A Novel Demand Response Management based on Tertiary Frequency Support Using Smart Meter

Seminar Report

submitted in partial fulfillment of the requirements

for the award of degree of

Masters Of Engineering

Submitted By

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DECLARATION

I hereby certify that the work which is presented in dissertation entitled, "*A Novel Demand Response Management based on Tertiary Frequency Support Using Smart Meter*", in fulfillment of the requirements for the award of the degree of **Master of Engineering** in **Electronics and Instrumentation Control**, submitted to Electrical & Instrumentation Engineering Department of Thapar University, Patiala is as authentic record of my own work carried under the supervision of **Mr. Nirbhowjap Singh and Dr. Mukesh Singh**. It refers others researchers work which are duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

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ACKNOWLEDGEMENT

I take the privilege to offer my deepest sense of gratitude to my supervisors **Mr. Nirbhowjap singh and Dr.Mukesh Singh**, for his understanding, encouragement and personal attention which have provided good and smooth basis for my dissertation tenure. I would also like to thank This work would not have been possible without their guidance, support and encouragement. Under their guidance I successfully overcame many difficulties and learned a lot.

I am also thankful to **Dr. Prakash Gopalan**, Director of Thapar Institute of Engineering & Technology University, Patiala for providing the facilities for the completion of M.E. I express my deep sense of gratitude towards **Dr. Ravinder Agarwal**, Head of the Department of Electrical & Instrumentation Engineering, Thapar Institute of Engineering & Technology University, Patiala for constantly encouraging each student to put their best foot forward in whatever field of work they take up, and **Mr. Nirbhowjap Singh**, Associate Professor & PG Coordinator for her motivational approach.

I extend my gratitude to the researchers and scholars whose hours of toil have produced the papers that I have used in the dissertation. I further express my indebtedness to my parents who have constantly helped me keep my morale high all through the work.

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Abstract

Frequency support is one of the ways to maintain stability and reliability in the power system. Different frequency control strategies such as turbine-generator control, load frequency control and economic dispatch are being implemented at the grid level. Uncertainty in the power demand makes these traditional control system less efficient. Demand side response is an appealing alternative method which can be utilized to control frequency at the consumer end. In such schemes, smart meters may play a crucial role for real-time implementation of demand side control. It will also help to control frequency, which reduces the dependency on generation side controller. To overcome these challenges, a measuring scheme has been proposed for smart meters by using PIC16F887 micro-controller. The smart meter is designed to sense the frequency of the grid with less error as compared to existing meters. Moreover, this smart meter controls the load based on these frequency variations. The smart meter, uses Zigbee technology as its communication protocol. It will control the frequency variations and thereby act a smart load cotroller. The proposed metering scheme has been tested at different frequency range and evaluated using various parameters such as voltage and current. The results obtained show that the proposed scheme efficiently reduces the error to a great extent by regulating the power demand optimally.

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List of Abbreviations

PID	Proportional Integrator Differential
IMC	Internal Model Control
AMR	Automatic Meter Reading
SG	Smart Grid
PLM	Peak Load Management
HAN	HOME Area Network
ADC	Analog To Digital Convertor
PWM	Pulse Width Modulation
AG	Aggregator
MSSP	Master Syanchronous Serial Port
SPI	Serial Peripheral Interface
I_2C	Inter Integrated Circuit

Chapter 1

Introduction

1.1 Frequency control in power system

The primary source of concern for the electrical utility companies today has been to maintain an excellent service reliability [1]. To realise this objective, power system is designed to operate at predicted power system condition, so that a balance occurs between the generation and transmission capabilities to full fill customer demands. However, due to the uncertain operating conditions which occurs due to the faults, forced outages or other kind of disturbances causes a shortage of generating capacity [2]. Therefore, it is essential that the insufficient generating capacity is realised quickly based on which the necessary steps are taken to recover system frequency before any kind of major outages occurs in the system [3].

The immediate problem is the declining of power system frequency caused by the condition of overloading affects. It will effect the working condition of power plant auxiliaries [4]. In order to attain balance condition either automatic load shedding method or increasing generation capacity method can be used. The increased generation capacity cannot be accomplished quickly due to two reasons. Firstly, it causes the system frequency to decrease further. Secondly, the insufficient availability of generating capacity to match the additional load demand instantly causes a burden on the power plants. The automatic load shedding at low frequency provides a quick and efficient method of maintaining a balance between generated power and load demand in order to bring system frequency to normal conditions. Load shedding method should be performed automatically and quickly as possible [5].

The load shedding for residential customers using smart meters can be an efficient method in order to control system frequency. Smart meters measures the frequency variation of the grid and act as controller to manage load. The proposed smart meters can be connected to individual homes and power demand can be regulated using a demand response schemes algorithm for load shedding. The Figure 1.1 shows the overview of demand side frequency control. The smart meter is connected to individual customers which will measure the rate of change of frequency more efficiently. These energy parameters measured by smart meter is communicated to distributed control centres from where the data is aggregated for individual customers [6]. Based on this aggregated data, the power consumption and frequency parameters are analysed. When the frequency variation goes beyond a certain limit, the control commands are sent to the smart meters and the load is disconnected via relay network depending upon the set priority of the load. It will bring the frequency of the grid within the limits and increase the reliability of the smart grid.

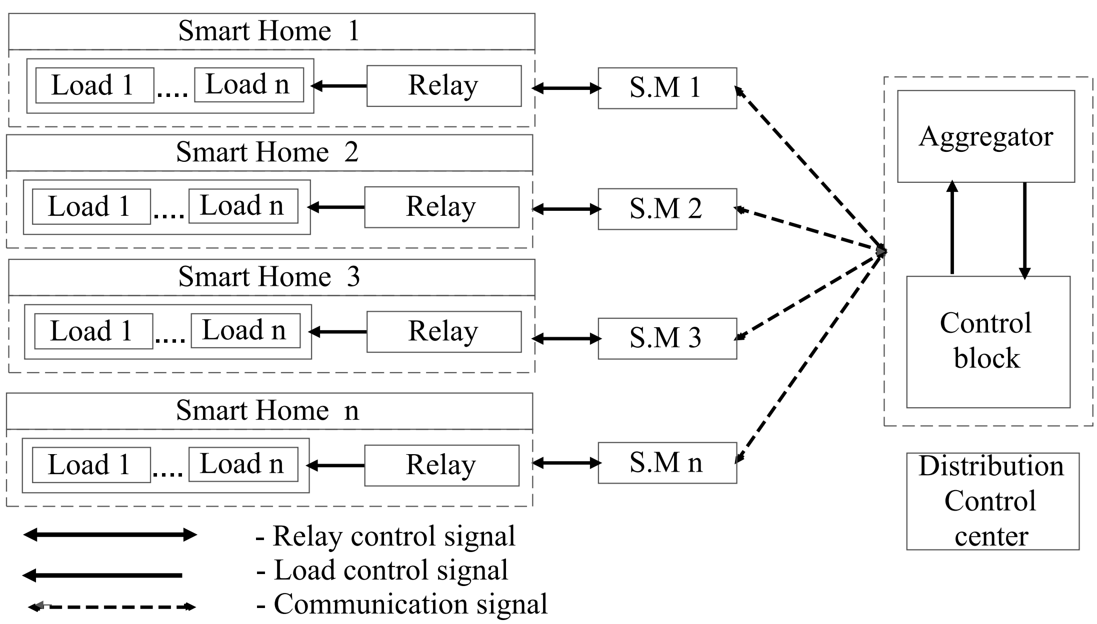

Figure 1.1: Schematic of the proposed system

1.2 Issues of frequency variation in smart grid

The excessive load connected for the available power generation declines the power system output. This causes the system frequency to deteriorate further and hence, resulting in following issues.

- The generators along with its associated prime movers speed begins to fall down.
- The frequency oscillations causes a certain degree of randomness in the operation of under-frequency relays i.e more amount of load is shed than actual required in the system.
- The drop of frequency leads to risk of generation itself. The hydro power plants can remain unaffected even to ten percentage variation in frequency, whereas as thermal power plants are sensitive to these variations and its power deteriorates causing the power output of the motor driven auxiliaries resulting in poor input to turbine-generator set.
- Unpredictable combination of operating conditions causes faults in transmission lines resulting in short circuits, overload tripping and other disturbances leads to an insufficient amount of generating capacity for the load demand.

These frequency variations will have catastrophic effect on the power system. Therefore, it is essential that precautionary measures are taken in advance in order to avoid disturbances in the line and major damage black out conditions in the system.

