DESIGN AND DEVELOPMENT OF COST EFFECTIVE `
IOT BASED SMART METER FOR SMART CITY
HOUSEHOLDS WITH HARMONIC ANALYSIS

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Submitted by

Guided by,

Dr. L. Ashok Kumar

Professor

PIC2018_326

Team members,

ABISHEK A T	PIC2018_223
SATHISH R	PIC2018_226
SATHISH KUMAR S	PIC2018_225
THILAK RAJ N	PIC2018_224

Department of Electrical and Electronics Engineering

PSG College of Technology

Post Box No. 1611, Peelamedu

Coimbatore, Tamil Nadu, India

PIN: 641 004

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ABSTRACT

The nonlinear loads that are used in households such as computers, fluorescent lamps, AC voltage regulator base fans, refrigerators, air conditioners, etc., causes electric pollution as they distort their current waveform and eventually distort the common voltage waveform thereby causing damage to the equipments. There is an increasing trend in the use of nonlinear loads and considering the Electric Vehicle scenario, harmonic will be a large problem in households in few years. In this work, a cost-effective energy meter is designed and harmonics measurement up to 25^{th} harmonic is incorporated into the system. The data is uploaded to a cloud platform from where the consumer can view his consumption at any time.

Fast Fourier Transform (256 point) algorithm is used to compute the harmonics. The voltage is sensed through a high precision potential transformer based sensor and the current is sensed through a Hall Effect based sensor. Then the values are fed into the microcontroller and various power related parameters are calculated by instantaneous power calculation technique. A display is provided for the user to view the parameters.

The experimental values are verified using 3 standard meters: FLUKE 434 series II power quality analyzer, FLUKE 317 clamp meter and MECO PLH 5760. The experimental values were reasonable with the standard meter values.

The experimental setup was test using a TRIAC based lamp load and a variable RL load. A large current harmonics was injected into the system and the values were compared. The experimental setup was close to accurate and had an error of +/- 3 %. The data were uploaded to a cloud platform called ThingSpeak. Various fields were created in that platform and the waveforms were plotted.

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CHAPTER 1

INTRODUCTION

Electricity has become an integral part of our daily lives. The growth of every sector in our state depends upon the availability of electricity. Nowadays, due to the tremendous growth of non-linear loads such as the usage of power converters, UPS, Rectifiers, Induction ovens, battery chargers, etc., the quality of the power delivered to the end user is highly reduced. As per **IEEE 519- 2014** standard, the allowable harmonics for LT lines (<1 kV) is 5%.

Power Quality is defined in the Institute of Electrical and Electronics Engineers (IEEE) 100 Authoritative Dictionary of IEEE Standard Terms as "the concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment." Nonlinear loads cause distortions in the power supply. These distortions consist of frequencies which are integral multiples of the fundamental frequency of the power line. They are called as harmonics. The intermediate frequencies which are not the integral multiples are called inter harmonics [4].

Voltage harmonics causes deteriorations in insulations coordination of capacitors bank, windings, power cables, etc [2]. It also causes source breakdown in power devices and converters that consume the stable voltage waveform for the synchronization. Motor windings may generate current harmonics which leads to electromagnetic interference (EMI). They occur due to irregular heating of the power lines [3].

TANGEDCO is the forerunner in our country, to set harmonic limit and consequently penalty for the same when exceeded. Tamil Nadu Electricity Board determines the power quality and harmonics of a consumer in two operating cycles with large non-linear loads into operation. This is just an assumption that presence of non-linear loads will pollute power. But actually the consumer might not have used those loads during the billing period.

These inaccuracies can be overcome if the energy meter installed is able to measure the Total Harmonic Distortion (THD) by itself, periodically and provide the data at the time of billing. This work focuses primarily on an IoT based smart meter with harmonic analysis [5].

This project is undertaken keeping in mind the **Smart City** projects and smart grid projects implemented in our country. A smart city is an urban area that uses different types of electronic data collection sensors to supply information which is used to manage assets and resources efficiently.

In this work, the next chapter deals with the instantaneous power calculation method. Chapter 3 deals with the components to be used, their properties and their calibration. Chapter 4 deals with the experimental setup of the module and trials with inductive and nonlinear loads. Chapter 5 deals with the comparison of the experimental setup with standard meters. The last chapter deals with the further improvement of this meter that we are working at present.

OBJECTIVES:

1. To develop a low cost domestic energy meter, **ATS SMART METER** (this name will be used to mention the developed meter) to provide voltage, current, active power, reactive power, power factor, units consumed, etc.
2. To incorporate harmonics measurement and maximum demand pattern study and control the loads accordingly.
3. To make way for consumers to do energy auditing and also to make provisions for this data to be available to the power supplier by interfacing IoT.

CHAPTER 2

INSTANTANEOUS POWER CALCULATION METHOD

Instantaneous power concept is used in calculating the total real power consumed by the appliances in the home. It is the most accurate method in calculating AC power. The results are always true in all kinds of loads; resistive, inductive, capacitive and even the modern harmonics-rich nonlinear loads. It is the product of instantaneous voltage and instantaneous current across an element. By calculating the active power all the other parameters can be calculated by basic formulae.

2.1 RESISTIVE LOADS:

Incandescent light bulbs, kettles, irons, electric water heaters, electric cookers are all quite straightforward. They use all the energy given to them. They are resistive loads, which mean their current draw is equal to the voltage divided by their resistance (Ohm's Law). A purely resistive load gives a voltage and current waveform output similar to the Fig 2.1.

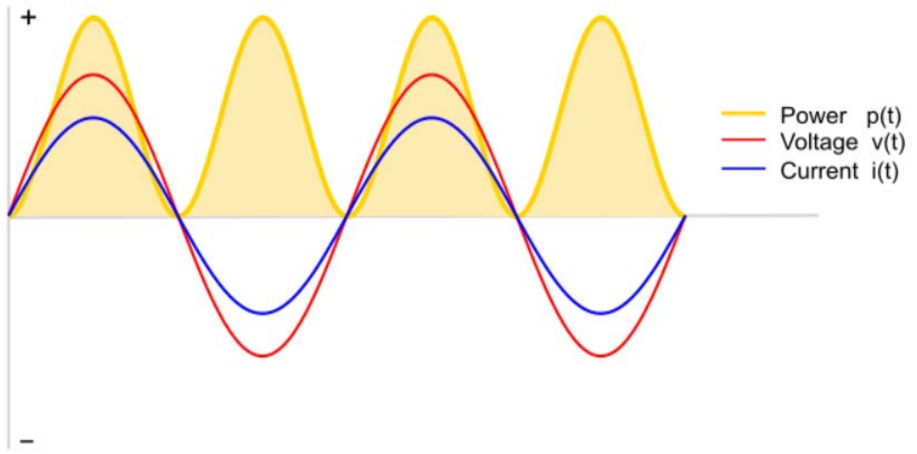

Fig 2.1: Voltage and current phase relationship for a resistive load

The yellow line is power at a given time (at any given instant it's called instantaneous power) which is equal to the product of the voltage and current at a given time. The power is always positive. In this case, the positive direction is energy flowing to the load.

2.2 PARTIALLY REACTIVE LOADS:

Appliances like fridges, washing machines, pillar drills and arc welders are not as straightforward as these appliances take in a certain amount of energy, then release some energy back into the mains supply. These have inductive (e.g. motors) or capacitive (e.g. arc welders) components in addition to the resistive component. A partially inductive load gives a voltage and current waveform output similar to the Fig 2.2.

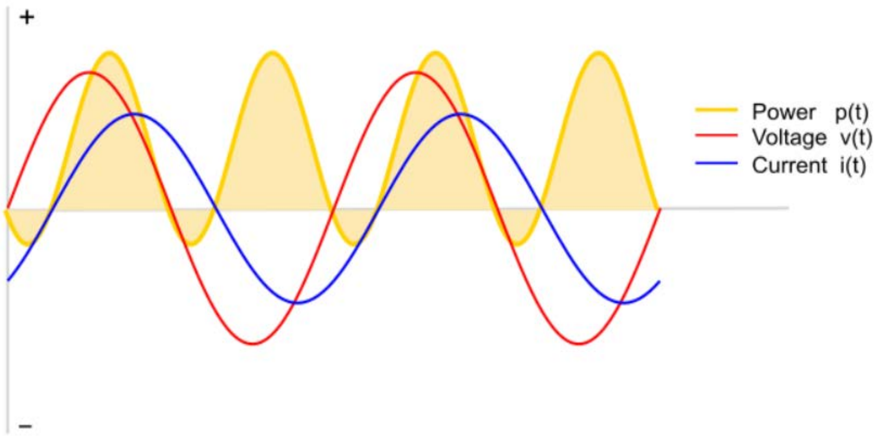

Fig 2.2: Voltage and Current phase relationship in a partially reactive load

2.3 NON-LINEAR LOADS:

Today, non-linear loads make up a large percentage of all electrical demand. Rectified input, switching power supplies and electronic lighting ballasts are the most common single-phase non-linear loads. Their current draw often looks like the Fig 2.3.

