	Typ	Max	Units
V_O	Output Voltage	$I_L = 500$ mA		14.4	15	15.6	V
		5 mA ≤ I_L ≤ 500 mA		**14.25**	**15**	**15.75**	
		P_D ≤ 7.5W, 18V ≤ V_{IN} ≤ 30V					
$V_{R\ LINE}$	Line Regulation	17.5V ≤ V_{IN} ≤ 30V	$I_L = 100$ mA			150	mV
			$I_L = 500$ mA			300	
$V_{R\ LOAD}$	Load Regulation	5 mA ≤ I_L ≤ 500 mA				300	
I_Q	Quiescent Current	$I_L = 500$ mA			4	10.0	mA
ΔI_Q	Quiescent Current Change	5 mA ≤ I_L ≤ 500 mA				0.5	
		10V ≤ V_{IN} ≤ 30V, $I_L = 500$ mA				1.0	
V_n	Output Noise Voltage	f = 10 Hz to 100 kHz			90		μV
$\frac{\Delta V_{IN}}{\Delta V_O}$	Ripple Rejection	f = 120 Hz, $I_L = 500$ mA			69		dB
V_{IN}	Input Voltage Required to Maintain Line Regulation	$I_L = 500$ mA		17.6			V
ΔV_O	Long Term Stability	$I_L = 500$ mA				60	mV/khrs

Note 1: Absolute maximum ratings indicate limits beyond which damage to the component may occur. Electrical specifications do not apply when operating the device outside of its rated operating conditions.

Note 2: The typical thermal resistance of the three package types is:

T (TO-220) package: $\theta_{JA} = 60$ °C/W, $\theta_{JC} = 5$ °C/W

M (TO-39) package: $\theta_{JA} = 120$ °C/W, $\theta_{JC} = 18$ °C/W

DT (TO-252) package: $\theta_{JA} = 92$ °C/W, $\theta_{JC} = 10$ °C/W
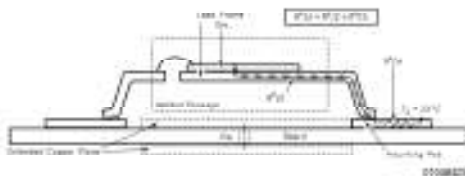
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Application Information

FIGURE 1. Cross-sectional view of Integrated Circuit Mounted on a printed circuit board. Note that the case temperature is measured at the point where the leads contact with the mounting pad surface
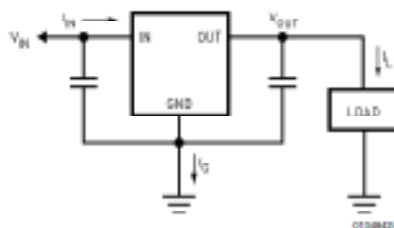
The LM78MXX/LM341XX regulators have internal thermal shutdown to protect the device from over-heating. Under all possible operating conditions, the junction temperature of the LM78MXX/LM341XX must be within the range of 0°C to 125°C. A heatsink may be required depending on the maximum power dissipation and maximum ambient temperature of the application. To determine if a heatsink is needed, the power dissipated by the regulator, P_D, must be calculated:

$$I_{IN} = I_L + I_G$$

$$P_D = (V_{IN} - V_{OUT}) I_L + V_{IN} I_G$$

shows the voltages and currents which are present in the circuit.

FIGURE 2. Power Dissipation Diagram

The next parameter which must be calculated is the maximum allowable temperature rise, T_R(max):

$$\theta_{JA} = TR \ (max)/P_D$$

If the maximum allowable value for θ_{JA} °C/W is found to be ≥60°C/W for TO-220 package or ≥92°C/W for TO-252 package, no heatsink is needed since the package alone will dissipate enough heat to satisfy these requirements. If the calculated value for θ_{JA} fall below these limits, a heatsink is required.