1.3 Literatue Survey

Smart grid (SG) is an integration of conventional power system with the communication technologies resulting to form a more robust electrical supply network. It helps in saving the energy consumption and reduces the expenses on maintenance of the electrical equipments [7]. The primary objective of SG is to accurately control the flow of power from multiple generators in an interconnected manner. Hence, it helps to maintain a balance between the generation and demand side of power network. When this power demand increases, an imbalance condition occurs which causes the variation in grid frequency. It leads to the failure or tripping of generators or transmission lines and hence, interconnection between the grid is lost. Therefore, a better demand side control schemes must be implemented in SG so that an imbalance and overload condition can be eliminated [8].

To manage these variations in power demand, different control strategies are implemented at the primary, secondary and tertiary level. At primary level, prime mover adjusts the output of the generators so that the frequency of the system does not drift from its normal value when the frequency is upset [9]. At the secondary level, frequency relays are used on transmission lines to adjust these frequency variations when their value falls below a set threshold value [10]. In order to maintain a constant frequency, the active power injected into the system is controlled by the reactive compensation technique [11]. A unified Proportional Integrator Differential (PID) and Internal Model Control (IMC) design method is often implemented which helps to restore the frequency and power exchanges value [12]. At the tertiary level, the load is often redistributed at the demand end to maintain the power output of the generators to a desired value. In the nutshell, SG implements various demand side management schemes at tertiary level to redistribute consumer load and reduces the peak demand. The incentive based program was developed by utility to modify the load of the system. These schemes are consumer friendly as it neither effects the degree of comfort nor impose any financial losses [13].

The demand side management schemes can also be used to control the frequency of the grid by reducing the dependency on the primary frequency control methods. Various researchers have proposed different mechanisms to control the frequency by managing demand response addressed the problem of frequency oscillations which mainly occurred due to variation of power consumption [14]. The authors proposed distributed control algorithm to randomize the response of smart appliances for controlling the frequency [15]. proposed a hybrid hierarchical control method where the frequency has been measured by the individual controllers. These controllers were connected to individual appliances and the control parameters were being decided at the control centre. As per the author in [16], a dynamic controller was developed which investigates method to control the frequency of the system owing to the sudden loss in generation. For better implementation of demand side management schemes, real-time metering information is essential. The real-time metering information is actually the measure of quantity of electricity supplied to end user. So the energy consumption and transportation charges can be calculated based on the metering information for customers energy billing.

Earlier these billing parameters were recorded manually over a set time intervals which lacked accuracy. This has necessitated the development of smart meters having many applications such as Automatic Meter Reading (AMR) which uses two way communication technologies for the development of the programs for better demand side integration. It consists of two important parts i.e communication network with its hardware which enables two way communication and smart meters [17]. Smart meter helps the utility companies to send commands to domestic users for multiple purposes. It includes real-time pricing information, demand response actions and remote service disconnections [18][19]. These real-time information helps in implementation of a better demand response schemes with smart meters playing a vital role. It will enable a better demand management of the distribution grid by reducing electricity losses and improve the quality of supply [20]. The consumers also shift their load based on the incentives given to consumers based on time of use or critical peak price tariff for a Peak Load Management (PLM) [21]. With the prior agreement with end consumers, the utilities are able to manage their load via Home Area Network (HAN) for PLM or frequency-based smart devices [22]. Utilities monitor load profiles and take proactive actions to reduce outages and response time [23]. Consumers can also participate in generation via renewable energy integration which includes the usage of roof top solar power or small windmills [24].

1.4 Research Gap

The ability of the smart meters to control domestic demand during system emergencies can help to control the frequency of the system. The direct load control schemes can be implemented by measuring frequency which is an important parameter measured by smart meters [24]. The control algorithms proposed in the paper are developed using a separate smart controller. But it lacked in variable frequency measurement control for smart meters. Another estimation error technique is used that measures the frequency of the input voltage to control it at demand end [25]. The effect of frequency variations on measurement has not been discussed on hardware part of the smart meters. Differential filtering technique for smart meters was proposed based on newton type algorithm to maintain the frequency of the system with limits [26]. However, the zigbee based communication system was not discussed. The frequency range specified by standards for the smart meter is 50Hz(+/- 5%) with maximum percentage error of 0.5%. The design proposed in this paper has improved this percentage error to 0.4% as compared to the smart meters avialable in the market which is 0.5%. Similarly the voltage range according to standards for smart meters requires measurement error to be not more than 0.7% and has been improved to 0.5% in this proposed design.

1.5 Motivation and Objectives

The demand-side management schemes developed in the past mainly focused on controlling the frequency by using primary and secondary frequency control methods. Smart meter is necessary for better management of frequency implementation of these demand response schemes at tertiary end. This will help to check the frequency variation of the grid and manage the load of the customers. The merits of a new bilateral communicating infrastructure in smart meters will help to observe the frequency of the grid and helps to regulate the customers power demand. It is indicated that frequency control is performed by demand response instead of generation resources which will ease and help customers to participate in energy saving.

1.5.1 Objectives

The main contributions of this paper are summarized as follows:-

- To implement a hardware design of smart meter that measures voltage, frequency and current parameters to enhance its accuracy level for variable frequency.

- Development of demand response schemes by using smart meters to improve the time response by directly disconnecting the load.
- The smart meter is designed to sense the frequency of the grid with less error as compared to existing meters. It will control the frequency variations where smart meter will act as a controller.

1.6 Organatization of Thesis work

- **Chapter1:** Discusses about the introduction of the thesis work.
- **Chapter2:** The hardware design of the smart meter is discussed in this section including the various important components of this design.
- **Chapter3:** The software design module of the smart meter is discussed here including the measurement algorithm and control algorithm.
- **Chapter4:** Discusses about the results obtained by the smart meter measurement and the demonstration the experimental rig.
- **Chapter5:** Discusses about the research objective and future work of this research work.

Chapter 2

System description

Some areas of power system starts to decline when there is more amount of load connected to the system as compared to the available generation. It will cause a drop in frequency of the generation. As the power system frequency decreases further, the power system auxiliaries begin to damage the turbine-generator set of the power plants. To prevent this decline in frequency level, under-frequency relays are used which automatically shed the load in order to balance the load with the available amount of generation. These under-frequency relays are affected by the oscillatory nature of the frequency decay that causes a certain degree of randomness while operating *i.e.*, sometimes more amount of load is shed than actually required. Hence, it is needed to implement a system in which load is precisely dropped in equal increments at all parts of the system instantaneously.

For shedding the load in equal increments precisely in smart grid, smart meters can play an important role to control the frequency of the system. A demand response algorithm is implemented using the smart meter. The smart meters measures the voltage, current and frequency parameters of the individual customers. These parameters are communicated to the distributed control centres via communication protocol where the data is aggregated from various customers. Based on this aggregated data, the power consumption and frequency parameters are analysed. When this frequency variation goes beyond a certain limit, the control commands are communicated to the smart meters and hence, load is disconnected via relay network. This will help to precisely shed the load at equal increments in steps. The priorities of the load will be set which will provide a precise frequency control at tertiary end of the system. This will help to bring the frequency of the grid within limits and increase the reliability of the smart grid.

2.1 Tertiary frequency control by smart meter

Tertiary control is an automatic change in the working points of the loads or generators which are designed in order to redistribute the output power from different generating station. The tertiary control is used to control load which can either be centralised or controlled load shedding program. For centralised load shedding to be implemented with high efficiency, smart meters can play a vital role. It will help to measure the rate of change of frequency with high accuracy level and the dependency on the traditional under-frequency relays can be decreased.

The smart meters connected to the individual customers senses the frequency of the grid with least error in accordance with the smart meter standards. This smart meter has the ability to handle the load based on the frequency variations of the grid. The smart meter connected to the individual customer premises consists of four basic units. These are signal conditioning unit, micro-controller unit, communication unit and the power unit as shown in Figure2. The domestic loads are connected to the smart meter through relay network. The power lines are directly connected to the power supply unit and the smart meter. The power supply provides power supply required by the operational amplifier of the system which requires a continuous supply of +5V, -5V for its operation. The smart meter connected in this system will send a control signal to the relay switching network. The data lines are sent to communication system. The communication medium consists of transmitter, range extender and receiver. This zigbee based communication protocol sends the data through transmitter and range extender to the distributed control centre by the utility. The receiver further sends it to the aggregator where the frequency control commands are sent to the smart meters. The frequency control commands provides load shedding by relay networking based on the set priority of the system.