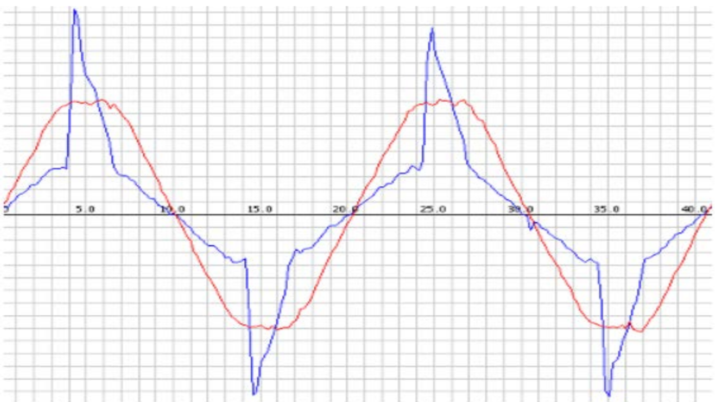

Fig 2.3: Voltage and Current relationship in a non-linear load

2.4 BLOCK DIAGRAM OF POWER CALCULATION:

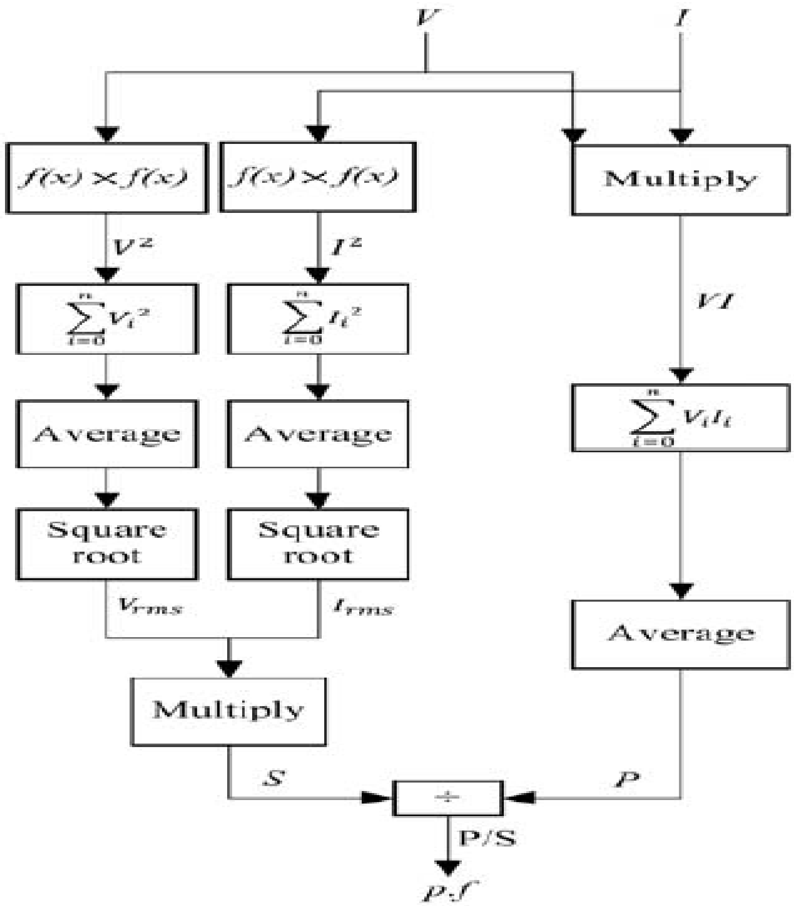

Fig 2.4: Block diagram of power calculation

The voltage and current waveforms are sampled every 390 us for 10 cycles (IEEE 519-2014 standard). During the first 5 cycles, voltage is monitored and 256 samples are obtained. During the next 5 cycles, current is monitored and 256 samples are obtained. The phase shifts due to sensors are corrected and the two waveforms are multiplied sample by sample to obtain real power. The block diagram of power calculation is followed and all the parameters related to power measurement are computed.

Then 256 point FFT is applied for voltage and current waveforms and harmonics up to 25^{th} order is calculated. Maximum demand is determined for every ‘x’ minutes (usually 15 min), according to the norms followed in a particular region.

2.5 METHODOLOGY:

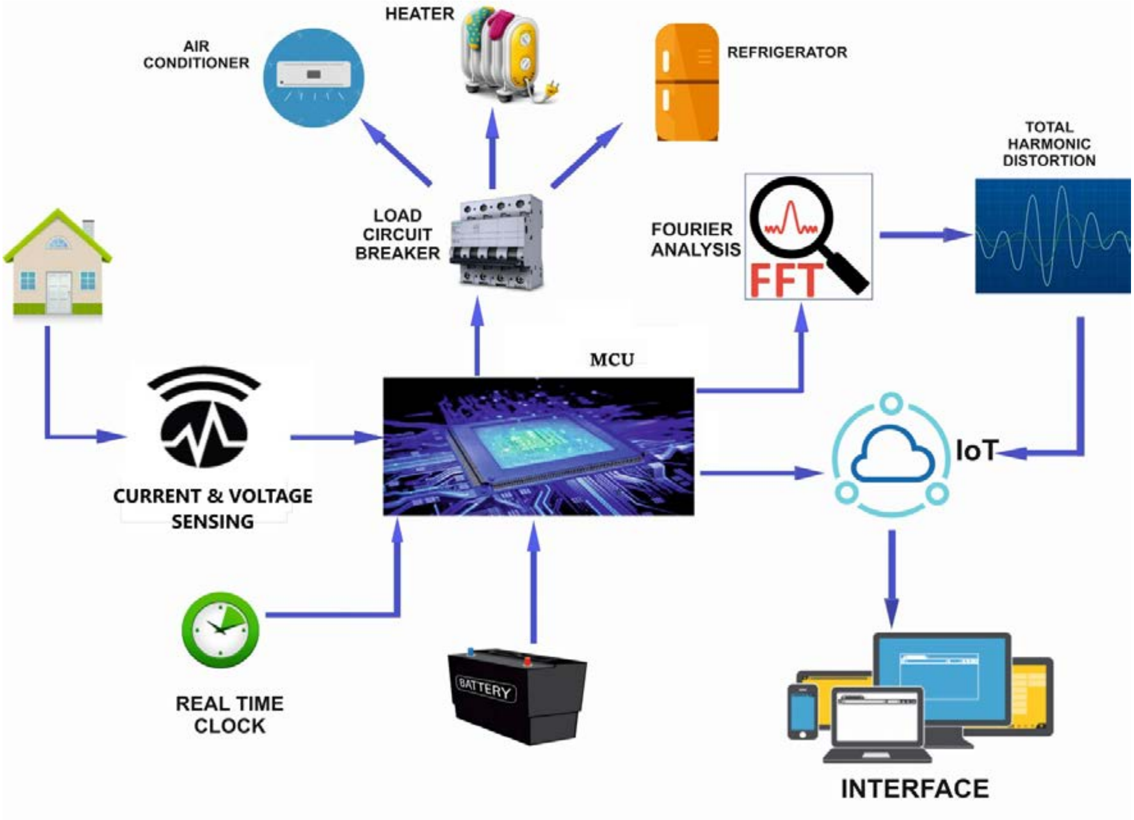

Fig 2.5: Block Diagram of the proposed concept.

Current sensor (ACS712) and voltage sensor (ZMPT101) will be the main sensing elements used. Computation of various parameters like active power, reactive power, power factor and harmonics can be done by energy measurement ICs such as ADE9153, ADE7880, etc., which have inbuilt DSP processor. But we are using the microcontroller itself for this purpose which saves the additional cost.

The output from the voltage and current sensor is given to the MCU which process the data and displays the information in an LCD. For this purpose ATMEGA 2560 is used and the parameters are displayed in a 20x4 LCD.