As a design aid, Table 1 shows the value of the θ_{JA} of TO-252 for different heatsink area. The copper patterns that

we used to measure these θ_{JA} are shown at the end of the Application Note Section. reflects the same test results as what are in the Table 1

shows the maximum allowable power dissipation vs. ambient temperature for the TO-252 device. shows the maximum allowable power dissipation vs. copper area (in²) for the TO-252 device. Please see AN1028 for power enhancement techniques to be used with TO-252 package.

Appendix C.4: LM79XX Series, 3-Terminal Negative Voltage Regulators

National Semiconductor

September 2001

LM79XX Series
3-Terminal Negative Regulators

General Description

The LM79XX series of 3-terminal regulators is available with fixed output voltages of −5V, −12V, and −15V. These devices need only one external component—a compensation capacitor at the output. The LM79XX series is packaged in the TO-220 power package and is capable of supplying 1.5A of output current.

These regulators employ internal current limiting safe area protection and thermal shutdown for protection against virtually all overload conditions.

Low ground pin current of the LM79XX series allows output voltage to be easily boosted above the preset value with a resistor divider. The low quiescent current drain of these devices with a specified maximum change with line and load ensures good regulation in the voltage boosted mode.

For applications requiring other voltages, see LM137 datasheet.

Features

- Thermal, short circuit and safe area protection
- High ripple rejection
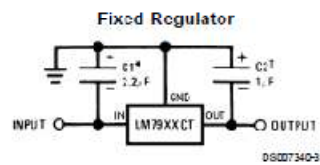- 1.5A output current
- 4% tolerance on preset output voltage

Connection Diagrams

TO-220 Package
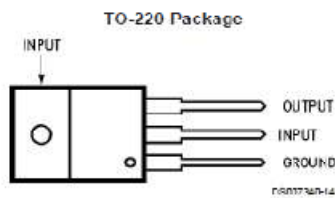
Front View
Order Number LM7905CT, LM7912CT or LM7915CT
See NS Package Number TO3B

Typical Applications

Fixed Regulator

*Required if regulator is separated from filter capacitor by more than 3". For value given, capacitor must be solid tantalum. 25μF aluminum electrolytic may be substituted.

†Required for stability. For value given, capacitor must be solid tantalum. 25μF aluminum electrolytic may be substituted. Values given may be increased without limit.

For output capacitance in excess of 100μF, a high current diode from input to output (1N4001, etc.) will protect the regulator from momentary input shorts.

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Absolute Maximum Ratings (Note 1)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/ Distributors for availability and specifications.

Input Voltage

($V_o = -5V$)	−25V
($V_o = -12V$ and −15V)	−35V

Input-Output Differential

($V_o = -5V$)	25V
($V_o = -12V$ and −15V)	30V
Power Dissipation (Note 2)	Internally Limited
Operating Junction Temperature Range	0°C to +125°C
Storage Temperature Range	−65°C to +150°C
Lead Temperature (Soldering, 10 sec.)	230°C

Electrical Characteristics

Conditions unless otherwise noted: I_{OUT} = 500mA, C_{IN} = 2.2µF, C_{OUT} = 1µF, 0°C ≤ T_J ≤ +125°C, Power Dissipation ≤ 1.5W.