The smart meter hardware design is developed which consists of a voltage sensing unit, current sensing unit and frequency sensing unit. The hardware design was developed for

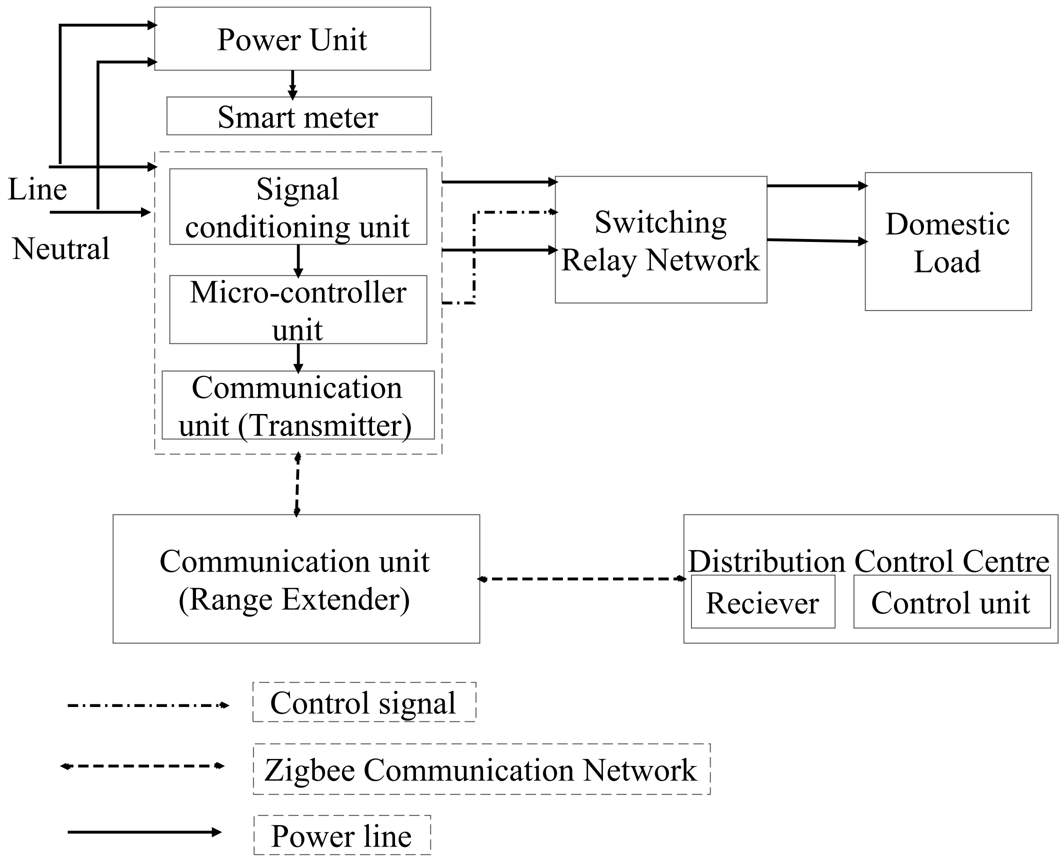

Figure 2.1: Schematic representation of smart meter for frequency control

all these three units which improved the accuracy of the system and the precise measure of the rate of change of frequency detection can be done. It will help to shed the load needed practically to bring the frequency to the set level of 50Hz. The rate of change of the frequency oscillations could be very high and the high rates of decay might occur in the system. So, a smart meter abilities to measure the same voltage value at different frequencies will be helpful for the utility companies to accurately shed the load at equal steps. The micro-controller used PIC16f887 that collected data using these integrated voltage, current and frequency sensing unit. Based on these measurement the algorithm is developed using this micro-controller for the demand side response management. This design decreases the response time of system to measure frequency which results in accurate load shedding.

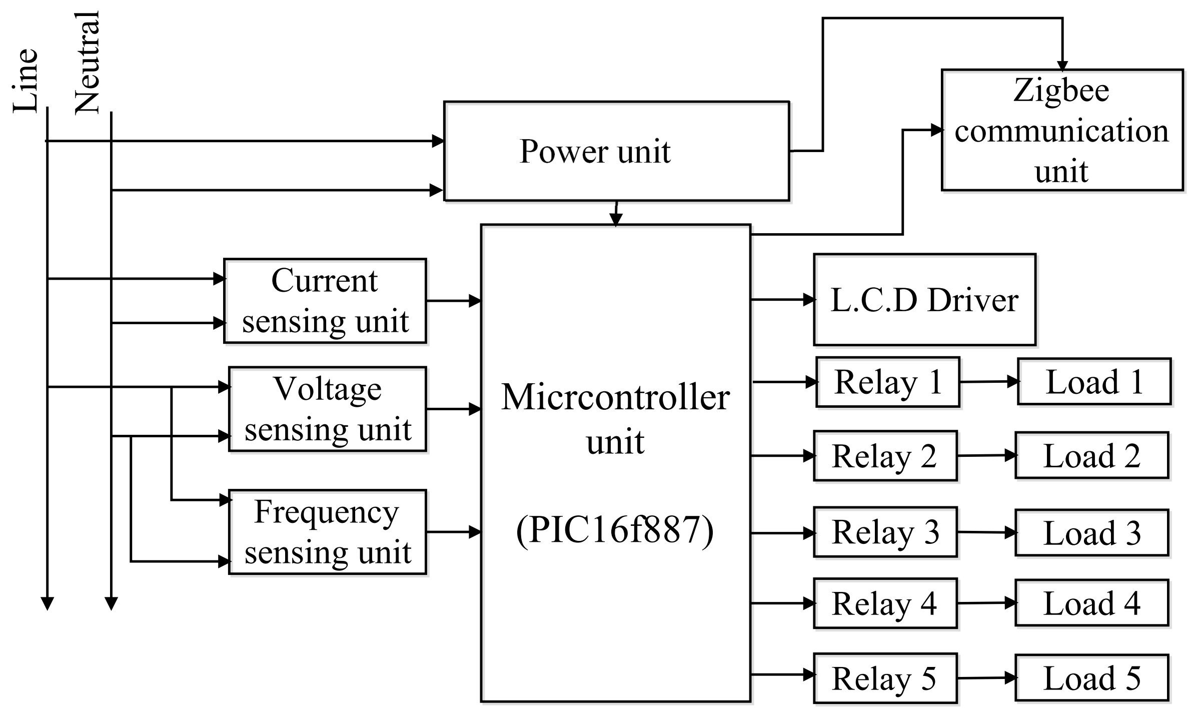

Figure 2.2: Architecture of smart meters

The smart meter design uses 8-bit MCU making it low cost and more efficient as compared to design proposed in [23] for the residential purposes. The 8-bit micro-controller used to design this smart meter is PIC16f887 micro-controller that is designed to measure electrical parameters with most accuracy. The whole digital circuit is protected from power surges using optical isolators. In this section, four units of this hardware design are discussed.

The synchronism of voltage sensing unit with the frequency sensing unit helped to accurately measure the rate of change of frequency decay and at that time accurate frequency measurement is done in order to timely control the frequency of the system. The hardware design of the voltage sensing unit, current sensing unit and frequency sensing unit are explained in the following section.

2.1.1 Current sensing unit

Current sensing unit senses the magnitude of the current flowing in the line and neutral wires. This section consists of a current transformer of transformation ratio 60/5 and a DC offset adder as shown in the Figure 2.3. The output of this section is fed to the microcontroller of the smart meter.

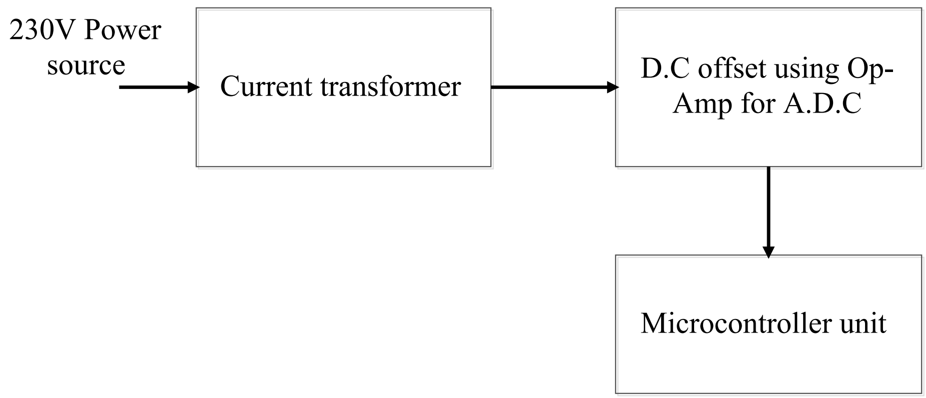

Figure 2.3: Block diagram of current sensing unit

The output voltage of the operational amplifier represented is calculated by the following equation.

$$N_1 * I_1 = N_2 * I_2 \tag{2.1}$$

$$V_{out2} = \frac{R_{21}}{R_{22}} + \left[\frac{(R_{22} + R_{21})}{R_{22}}\right]\left[\frac{(R_{20})}{R_{19} + R_{20}}\right] V_{cc} \tag{2.2}$$