The communication can be established by a GSM or a Wi-Fi module. We are using a Wi-Fi shield called ESP8266. Load break switches are to be incorporated to control certain loads in accordance to energy consumption. IoT forms a hub for this system interface and takes care of remote monitoring and control. The data is uploaded to “ThingSpeak”, which is an open IoT platform with MATLAB analytics.

CHAPTER 3

COMPONENTS USED IN THE ENERGY METER

3.1 VOLTAGE SENSOR:

Electrical voltage sensors measure AC and/or DC voltage levels. They receive voltage inputs and provide outputs as analog voltage signals, analog current levels, switches, or audible signals. They can also provide frequency and modulated frequency outputs.

Fig 3.1: ZMPT101B

The voltage sensor used is ZMPT101B as shown in Fig 3.1. It is designed to measure the maximum AC voltage that is less than 250 VAC. this circuit uses a differential attenuator after the 230 VACrms with tolerance less than 5 VACpp. The output waveform (5 VAC) of the circuit is riding on DC voltage as an offset (about 2.5 V) and the amplitude can be adjusted by potentiometer but not greater than 5 V. The output of the circuit is connected directly to the ADC pin of the microcontroller.

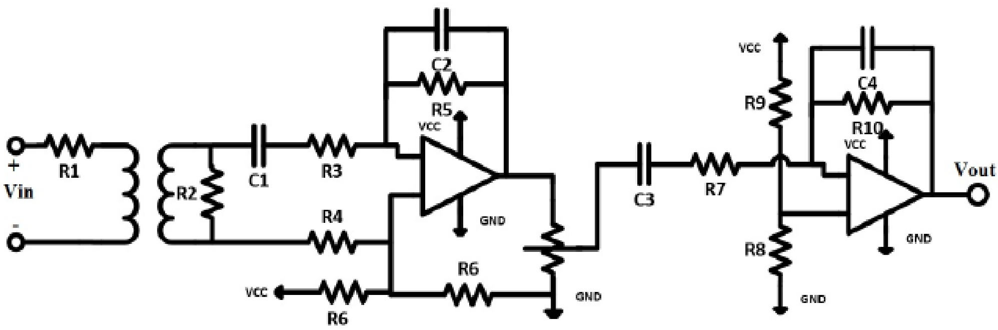

Fig 3.2: Voltage sensor circuit – A band pass (~50 Hz)

The voltage sensor circuit design is based on three stages:

1. A ZMPT101B current transformer (Interplus Industry Co. Ltd., Shenzhen, China) with low impedance load. The ZMPT101B is a small size current transformer with good consistency and isolation for voltage measurements.

2. Two stages of band pass – amplifier are based on LM358IC. This chip consists of two operation amplifiers with the properties of:

- Low power consumption
- A wide single power supply (3 V to 32 V)

Parameter	Value
Turns Ratio	1000:1000
Primary and Secondary Current	2 mA and 2 mA
Dielectric Level	3000 VAC/min
Frequency Range	50~60 Hz
Phase Angle Error	$\leq 20°$, (50 Ω)

Table 3.3: Main properties of ZMPT101B

3.2 CURRENT SENSOR:

A current sensor is a device that detects electric current in a wire, and generates a signal proportional to that current. The generated signal could be analog voltage or current or even a digital output. The generated signal can be then used to display the measured current in an ammeter, or can be stored for further analysis in a data acquisition system, or can be used for the purpose of control.

Fig 3.4: ACS712

The current sensing circuit is based on the Allegro ACS712 IC sensor as shown in Fig 3.4. The ACS712 IC is a linear current sensor used for measuring AC and DC currents. This device comes in three types from the manufacturer according to the maximum current sensed (±5, ±20, and ±30 A). We have used the ACS712-30A current sensor. The ACS712-30A can measure currents up to ±30 A and with 66 mV/A output sensitivity on a +5 V DC.

The main properties of the ACS712 chip are available from its datasheet. It also provides a curve of relation between the DC input voltage and measuring current which is as shown in Fig 3.6.

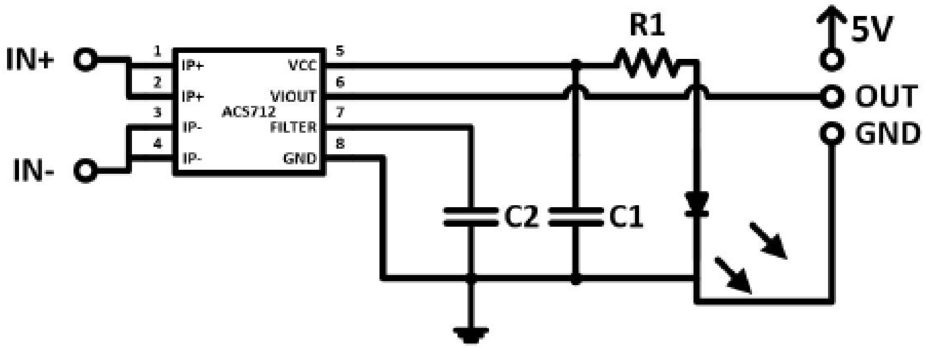

Fig 3.5: Current sensor circuit

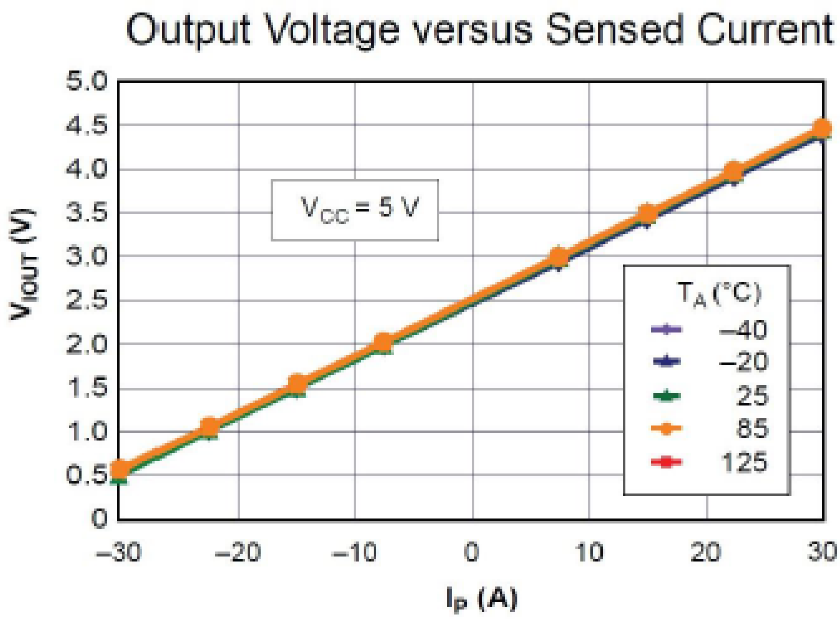

Fig 3.6: The ideal curve of measuring current of ACS712 (Imax = 30 A)

3.3 THE MICROCONTROLLER:

A microcontroller (MCU for microcontroller unit, or UC for μ-controller) is a small computer on a single integrated circuit. In modern terminology, it is similar to, but less sophisticated than, a system on a chip or SoC. A SoC may include a microcontroller as one of its components. A microcontroller contains one or more CPUs (processor cores) along with memory and programmable input/output peripherals. Program memory in the form of ferroelectric RAM, NOR flash or OTP ROM is also often included on chip, as well as a small amount of RAM. Microcontrollers are designed for embedded applications, in contrast to the microprocessors used in personal computers or other general purpose applications consisting of various discrete chips.

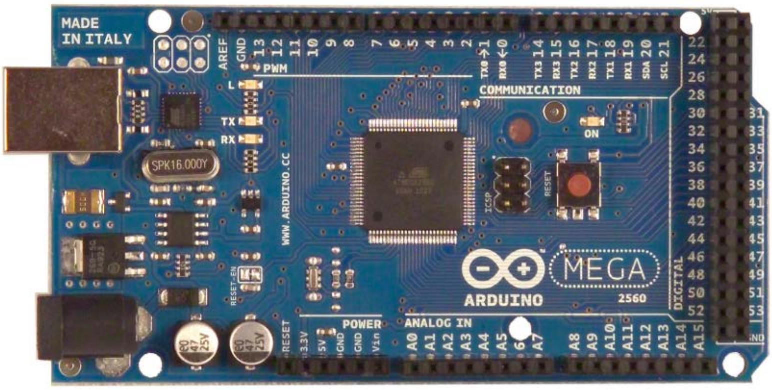

Fig 3.7: Arduino 2560

The Fig 3.7 shows Arduino MEGA 2560. The Arduino MEGA 2560 is designed for projects that require more I/O lines, more sketch memory and more RAM. Since we have to apply 256 point FFT for voltage and current waveforms, a larger flash memory is required. MEGA 2560 has 8 kB of flash memory which is enough for this application. The table 3.8 shows the specifications of Arduino MEGA 2560.

Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limit)	6-20V
Digital I/O Pins	54 (of which 15 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	20 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	256 KB of which 8 KB used by bootloader
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz

Table 3.8: Arduino MEGA 2560 properties

3.4 COMMUNICATION MODULE:

NodeMCU is an open source IoT platform. It includes firmware which runs on the ESP8266 Wi-Fi SoC from Espressif Systems, and hardware which is based on the ESP-12 module. The term "NodeMCU" by default refers to the firmware rather than the development kits. The firmware uses the Luascripting language. It is based on the eLua project, and built on the Espressif Non-OS SDK for ESP8266.

Fig 3.9: ESP8266

The ESP8266 is a low-cost Wi-Fi microchip with full TCP/IP stack and microcontroller as shown in Fig 3.9. The table 3.10 shows the specifications of ESP8266.

Specifications	ESP8266
MCU	Xtensa® Single-Core 32-bit L106
802.11 b/g/n Wi-Fi	Yes, HT20
Bluetooth	None
Typical Frequency	80 MHz
SRAM	160 kBytes
Flash	SPI Flash , up to 16 MBytes
GPIO	17
Hardware / Software PWM	None / 8 Channels
SPI / I2C / I2S / UART	2/1/2/2
ADC	10-bit
CAN	None
Ethernet MAC Interface	None
Touch Sensor	None
Temperature Sensor	None
Working Temperature	- 40℃ ~ 125℃

Table 3.10: Specifications of ESP8266

CHAPTER 4

EXPERIMENTAL SETUP OF THE DEVELOPED METER

The voltage sensor is connected across live and neutral terminals directly. It is powered using the microcontroller and then the output waveform is viewed through a digital oscilloscope. The potentiometer is adjusted to set the required voltage and the sensor is calibrated using a standard meter. The same procedure is done for the current sensor, which is calibrated based on its sensitivity. The two sensor outputs are given to the ADC pins of the microcontroller. A 20x4 LCD is interfaced with the microcontroller whose display can be flipped by a push button. The Wi-Fi shield is also interfaced with the microcontroller.

A rheostat connected in series with a variable inductance forms the first load. Current enters through the rheostat, passes through the variable inductance and then through the current sensor and then into the neutral. Another load consisting of a rheostat in series with a TRIAC and a lamp load is connected in parallel with the first load.

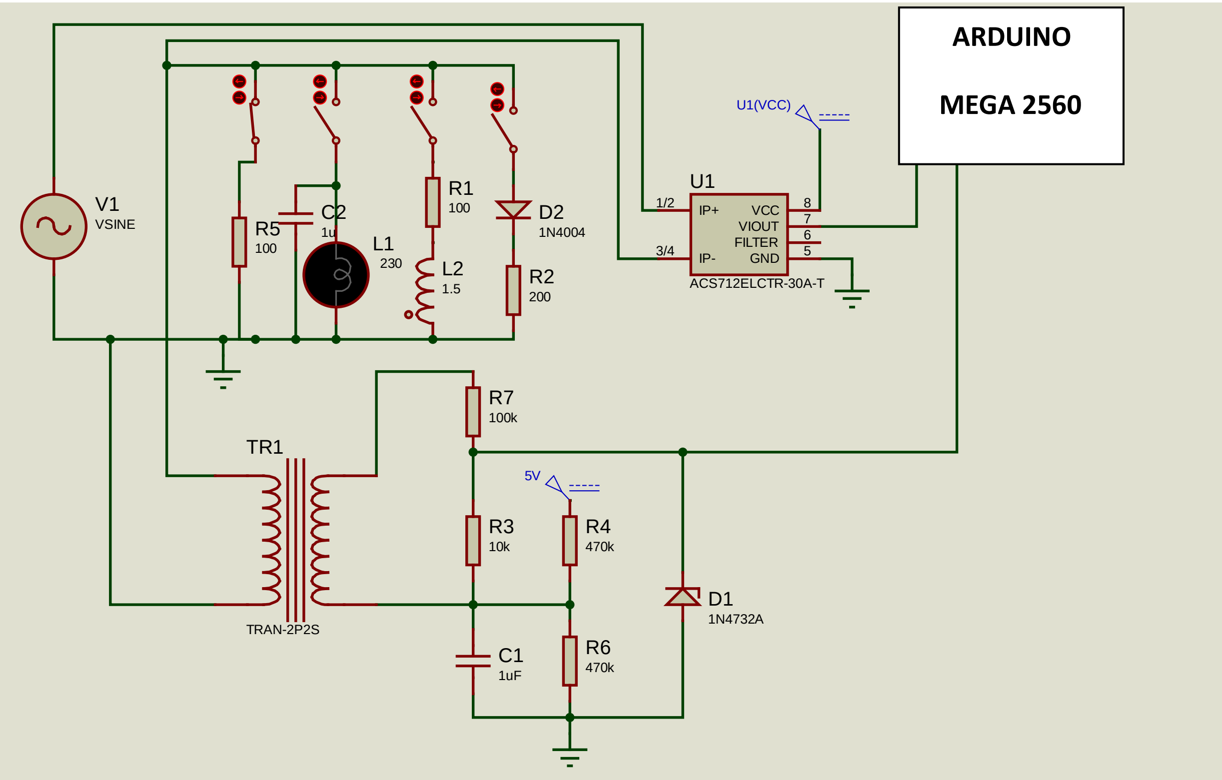

Fig 4.1: Proteus Simulation Model

The Fig 4.2 represents the experimental setup consisting of resistive (R) load using rheostat, inductive (L) load using variable inductor and a lamp load. These loads are connected to form series parallel network for our calculation purpose. The standard meters are used to evaluate our meter. The meters used are Fluke 317, Mecho 5760 and Fluke 434 series – II Power Quality Analyzer.

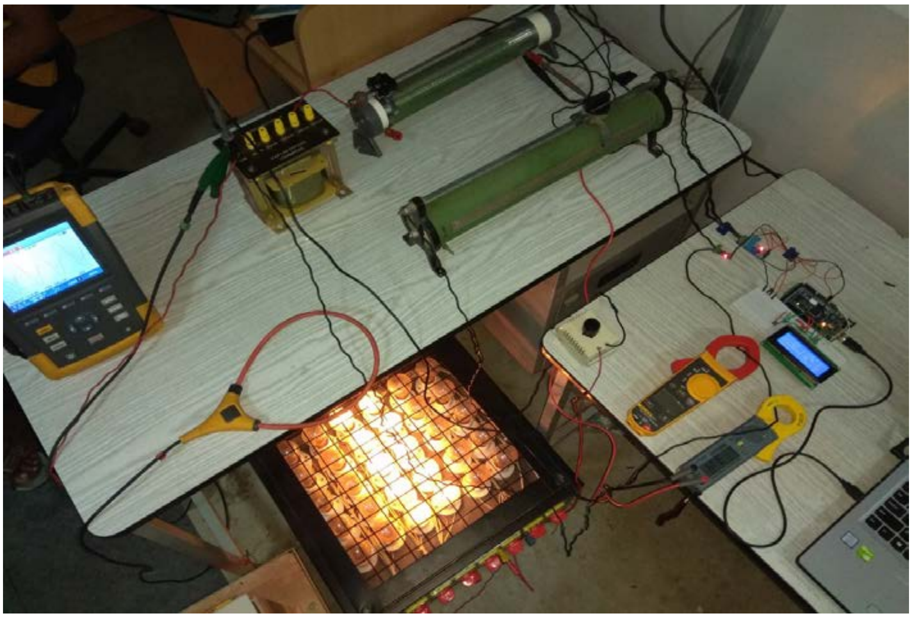

Fig 4.2: Experimental setup with loads and standard meters

The Fig 4.3 shows the ZMPT101 a voltage sensor connected in parallel with load and ACS712 a current sensor connected in series with the load. These are used to monitor the voltage and current for our experimental setup.