	Part Number		LM7905C			Units
	Output Voltage		−5V			
	Input Voltage (unless otherwise specified)		−10V			
Symbol	Parameter	Conditions	Min	Typ	Max	
V_O	Output Voltage	T_J = 25°C	−4.8	−5.0	−5.2	V
		5mA ≤ I_{OUT} ≤ 1A,	−4.75		−5.25	V
		P ≤ 15W		(−20 ≤ V_{IN} ≤ −7)		V
ΔV_O	Line Regulation	T_J = 25°C, (Note 3)		8	50	mV
				(−25 ≤ V_{IN} ≤ −7)		V
				2	15	mV
				(−12 ≤ V_{IN} ≤ −8)		V
ΔV_O	Load Regulation	T_J = 25°C, (Note 3)				
		5mA ≤ I_{OUT} ≤ 1.5A		15	100	mV
		250mA ≤ I_{OUT} ≤ 750mA		5	50	mV
I_Q	Quiescent Current	T_J = 25°C		1	2	mA
ΔI_Q	Quiescent Current Change	With Line			0.5	mA
				(−25 ≤ V_{IN} ≤ −7)		V
		With Load, 5mA ≤ I_{OUT} ≤ 1A			0.5	mA
V_n	Output Noise Voltage	T_A = 25°C, 10Hz ≤ f ≤ 100Hz		125		µV
	Ripple Rejection	f = 120Hz	54	66		dB
				(−18 ≤ V_{IN} ≤ −8)		V
	Dropout Voltage	T_J = 25°C, I_{OUT} = 1A		1.1		V
I_{OMAX}	Peak Output Current	T_J = 25°C		2.2		A
	Average Temperature Coefficient of Output Voltage	I_{OUT} = 5mA, 0 C ≤ T_J ≤ 100°C		0.4		mV/°C

Electrical Characteristics

Conditions unless otherwise noted: I_{OUT} = 500mA, C_{IN} = 2.2µF, C_{OUT} = 1µF, 0°C ≤ T_J ≤ +125°C, Power Dissipation ≤ 1.5W.

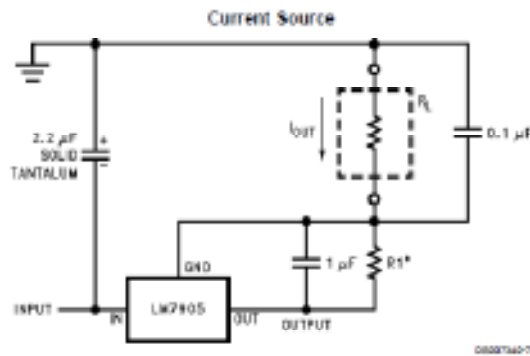|	Part Number		LM7912C			LM7915C			Units
	Output Voltage		−12V			−15V			
	Input Voltage (unless otherwise specified)		−19V			−23V			
Symbol	Parameter	Conditions	Min	Typ	Max	Min	Typ	Max	
V_O	Output Voltage	T_J = 25°C	−11.5	−12.0	−12.5	−14.4	−15.0	−15.6	V
		5mA ≤ I_{OUT} ≤ 1A,	−11.4		−12.6	−14.25		−15.75	V
		P ≤ 15W		(−27 ≤ V_{IN} ≤ −14.5)			(−30 ≤ V_{IN} ≤ −17.5)		V
ΔV_O	Line Regulation	T_J = 25°C, (Note 3)		5	80		5	100	mV
				(−30 ≤ V_{IN} ≤ −14.5)			(−30 ≤ V_{IN} ≤ −17.5)		V
				3	30		3	50	mV
				(−22 ≤ V_{IN} ≤ −16)			(−26 ≤ V_{IN} ≤ −20)		V
ΔV_O	Load Regulation	T_J = 25°C, (Note 3)							

Typical Applications

Bypass capacitors are necessary for stable operation of the LM79XX series of regulators over the input voltage and output current ranges. Output bypass capacitors will improve the transient response by the regulator.