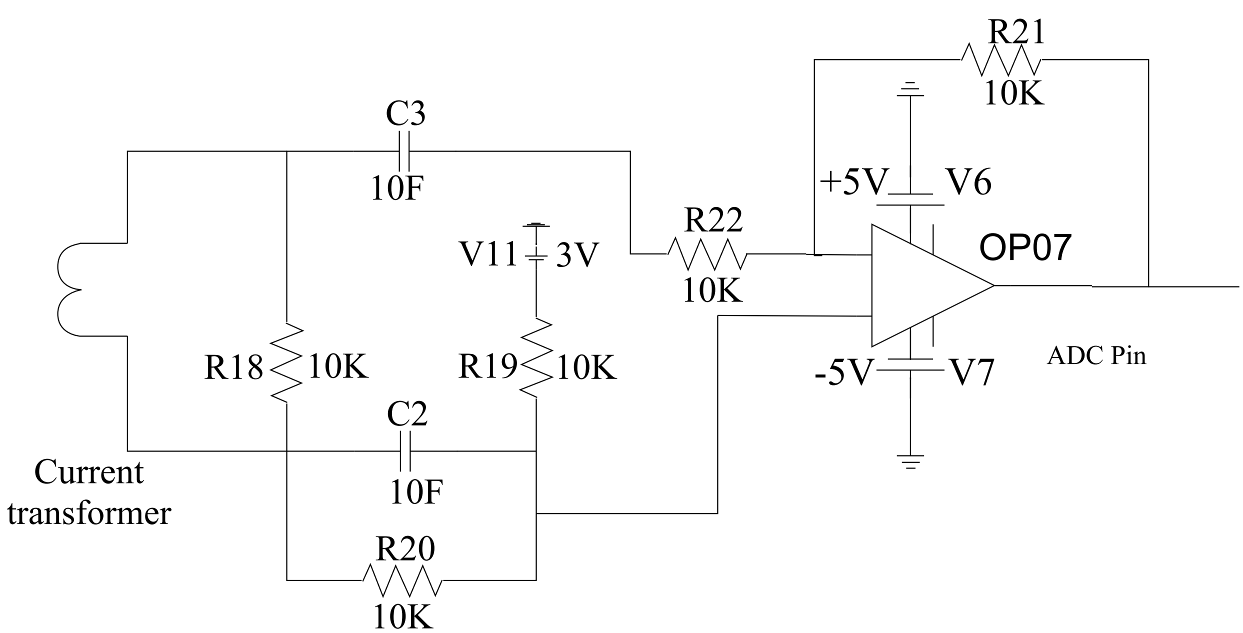

Figure 2.4: Signal Conidtioining circuit of current sensing unit

This output voltage given as an input to the analog to digital converter(ADC) of the micro-controller and hence, the rms value of the current is calculated as shown in the following equations.

$$I_{max} = 1023 \left[\frac{V_{out2}}{5 * \sqrt{2}} \right] \tag{2.3}$$

$$I_{rms} = \frac{I_{max}}{\sqrt{2}} \tag{2.4}$$

This digital output of the ADC is displayed on LCD.

2.1.2 Voltage sensing unit

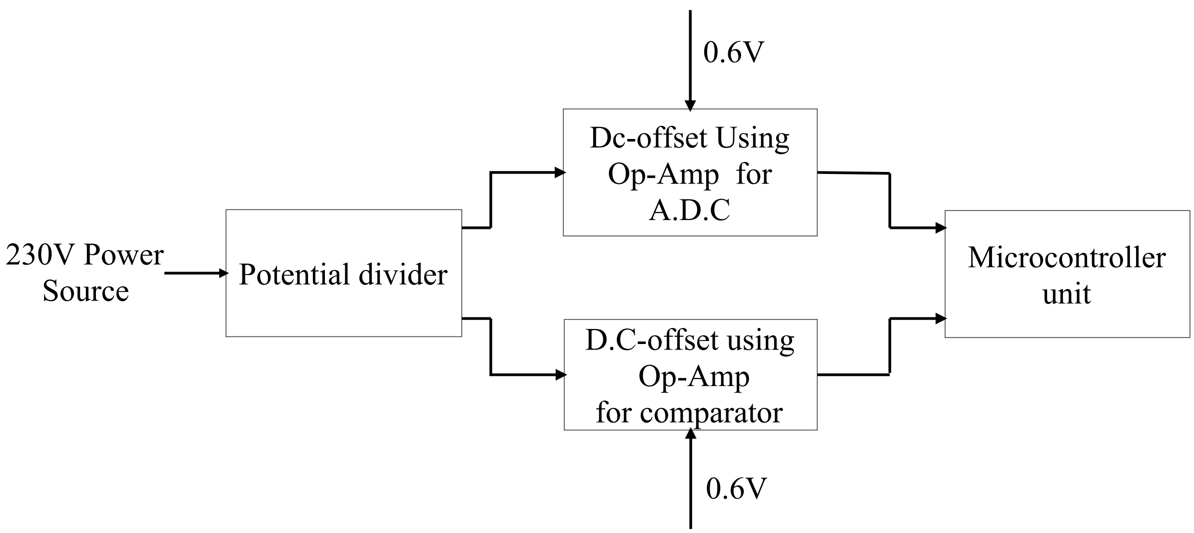

Figure 2.5: Block diagram of voltage sensing unit

In the voltage sensing unit, high input voltage at utility end is stepped down to a lesser magnitude which is further interfaced with the micro-controller of the smart meter. Figure 2.5 shows the block diagram of voltage sensing unit. This unit consists of potential divider circuit, comparator hardware module and A.D.C hardware module which are connected to the input pins of this micro-controller unit. Initially, the magnitude of voltage is scaled down using a potential divider circuit. The stepped down voltage is given as an input to A.D.C and comparator hardware section as shown in the Figure 2.6.

V_{cc} which is set to 5V for both the op-Amp, is connected to variable resistor R_7 .The DC off-set of 0.6V is added to the voltage across operational amplifier as given by the following equation.

$$V_{dc} = V_{cc}\left[\frac{R_{8a}}{R_{8b}+R_{8a}}\right] \tag{2.5}$$

The minimum reference input voltage of the comparator module in micro-controller is 0.6V. It is due to the transistor present in the voltage reference circuit of the comparator module having an activation voltage. The peak to peak voltage tapped across operational amplifier is represented by the following equation.

$$V_{pp} = 2*\sqrt{2}*(1.15*230)*\left[\frac{R2}{R1+R2}\right] \tag{2.6}$$

This output voltage is given as input to non-inverting pins of both the operational amplifiers of ADC and comparator. The maximum magnitude of the signal read by ADC of micro-controller is given by the following equation.

$$V_{max} = V_{pp} + V_{dc} \tag{2.7}$$

This is done so that the maximum output voltage of the signal is not more than 3.3V as represented by the following equation.

$$V_{out1} = V_{max}\left[\frac{R_9+R_6}{R_6}\right] \tag{2.8}$$

The output voltage of the voltage sensing unit is given as input to the ADC of the micro-controller which reads the maximum value of the input voltage and the maximum value of this voltage varies between 0-3.3V and is calculated as shown in the following equations.

$$V_{max} = 1023\left[\frac{V_{out1}}{5*\sqrt{2}}\right] \tag{2.9}$$

Based on this maximum value of the voltage the r.m.s value of the voltage signal is calculated as follows.