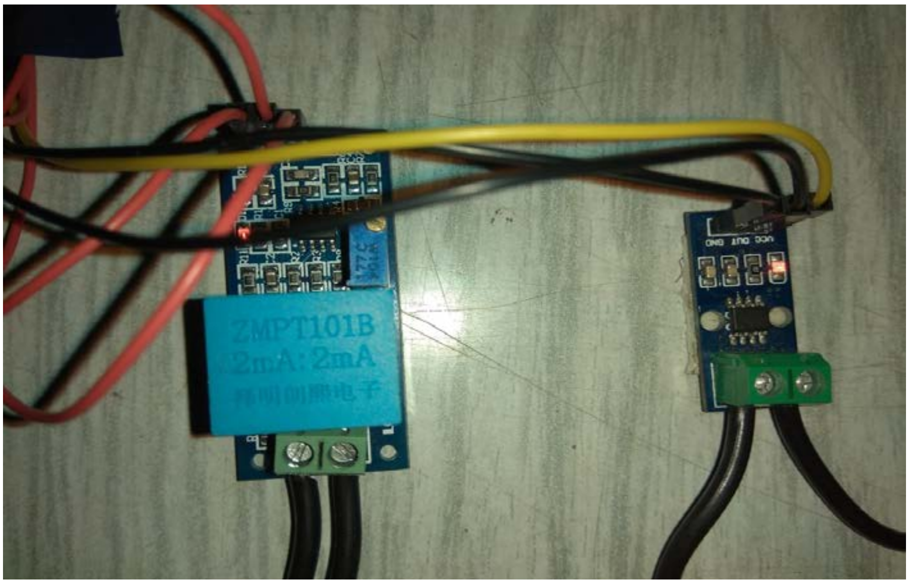

Fig 4.3: Voltage sensor connected across supply and current sensor in series with load

The Fig 4.4 represents the developed energy meter. The image consists of sensors, controller and a LC display.

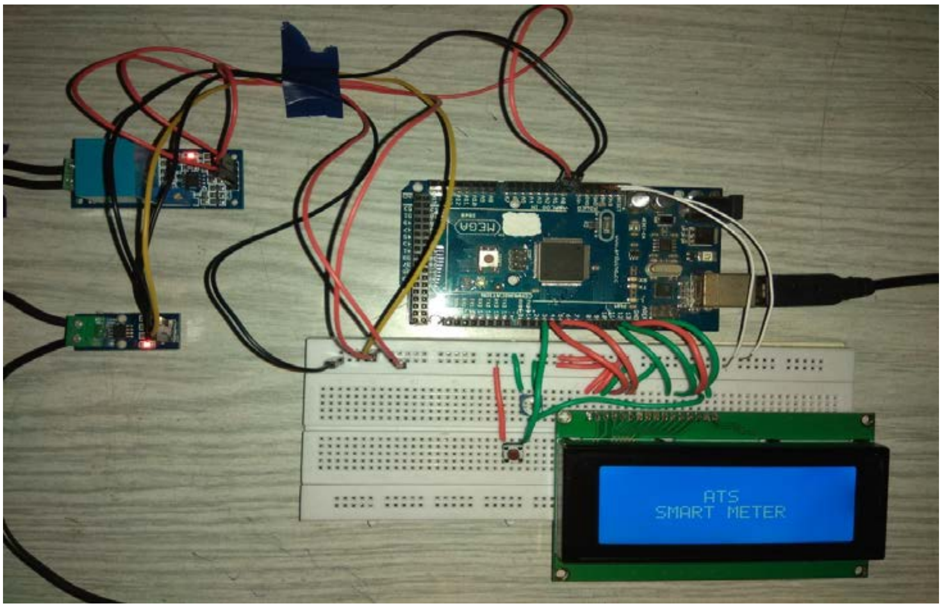

Fig 4.4: The developed energy meter (ATS Smart Meter)

The Fig 4.5 shows the reading of standard meters and developed meters which shows the current values.

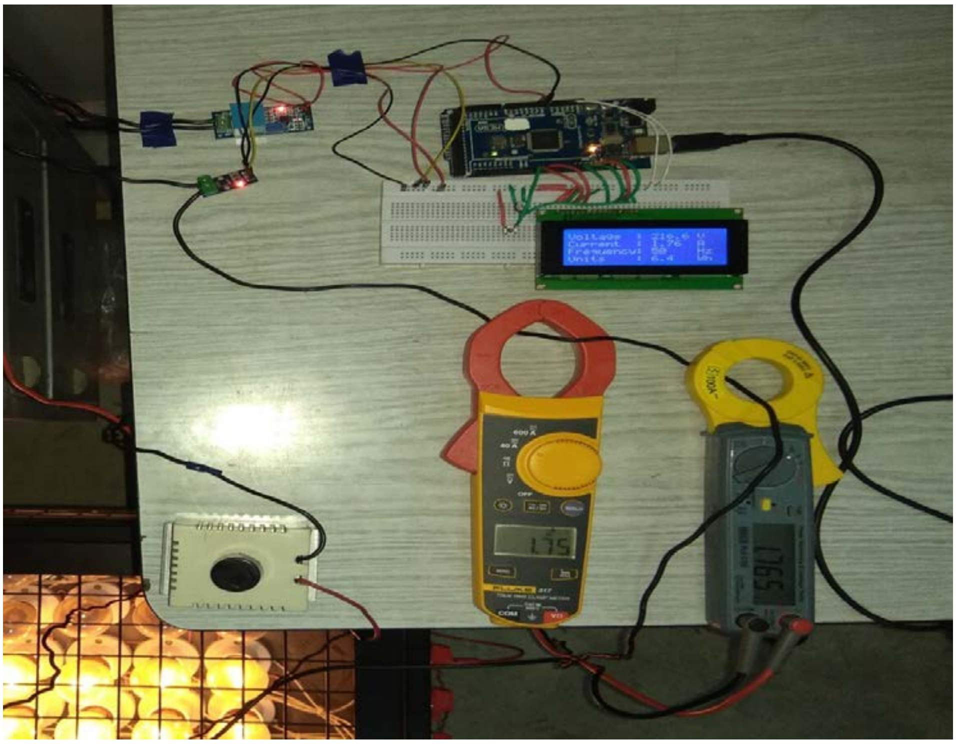

Fig 4.5: Comparison of current value with standard meters

Fig 4.6.: Calibrating the voltage and current sensors

The Fig 4.7 shows the all the parameters computed and displays it in serial monitor. The parameters are Irms. Vrms, P (W), Q (Var), S (VA), VTHD, ITHD, 25th order of harmonics.

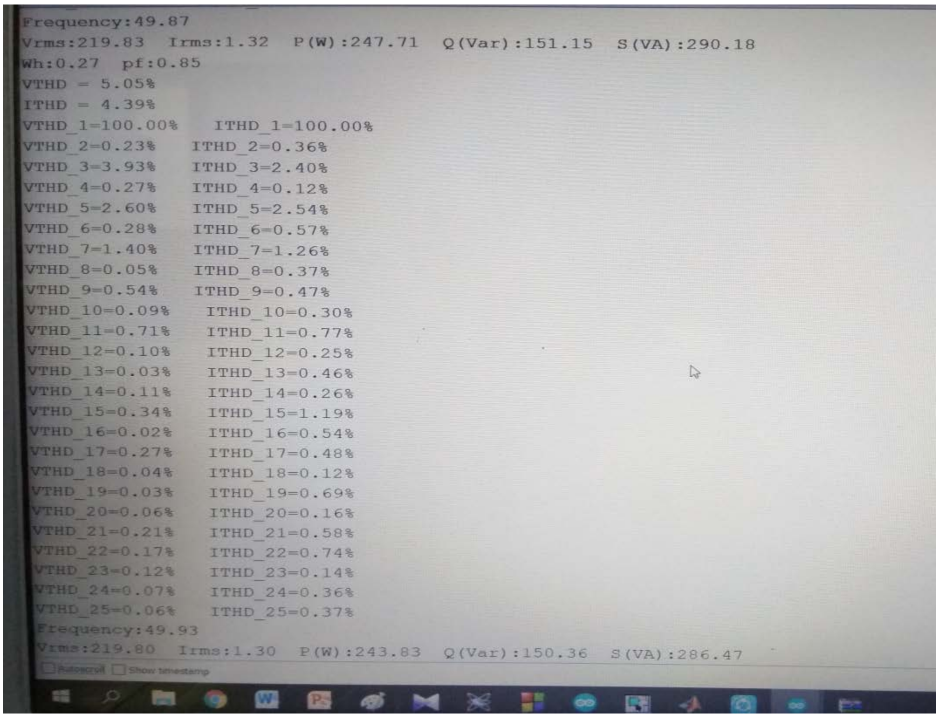

Fig 4.7: Measured values are printed on the serial monitor. Up to 25th harmonics were computed

The Fig 4.8 represents the necessary parameters that are uploaded to the ThingSpeak Cloud platform. The experimental setup sends the data to the ThingSpeak cloud platform for every 15 seconds.