The bypass capacitors, (2.2µF on the input, 1.0µF on the output) should be ceramic or solid tantalum which have good high frequency characteristics. If aluminum electrolytics are used, their values should be 10µF or larger. The bypass capacitors should be mounted with the shortest leads, and if possible, directly across the regulator terminals.
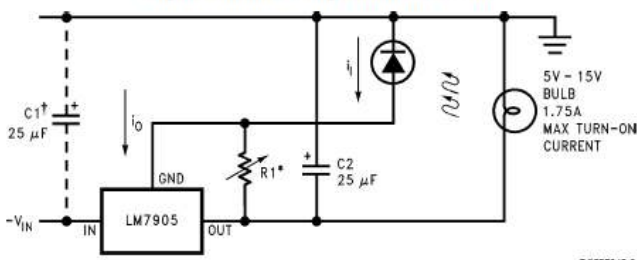
High Stability 1 Amp Regulator
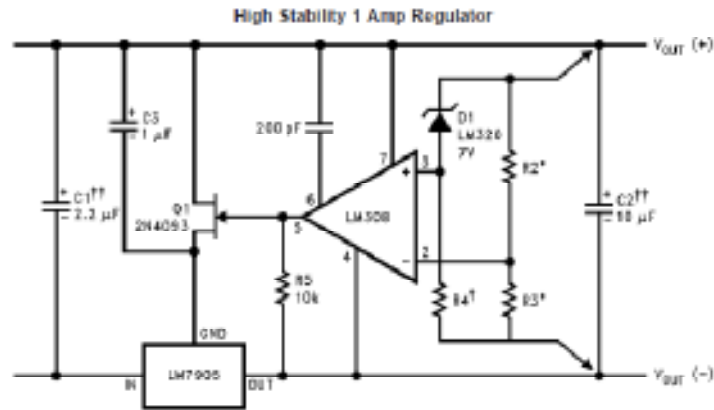
Load and line regulation < 0.01% temperature stability ≤ 0.2%
†Determine Zener current
††Solid tantalum
*Select resistors to set output voltage. 2 ppm/°C tracking suggested

Current Source

$$*I_{OUT} = 1\,mA + \frac{6V}{R1}$$

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Typical Applications (Continued)

Light Controller Using Silicon Photo Cell

C1† 25 μF

−V$_{IN}$

IN LM7905 OUT

GND

R1*

C2 25 μF

i$_O$

i$_l$

5V − 15V BULB 1.75A MAX TURN−ON CURRENT

DS007340-8

*Lamp brightness increase until i$_l$= i$_O$ (≈ 1 mA) + 5V/R1.
†Necessary only if raw supply filter capacitor is more that 2" from LM7905CT

High-Sensitivity Light Controller

C1† 25 μF

Q1 2N4143

R2 100k

Q2 2N4141

IN LM7905 OUT

GND

C2 25 μF

D1 1N457

R1*

i$_l$

8V − 15V BULB 1.75A MAX TURN−ON CURRENT
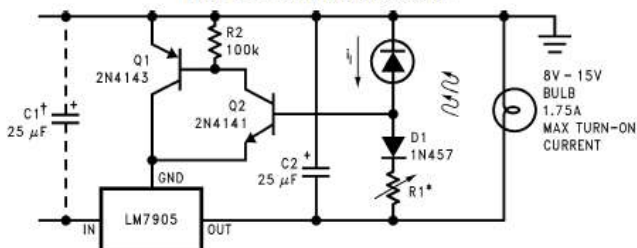
DS007340-9

*Lamp brightness increases until i$_l$ = 5V/R1 (i$_l$ can be set as low as 1 μA)
†Necessary only if raw supply filter capacitor is more that 2" from LM7905

Variable Output

C1 2.2 μF SOLID TANTALUM

INPUT

IN LM79XXCT OUT

GND

C3* 25 μF

R1

R2

C2 1 μF SOLID TANTALUM

OUTPUT
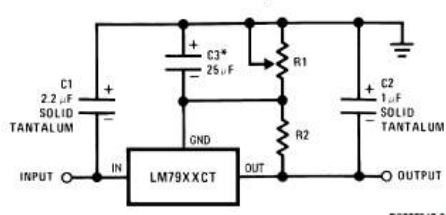
DS007340-2

*Improves transient response and ripple rejection. Do not increase beyond 50 μF.

$$V_{OUT} = V_{SET} \left(\frac{R1 + R2}{R2} \right)$$

Select R2 as follows:

LM7905CT   300Ω
LM7912CT   750Ω
LM7915CT   1k

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