$$V_{rms} = \frac{V_{out1}}{\sqrt{2}} \tag{2.10}$$

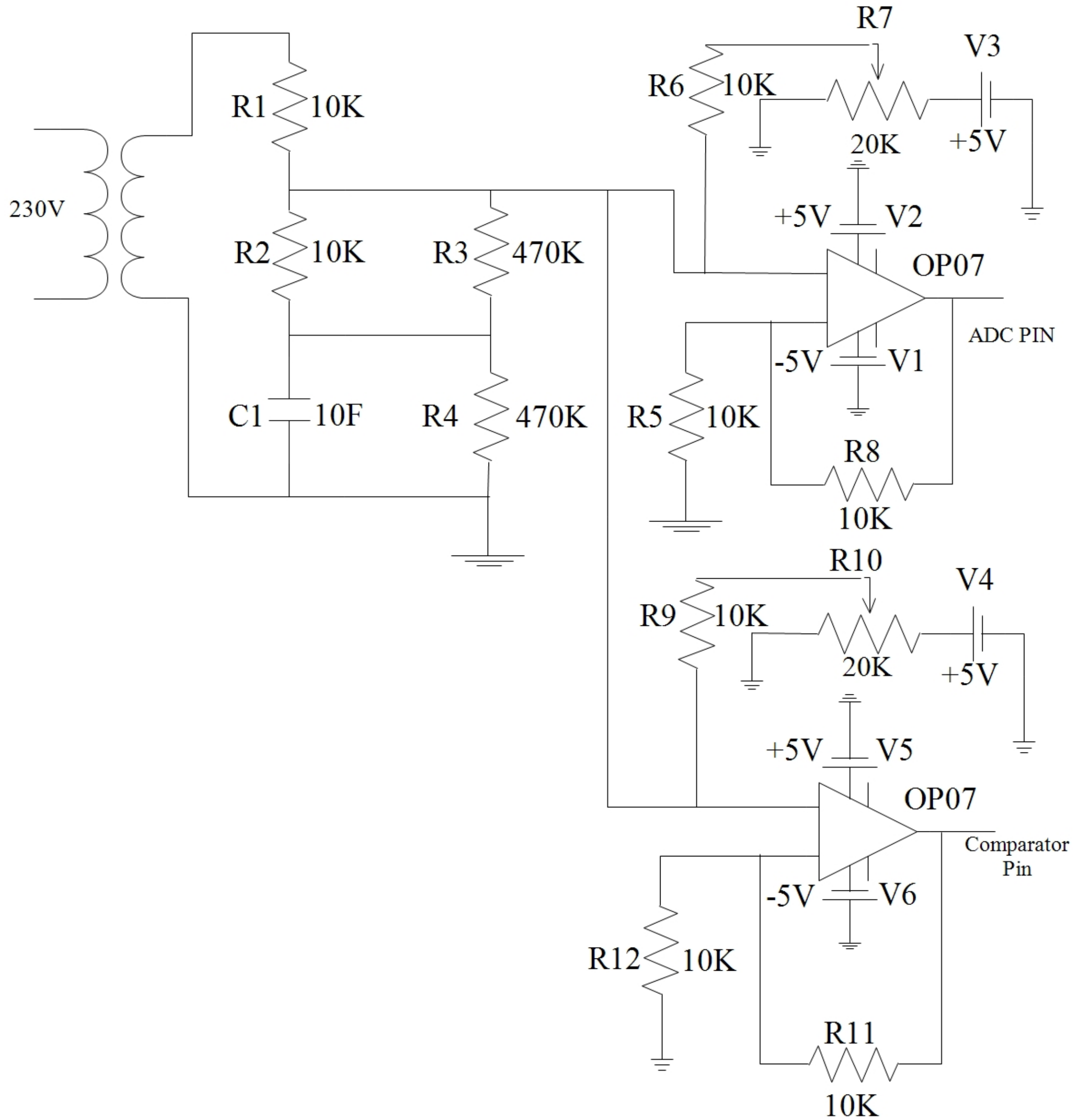

Figure 2.6: Signal conditioning ciruit of voltage sensing unit

2.1.3 Frequency sensing unit

The frequency sensing unit of smart meter is used to measure the frequency of the input analog signal. The frequency sensing unit consists of voltage divider circuit and operational amplifier in its saturation state as shown in Figure 2.7.

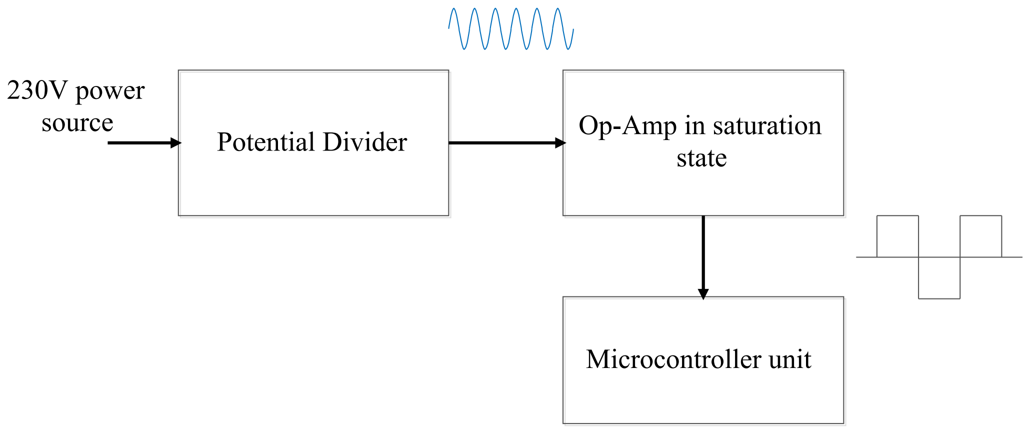

Figure 2.7: Block diagram of frequency sensing unit

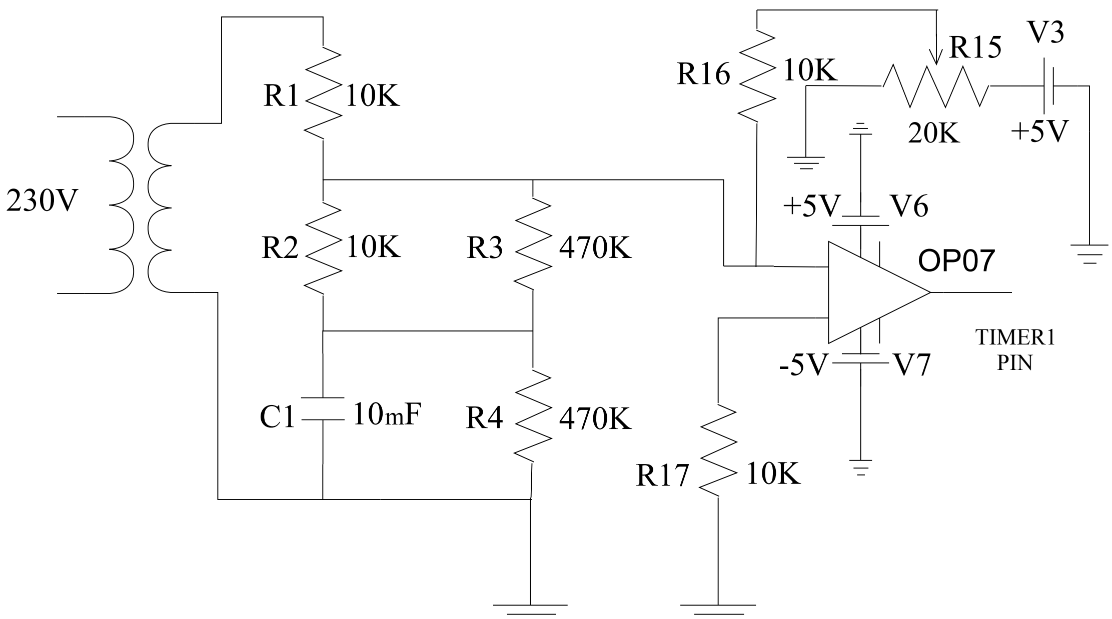

Figure 2.8: Signal conidtioning circuit of frequency sensing unit

Initially, the line voltage is stepped down using the voltage divider circuit as shown in Figure 2.8. The output of this circuit is synchronized with the input voltage of the operational amplifier of the voltage sensing unit. It helps to measure the slight variation of the input supply voltage signal. The analog signal is converted to a square wave signal by using operational amplifier in its saturation state as represented in the following equation.

$$V_{out2} = Gain(A) * [(V_2 - V_1)] \tag{2.11}$$

The square wave is used by the timer capture pin to measure time period and hence frequency as given by the following equations:-

T_1 = Timer2 value when first rising edge is detected

T_2 = Timer2 value when first falling edge is detected

$$Timeperiod = \left[\frac{2 * (T_2 - T_1) * 0.2}{1000}\right] \tag{2.12}$$

$$Freuency = \frac{1}{Timeperiod} \tag{2.13}$$

2.1.4 Power supply unit

The power supply unit provides supply voltage for the whole smart metering circuit. The analog input voltage is transformed and rectified using bridge rectifier circuit, with capacitors used for the smoothing of the output voltage signal and ground potential is set as reference level. The power supply demand required by different units of the smart metering circuit are micro-controller units requires a V_{cc}supply of +5V, operational-amplifier requires a supply of +5V and -5V and Zigbee module requires a 3.3V. To provide the different voltage demand of the circuit three voltage regulators are used which reduces the output voltages to +5V,-5V and 3.3V.

2.1.5 Micro-controller Unit

The micro-controller unit uses PIC16F887 MCU for controlling and measuring function as shown in Figure2.9. Some of the important features of this micro-controller include 14 channels of 10-bit Analog to Digital converter, 2 independent comparators, 1 enhanced, capture/ compare/ PWM function, master synchronous serial port (MSSP) which can operate in two modes as Serial Peripheral Interface (S.P.I) and inter integrated circuit(I_2C) and an enhanced and universal asynchronous receiver transmitter. All these features makes it ideal to measure single-phase energy in either 2 wires or 3 wires configuration.