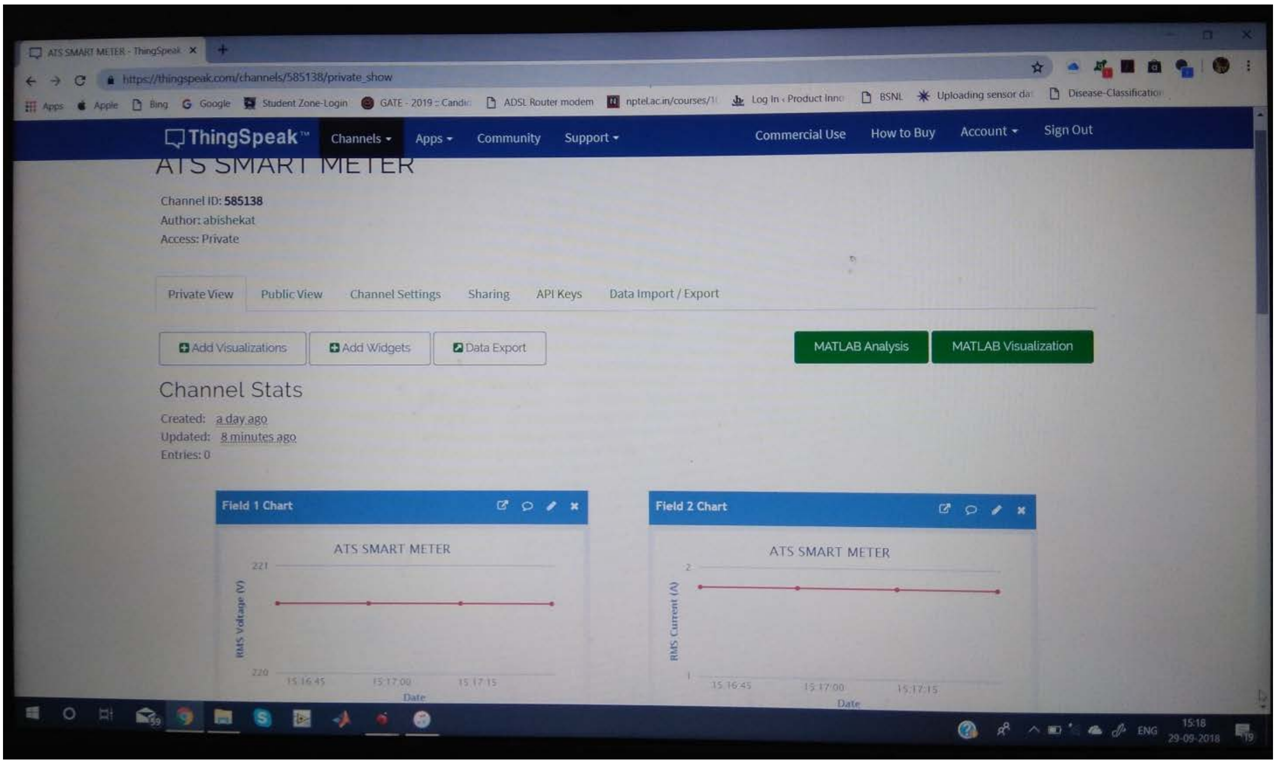

Fig 4.8: ThingSpeak platform where parameters are uploaded

CHAPTER 5

COMPARISON OF RESULTS WITH STANDARD METERS

5.1 TABULATION FOR INDUCTIVE LOAD

PARAMETERS	ATS METER (Our Experimental Setup)	MECO PLH-5760	FLUKE 434	FLUKE 317
Vrms	**221**	220.8	221	220
Irms	**1.31**	1.313	1.7*	1.3
P(KW)	**0.285**	0.287	0.35*	NA
Q(KVAR)	**0.057**	0	0.04*	NA
S(KVA)	**0.29**	0.289	0.37*	NA
P.F	**0.98**	0.99	0.98	NA
V (THD %)	**4.67**	4.5	4.6	NA
V %3	**3.8**	NA	3.7	NA
V %5	**2.31**	NA	2.2	NA
V %7	**1.32**	NA	1.2	NA
V %9	**0.56**	NA	0.6	NA
V %11	**0.49**	NA	0.52	NA
V %13	**0.18**	NA	0.1	NA
V %15	**0.34**	NA	0.3	NA
I (THD %)	**4.08**	3.9	4.1	NA
I %3	**2.83**	NA	2.8	NA
I %5	**2.1**	NA	2.3	NA
I %7	**1.1**	NA	1.1	NA
I %9	**0.33**	NA	0.4	NA
I %11	**0.56**	NA	0.6	NA
I %13	**0.65**	NA	0.4	NA
I%15	**0.45**	NA	0.5	NA

***NOTE**: FLUKE 434 current probe is rated for 6000A operation. Measuring low current causes large error. So the current and power values measured from FLUKE 434 is larger than the actual value

5.2 WAVEFORM FOR INDUCTIVE LOAD:

The waveforms of current and voltage are shown in fig 5.1. Since the power factor is close to 1, the graph shows the voltage and current in phase.

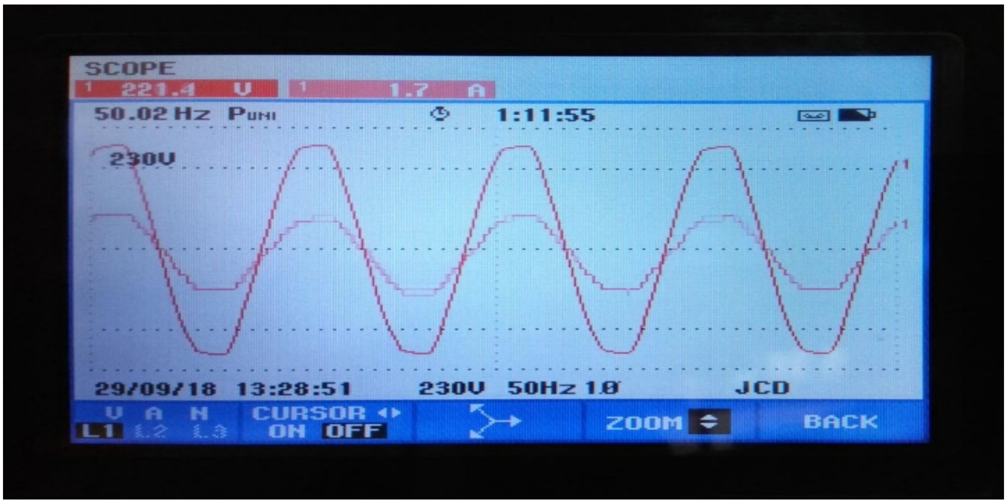

Fig 5.1: Waveform for Inductive Load as seen in Fluke 434 Power Quality Analyser

5.3 CIRCUIT FOR TRIAC WITH LAMP LOAD:

The tabulation in section 5.1 is for the circuit mentioned in Fig 5.2. The lamp was in OFF condition so that only the resistance and inductance act as load. The tabulation for the same circuit with lamp load turned ON is shown in section 5.4.