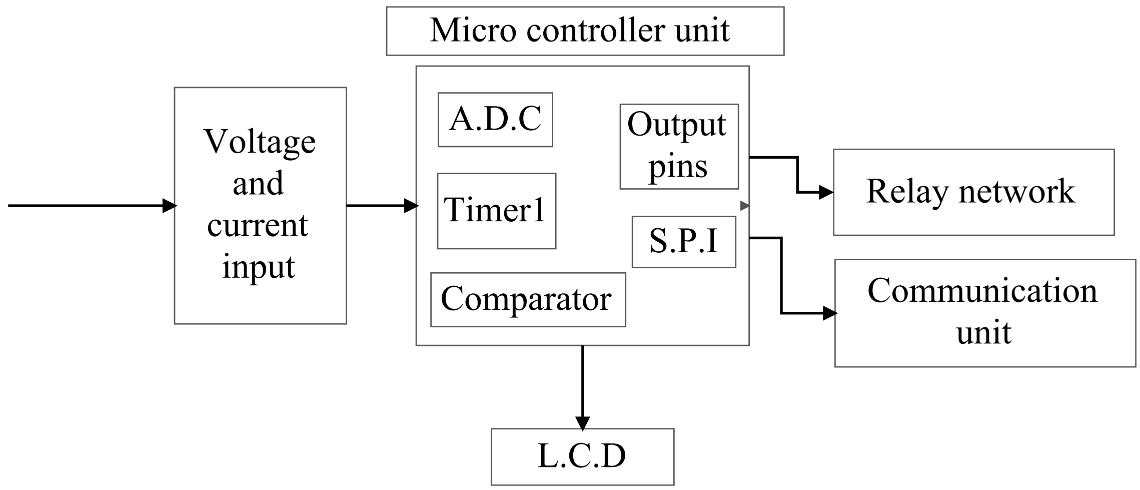

Figure 2.9: Microcontroller unit

The microcontroller unit uses three of its modules:-

- Comparator module:

  Comparator module is used for comparing the input analog voltage and with the set reference voltage of 0.6V. It provides a digital output pulse of low to high which turns on the timer2. The value of reference voltage 0.6V is calculated by the following equation.

$$V_{ref} = \left[\frac{(VR < 3:0 >)}{24}\right] V_{LADDER} \tag{2.14}$$

- A.D.C module

  A.D.C is used to provide analog -to-digital converter that allows conversion of analog input voltage signal to a 10-bit binary representation of the input signal. The output the A.D.C used in this module consists of voltage and current channels. The ADC samples these channels depending upon the samples specified in the program and the output of which is represented by the following equation. .

$$V_{rms/phase} = \frac{K_{vph}}{\sqrt{2}}\left[\frac{\sum_{n=0}^{50} V_{max}(n)}{samplecount}\right] \tag{2.15}$$

$$I_{rms/phase} = \left[\frac{K_{iph}}{\sqrt{2}}\right]\left[\frac{\sum_{n=0}^{50} I_{max}(n)}{samplecount}\right] \tag{2.16}$$

$$P_{active/phase} = K_{active/phase}\left[\frac{\sum_{n=0}^{50} V_{max}(n) I_{max}(n)}{samplecount}\right] \tag{2.17}$$

- Timer module

  Thus M.C.U consists of three timers: timer0, timer1 and timer2. Timer0 and timer2 both are of 8-bit each and the timer1 is of 16-bit. These timers has three modes of operation. A timer capture and timer compare modes are used in this design.

Chapter 3

Methodology Adopted

3.1 Software design of smart meter

In this chapter the software design of the smart meter is discussed. The software module of the smart meter is divided into two modules : 1.measurement module and 2.control module as shown in Figure 3.1. In the measurement module section the software algorithm required to measure the frequency and electrical parameters of the system is developed. The control module is designed to measure electrical parameters at different frequency and its load shedding algorithm for its demand side management.

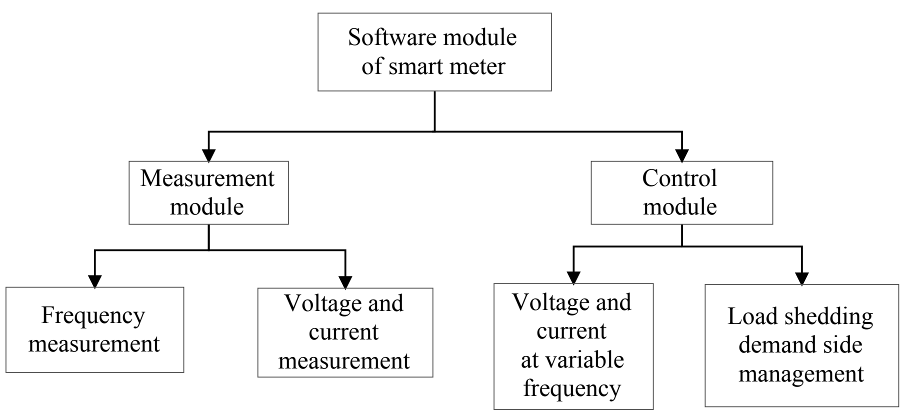

Figure 3.1: Software module of smart meter

3.2 Measurement module

The measurement module is developed to measure the actual instantaneous electrical parameters of the power system which includes frequency, voltage and current. In this section measurement technique is discussed first and then the voltage,current measurement algorithm is discussed.

3.2.1 Frequency measurement

The voltage output of the voltage and frequency signal conditioning unit is provided as an input in the micro-controller. The output voltages of the voltage sensing unit and the frequency sensing unit are the inputs in the micro-controller. The micro-controller uses a comparator and timer2 modules in its software program to measure the frequency of the signal with an accuracy of 10mHz. The micro controller has a crystal frequency of 20MHz and the 8-bit timer uses one fourth of this frequency to count its reading. As a result a timer period of 13.30ms is calculated before the timer overflows to generate an interrupt. Timer2 capture and compare module helps in timing the duration of input analog signal. The zero crossing of the input signal detected by the comparator. At the first zero crossing a square wave output of the frequency sensing unit is provided instantly to the timer2 capture pin of the MCU. This pin detects the rising and falling edge of the signal. Whenever a rising and falling edge of the input signal is detected by the pin an interrupt request flag bit of the peripheral interrupt register is set. When a rising edge occurs at the first zero the timer interrupt is activated and the time of its occurrence is stored in the timer2 register TMR2 and PR2. This captured timer value is stored in a new register. Similar capture is made at the falling edge of the second zero crossing. From these two values are captured time period of the signal is calculated. Then the frequency is calculated by using the time period as given by eq.(8 & 9). As for a 50Hz sinusoidal sine wave a zero crossing occurs every 10ms and as result normal frequency variations never cause a timer value to overflow. The low timer period helps to measure the frequency of signal with an accuracy of 0.4%.

Algorithm 1 Measurement of peak value of voltage and current

Input: $V_{Line}, V_{Neutral}, V_{out1}$, V_{out3}
Output: V_{rms}, I_{rms}

Intialization of Comparator,Timer2 in compare mode and A.D.C
loop
  comparator module
  if PIR2.C2IF==1 ; // Comparator interrupt flag is high **then**
    PIR2.C2IF==0;// Comparator interrupt flag is cleared software
  end if
  Timer2 is turned on
  if CM2CON0.C2OUT==1;// Comparator interrupt is high **then**
    T2CON.TMR2ON=1;// Timer 2 is switched on
  end if
  A.D.C reads (V_{rms}) and $I_(rms)$ when timer2 interrupt occurs
  if PIR1.TMR2IF==1;// Timer2 interrupt is high **then**
    T2CON.TMR2ON=0;// Timer2 is turned off
    V1=$ADC_{Read}(1)$;// volatge value read by adc channel 1
    V2=$ADC_{Read}(2)$;// current value read by adc channel 2
  end if
  Calculation of voltage and current by equation(12) and equation(13)
  if ADC.bit==1;// ADC interrupt is set high **then**
    V_{rms}=V1/4.89;//calculation of the analog utility voltage
    I_{rms}=V2/2.45;//calculation of the current following in the circuit
    Value of measured current and voltage are displayed on L.C.D
  end if
end loop

3.2.2 Voltage and current measurement

Once the frequency of the input signal is measured and the time period for its peak value is calculated then smart meter measures the peak value of its analog signal. The output voltages of the voltage sensing unit and the current sensing unit are used as an input in this algorithm. The micro-controller uses ADC, comparator and timer2 compare modules in its software program to measure the actual value of the voltage with a maximum error of 0.5%. The timer2 is de-initialized after the frequency is measured and the timer value corresponding to the maximum value of the signal is substituted in the timer2 register pair. The comparator is initialized and it sets the interrupt flag bit for every zero-crossing . When the comparator interrupt flag is set in the peripheral interrupt register the timer2 is turned on in its interrupt service routine. The timer compare mode gives an interrupt on overflow which corresponds to peak value and the A.D.C measures that value and the analog value is converted to 10-bit digital value the A.D.C conversion bit is set and the resulted value is displayed on the L.C.D. The acquired number of samples for one second is equivalent to accumulation of 50 to 60 cycles of samples for incoming voltage signal. The peak value is measured for each cycle and R.M.S values of voltage and current are obtained for each phase.

Algorithm 2 Measurement of peak value of voltage and current

Input: $V_{Line}, V_{Neutral}, V_{out1}$, V_{out3}
Output: V_{rms}, I_{rms}

Intialization of Comparator,Timer2 in compare mode and A.D.C
loop
  comparator module
  if PIR2.C2IF==1 ; // Comparator interrupt flag is high **then**
    PIR2.C2IF==0;// Comparator interrupt flag is cleared software
  end if
  Timer2 is turned on
  if CM2CON0.C2OUT==1;// Comparator interrupt is high **then**
    T2CON.TMR2ON=1;// Timer 2 is switched on
  end if
  A.D.C reads (V_{rms}) and $I_(rms)$ when timer2 interrupt occurs
  if PIR1.TMR2IF==1;// Timer2 interrupt is high **then**
    T2CON.TMR2ON=0;// Timer2 is turned off
    V1=$ADC_{Read}(1)$;// volatge value read by adc channel 1
    V2=$ADC_{Read}(2)$;// current value read by adc channel 2
  end if
  Calculation of voltage and current by equation(12) and equation(13)
  if ADC.bit==1;// ADC interrupt is set high **then**
    V_{rms}=V1/4.89;//calculation of the analog utility voltage
    I_{rms}=V2/2.45;//calculation of the current following in the circuit
    Value of measured current and voltage are displayed on L.C.D
  end if
end loop

3.3 Control module

The control algorithms are implemented in the software module that helps smart meter to measure the exact electrical parameters at different frequencies and then the load shedding algorithm for demand side management is discussed. This section is actually shows how a smart meter can be used as a smart load controller for the utilities to shed the load instantaneously.

3.3.1 Voltage and current at variable frequencies

This algorithm is designed to measure maximum value of voltage and current at different frequency with an accuracy of 10mHz. The frequency of the input signal is measured by the algorithm1. Then the peak time period of the signal is calculated which helps to measure the peak magnitude of the voltage and current signal. Now after the 50 cycles the frequency of the signal is calculated again. If the value of new frequency $freq2$ is equal to the previous value$freq1$ then the magnitude of voltage and current is measured. And if the value of this new frequency $freq2$ is not equal to the previously measured frequency value$freq1$. Then the T_{max2} value is calculated again and the peak value of the signal is calculated for this new frequency.

Algorithm 3 Measurement of voltage and current at variable frequency

Input: $Freq_1, V_{out1}, V_{out2}, T_{max1}, N = 50$
Output: $Freq_2, T_{max2}$

Initialization of port pins,Comparator,Timer2 in capture mode and LCD
Frequency value calculated as in algorithm 1
loop

  if Freq1 value is calculated **then**
    T_{max1} peak value is calculated for the Freq1 value
  end if
  if N=50 **then**
    Freq2 value is calculated using eq(8)& eq(9)
  end if
  if Freq1 $\neq$ Freq2 **then**
    T_{max2} is calculated for the freq2 value
  end if
  if Freq1=Freq2 **then**
    $T_{max1} = T_{max2}$
  end if
end loop

3.3.2 Demand response management scheme

The load shedding program should rapidly identify the demand in generation shortage, percentage of overload in the line [28]. Based on the parameters load should be shed precisely so that the frequency of the system can be brought to normal condition. Due to the oscillation of frequency decay in the system, it will be difficult to design a load shedding program which will shed load at equal increments. These frequency variations will cause a degree of haphazard condition in under frequency relay operations and will shed more load required in the system locations. Due to this unpredictable nature of these frequency variations, it is difficult to predict the percentage of load to be shed [29]. In spite of these uncertain parameters, it is possible to design an effective load shedding programs. The programs are developed depending upon the type of frequency decay curves for the systems. The factors required for the development of load shedding schemes are discussed in the following sections. There is an essential requirement to know the maximum overload condition the program should protect, the maximum load it should shed, the frequency of the system at which load shedding program should begin and the maximum frequency variation which the system can with stand.

- **Maximum system overload voltage** Every load shedding program is designed by keeping in view the maximum overload voltage to be protected. For a very large interconnected system, it is difficult to determine the exact value of the overload. For these systems, the stability studies can be done which will help to estimate the actual load to be separated. For the residential customers, the smart meters can help to determine the voltage parameters accurately with help of which the load can be shed. These smart meters have the communication medium which will help to accurately transmit the voltage parameters to the utility side to determine the demand of the area at particular instant.

- **Maximum Load to be shed:** The percentage of load to be shed must be sufficient enough. To restore the system frequency to normal level or closer to the set standards. To fulfill this, it would mean the load that is shed is nearly proportional to the percentage of overload on the system [30]. It is not necessary that the frequency is exact 50Hz. If the system maintained at 49Hz, the turbine-governor set have the capability to maintain the system frequency to set normal value. At the demand end, smart meters connected with the different loads at the residential premises shed the load via relay switching network.

- **Frequency level:** Frequency at which the load shedding starts depends upon the number of factors. The frequency level is adjusted such that the system continues to operate at that frequency without any catastrophic effect on the system for a short duration of time [31].

- **Permissible Freuqnecy reduction:** The frequency reduction that can occur in the system depends upon the operating frequency limitations of the equipments of power plant [32]. The performance of these equipments starts to decrease when frequency falls below 49Hz. The maximum frequency limit is set to a value of 46Hz.

Algorithm 4 Load shedding algorithm for demand side management

Input: V_{rms}, I_{rms}, Freq
Output: R_1, R_2... R_n

```
Initialization of Comparator,Timer2 in compare mode and A.D.C
loop
    Measurement of frequency and voltage parameters by algorithm(1) and algorithm(2)
    for N-Smart meters
    Percentage overloading calculated based on voltage readings N-Smart meter read-
    ings
    Freq parameter is measured by smart meters
    if Freq <49.3Hz then
        Controllable load is shed by relay network
    end if
    if Freq <49.0Hz then
        Differ-able Load is shed by relay network
    end if
    if Freq <48.5Hz then
        non-differ-able Load is shed by the relay network
    end if
    if freq >50Hz then
        Controllable Load is connected by the relay network
    end if
end loop
```

The method of selectivity is the best way to control the load shedding in order to restore the system frequency of the system to 50Hz. The residential load is distinguished into three types of loads i.e controllable loads, differ-able load and non-differ-able loads [33]. The load shedding program is initiated at 49.3Hz and the maximum permissible frequency drop of the system will be 47Hz. This simplified algorithm of the frequency control is possible using the smart meters. The number of load shedding steps depends usually on the maximum load to be shed [34]. For the residential customers the load shedding programs are limited to the above mentioned load types. The high accuracy smart meter developed in the above section helps to measure the frequency of the grid and the voltage of the system is measured by it that helps to measure the degree of percentage overload of the system [35].

$$Percentage\ Overloading = \frac{Load - Remaining\ generation}{Remaining\ generation} * 100 \tag{3.1}$$

This percentage amount of overloading causes the frequency of the system to deviate form the set normal frequency ranges. The frequency of the grid is measured by individual smart meter connected to the residential customers premises and the parameters are communicated to the demand side system. When the frequency of the system measured by the smart meter reaches to 49.3Hz, the load shedding program is initiated. Firstly, the controllable load is shed at 49.3Hz. If the frequency of the system still deteriorates, the differentiable load is shed by the relay network of the smart meters. As the frequency of the system still deteriorates and reaches the 49Hz, differ-able load is shed. And the maximum frequency variation of the system permitted is 47Hz. The frequency falls to 48.5Hz, the differ-able load is also shed by the system [36]. The system frequency is restored to the closer to the 50Hz. And when ever the frequency of the system increases the controllable load is connected in order to maintain the frequency level. This load shedding program helps to control the frequency of the power system by using smart meters.

Chapter 4

Results and discussions

4.1 Results and discussions

In order to validate the accuracy of proposed smart meter, an experimental setup has been conducted in ISD lab. The experiment aims to demonstrate the demand response scheme for load shedding. The test rig is developed in which an individual load is connected to smart meter via relay network and current driver. In this test, smart meter acts as smart load controller. The smart meter measured the grid frequency and the electrical parameters. Based on the measured frequency, an algorithm has been implemented in Embedded C. According to the pre decided priority scheme total load on the system which decides whether to switched on or switch off the loads. In this experimental set-up, the appliances are represented by light lamps. A function generator is used to vary the frequency of the input signal which resembled the frequency variations that occurs in the actual power system. The frequency is dropped in three steps at 49.3Hz, 49.0Hz and 48.5Hz.

4.2 Accuracy of frequency measurement

In this test, frequency of the input signal is varied between (45-55Hz) and the smart meter measured this frequency. Then the results have been compared which proved that the maximum percentage error in measurement was not more than 0.4% as shown in the Table 4.1.