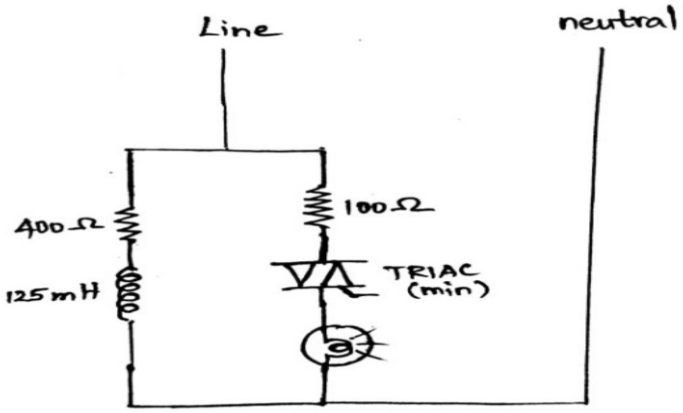

Fig 5.2: Circuit Diagram of the Experimental Setup

5.4 TABULATION FOR TRIAC WITH LAMP LOAD:

PARAMETERS	ATS METER (Our Experimental Setup)	MECO PLH-5760	FLUKE 434
Vrms	**220.65**	220.8	220.1
Irms	**1.82**	1.82	2.2*
P(KW)	**0.351**	0.363	0.45*
Q(KVAR)	**0.192**	0.18	0.12*
S(KVA)	**0.4**	0.4	0.47*
pf	**0.88**	0.89	0.9
V (THD %)	**5.4**	5.4	5.4
V %3	**4.07**	NA	4.2
V %5	**2.97**	NA	2.6
V %7	**1.22**	NA	1.2
V %9	**0.64**	NA	0.6
V %11	**0.68**	NA	0.7
V %13	**0.22**	NA	0.2
V %15	**0.26**	NA	0.3
I (THD %)	**27.63**	27.8	23
I %3	**23.27**	NA	17.4
I %5	**8.035**	NA	7.1
I %7	**6.11**	NA	5.3
I %9	**6.88**	NA	5.8
I %11	**3.56**	NA	3.4
I %13	**3.79**	NA	3.3
I%15	**3**	NA	3.1

***NOTE:** FLUKE 434 current probe is rated for 6000A operation. Measuring low current causes large error. So the current and power values measured from FLUKE 434 is larger than the actual value

5.5 GRAPH FOR TRIAC WITH LAMP LOAD:

Fig 5.3 shows the voltage and current waveforms for TRIAC controlled lamp load. The current waveform is highly distorted and a large harmonics is injected into the system. This is verified from the table in section 5.4.

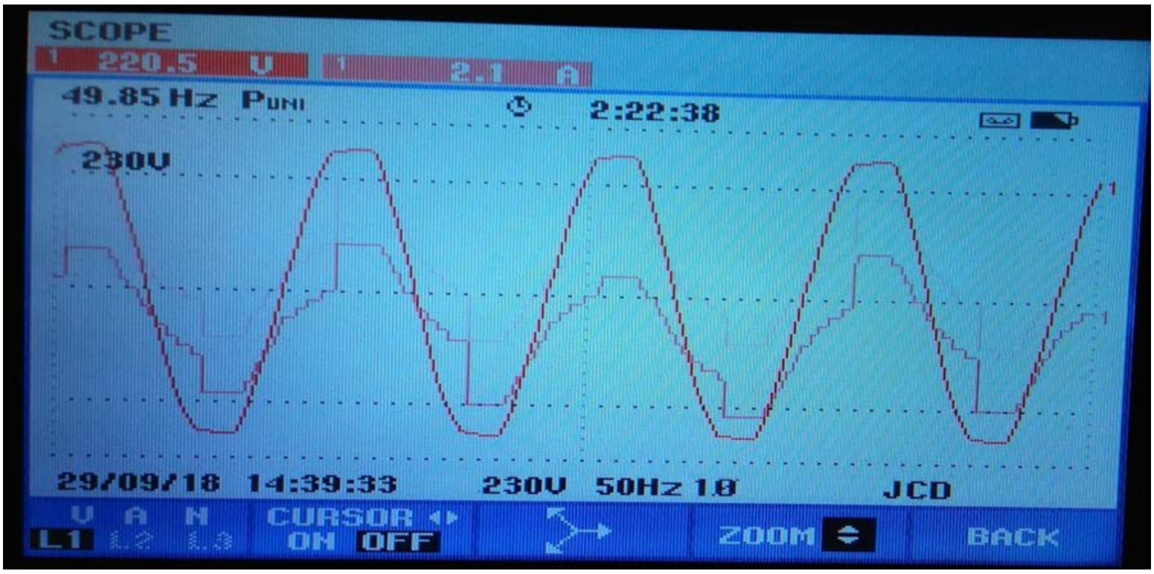

Fig 5.3: waveform for TRIAC with lamp load

5.6 INFERENCE

The maximum deviation of the developed meter from the standard meter was calculed to be **4 %** while measuring less than 5% THD. As the harmonics injected increases, the deviation reduced to less than **2 %.** So the developed meter is fairly accurate when compared with the power quality meters available in the market.

With proper calibration of voltage and current sensing modules, we hope to bring our meter’s deviation to less than 1%

CONCLUSION

The progress in technology about electrical distribution network is a non-stop process. In the present work wireless meter reading system is designed to continuously monitor the meter reading. It avoids the human intervention, provides efficient meter reading, avoids the billing error and reduces the maintenance cost. It displays the corresponding information on LCD for user notification. The advantages of Smart Energy Meter are it requires less manpower, there is no need to chase payments, power theft detection is possible, bill is sent to the consumer with due date, the meter can act as either prepaid or post-paid meter, can minimize the power consumption in a house.

Currently we are working on establishing communication from the consumer to the meter, so that controlling of loads can be done by the meter. Once we are able to send a message from the consumer and decode it properly in the microcontroller, we hope work on incorporating Power Line Carrier communication with this module.

Project Outcomes:

1. To be able to commercially implement this meter as a part of the smart city project undertaken by the government.
2. To make this meter an alternative for the conventional Harmonic Analyzer used by TANGEDCO and other power supply companies.
3. To make way for consumers to do energy auditing and also to make provisions for the power supply company to access the data from this meter.

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APPENDIX - I

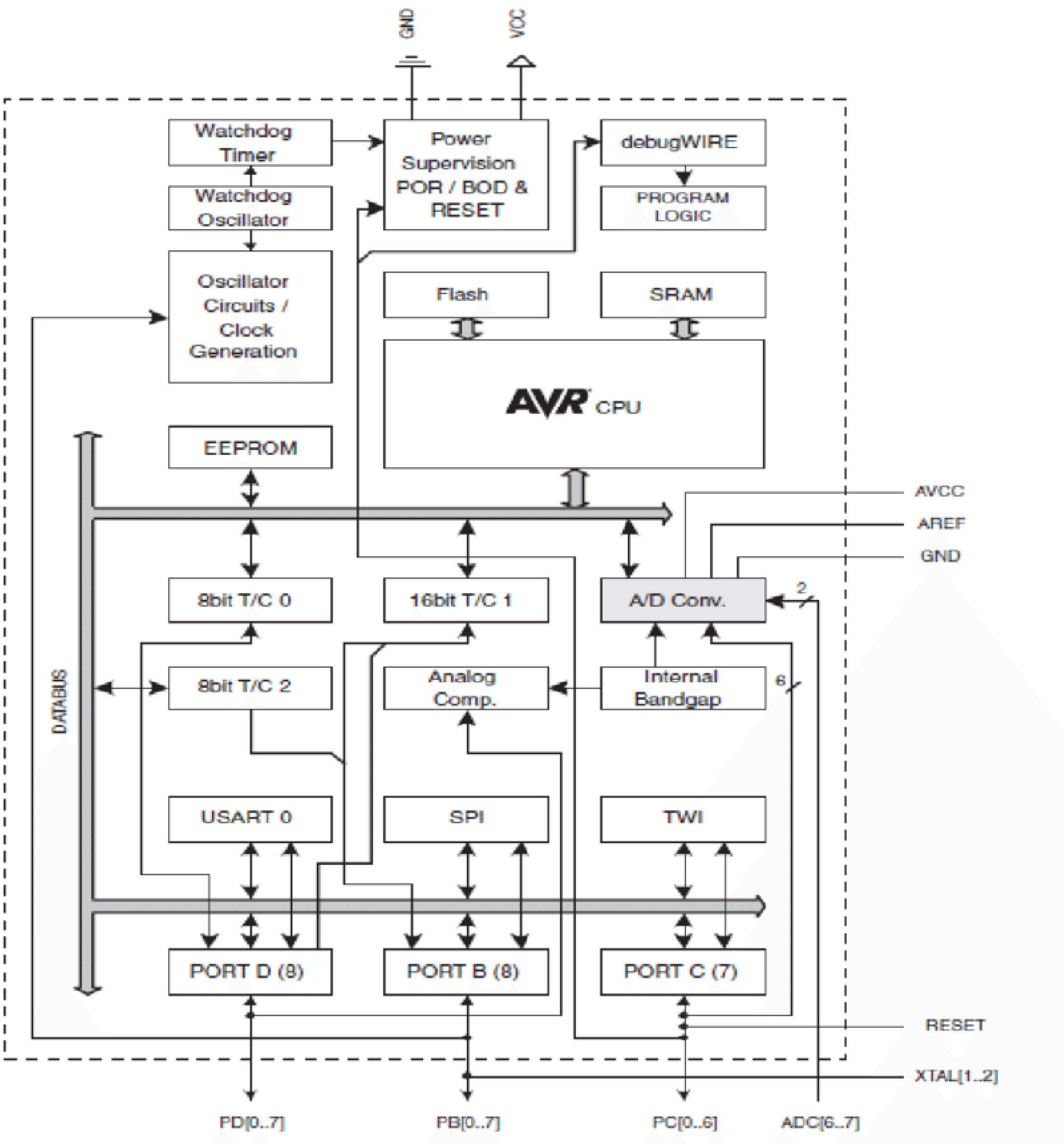

Fig 6.1: Block Diagram of ARDUINO 2560 ATmega

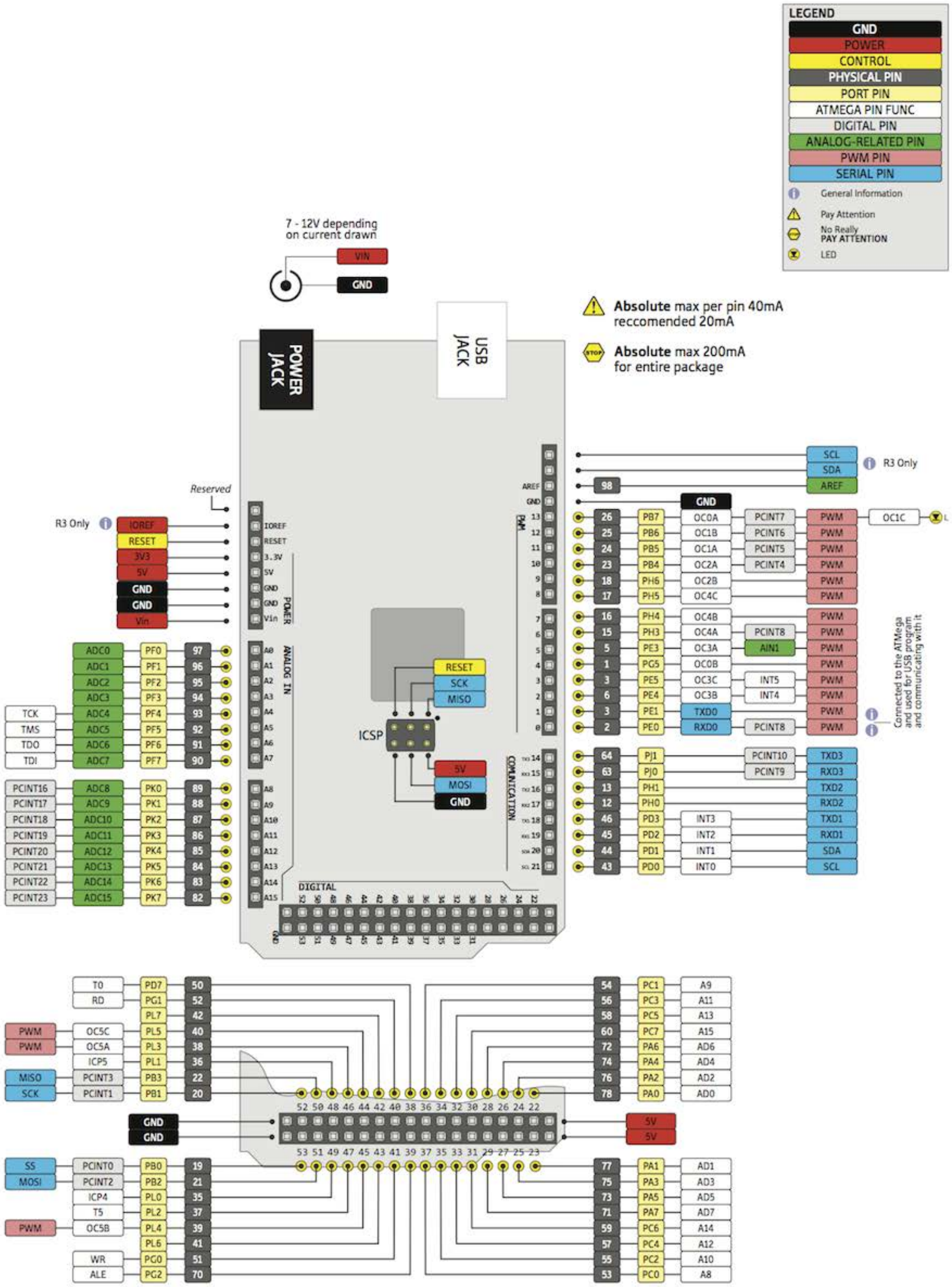

Fig 6.2: PIN Diagram of ARDUINO 2560 ATmega

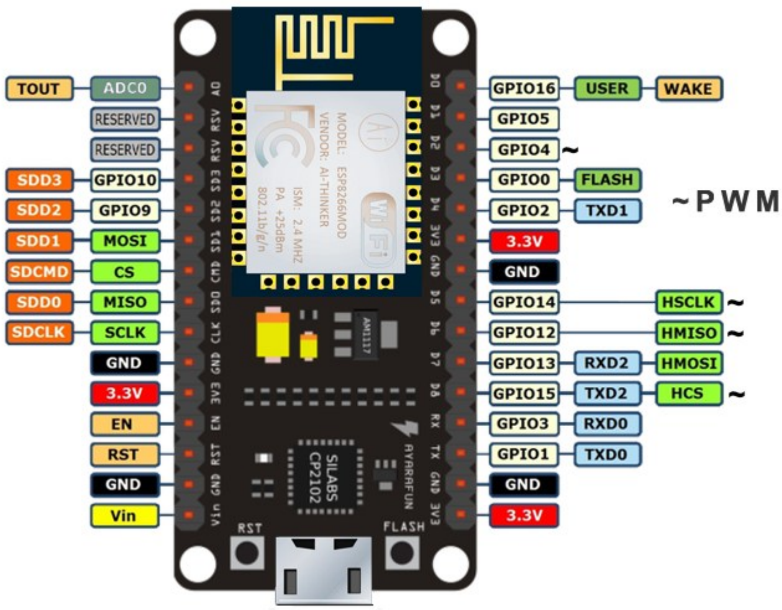

Fig 6.3: NodeMCU pin diagram

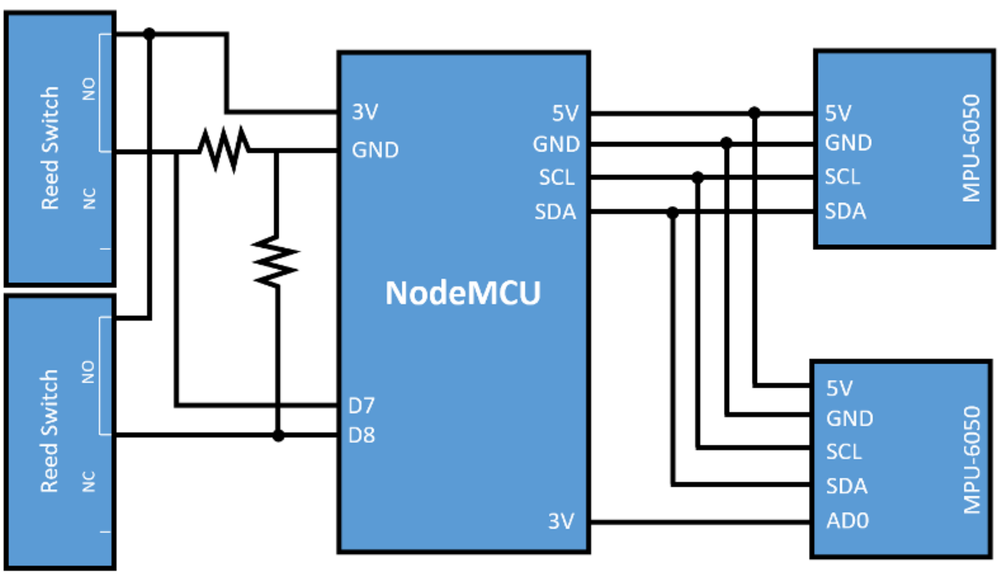

Fig 6.4: Block Diagram of NodeMCU