S.no	Input frequency	Output frequency	Maximum error(%)
1	44.3Hz	44.14Hz	0.36117
2	46.6Hz	46.53Hz	0.15021
3	48.2Hz	48.02Hz	0.37344
4	50.6Hz	50.48Hz	0.23715
5	52.2Hz	50.18Hz	0.03831
6	54.5Hz	54.42Hz	0.14678
7	56.1Hz	56.1Hz	0

Table 4.1: Accuracy of frequency measurement

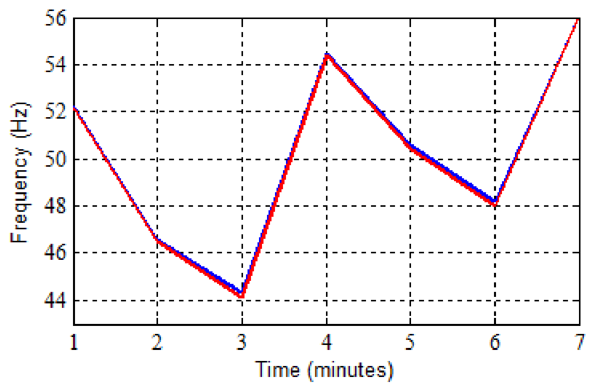

Figure 4.1: Accuracy of frequency measurement

In graph 4.1, the red curve represents the input frequency signal and the blue curve represents the output frequency measured by smart meter.

4.3 Accuracy of voltage measurement

In this test, voltage of the input signal is varied between (226-236V) and smart meter measured the voltage. Then the input and output voltages are compared in order to find the maximum percentage error in measurement. The experimental result showed that the maximum percentage error in measurement was not more than 0.5% as shown in Table 4.2. The accuracy of this designed smart meter was within the tolerance band as per the smart meter standard.

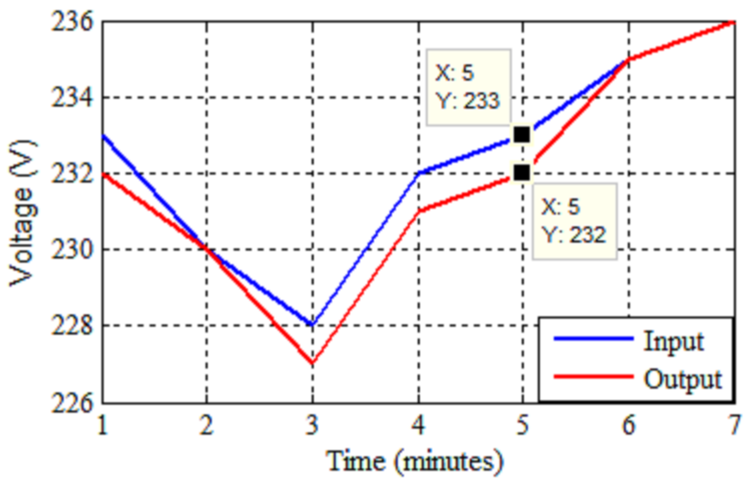

Figure 4.2: Accuracy of Voltage measurement

S.no	Input voltage	Output voltage	Maximum error(%)
1	233V	232V	0.42918
2	230V	229.35V	0.28260
3	228V	227V	0.43859
4	232V	231V	0.43103
5	233V	232V	0.42918
6	235V	234.8V	0.085106
7	236V	235.4V	0.25423

Table 4.2: Accuracy of Volatge measurement

4.4 Variable frequency test

This test was conducted in the laboratory where frequency of the input signal was varied by the function generator without changing the amplitude of the input signal. This test was conducted in three steps: firstly the voltage was measured. In the second step the current is measured by keeping a constant load. In the third step active power is measured at constant power factor of 0.9.

- **Voltage measurement at different frequencies:** The frequency of the input signal was varied between (45-55Hz) to measure the actual voltage of the smart meter. The results showed that the designed smart meter has been able to read the same voltage magnitude within the set frequency band width as shown in Figure 4.3.

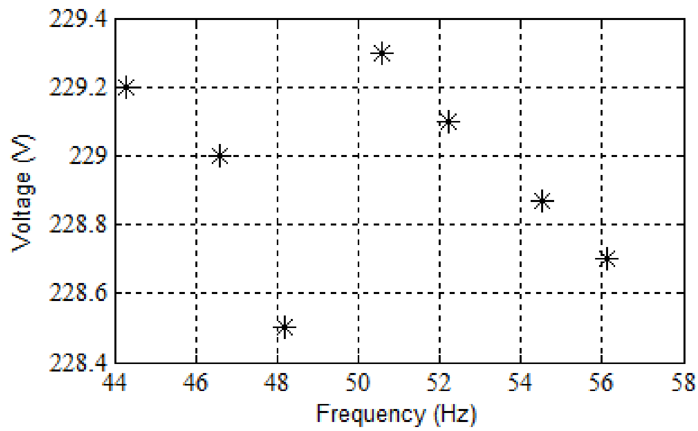

Figure 4.3: Variable frequency measurement

S.no	**Frequency**	**voltage**
1	45.1Hz	228.7V
2	46.53Hz	228.5V
3	48.02Hz	229.1V
4	50.60Hz	229.01V
5	52.2Hz	229.11V
6	54.5Hz	229.29V
7	56.1Hz	228.30V

Table 4.3: Measurement of voltage(229V) at different frequencies

- **Current measurement at different frequencies:** The loads connected in the residential premises are mostly resistive in nature. Hence, a resistive heater of 1.5Kw was used in order to demonstrate it in the laboratory. The amplitude of the current was measured within a frequency bandwidth of (49.5-55.5)Hz as shown in Table 4.4 and Figure 4..4.

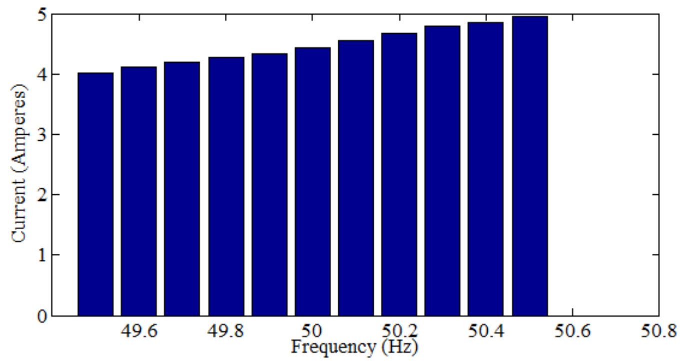

Figure 4.4: Current at different frequency

S.no	**Frequency(Hz)**	**current(A)**
1	49.5	4.02
2	49.6	4.11
3	49.7	4.19
4	49.8	4.27
5	49.9	4.34
6	50.0	4.44
7	50.1	4.56
8	50.2	4.67
9	50.3	4.79
10	50.4	4.86
11	50.5	4.95

Table 4.4: Measurement of current at different frequencies

- **Power demand at different frequencies:** To implement the load shedding scheme, it is required to measure the customers actual power demand when the frequency of the system varies. This will help the utility companies to calculate the actual load torque required to be maintained. In this test, the power factor of the load is kept constant value at 0.9. The result of this test are shown in th Figure 4.5.

S.no	frequency(Hz)	Power(W)
1	49.5	839.673
2	49.6	856.017
3	49.7	872.361
4	49.8	882.756
5	49.9	907.092
6	50.0	931.608
7	50.1	949.878
8	50.3	969.975
9	50.4	984.15
10	50.5	1002.375

Table 4.5: Power Vs Frequency variations

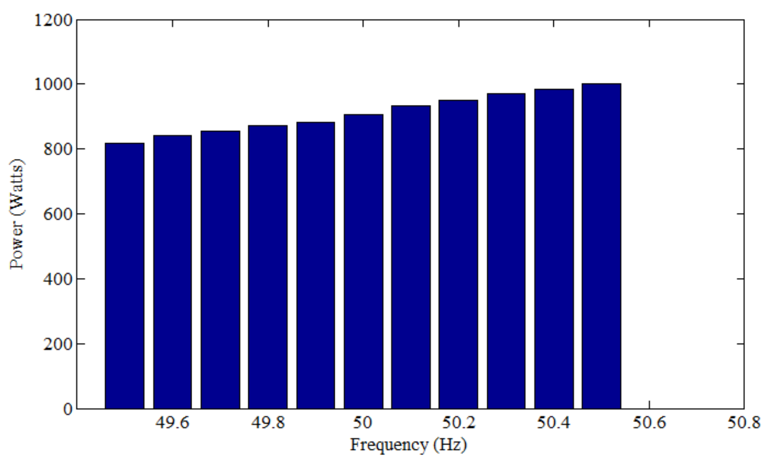

Figure 4.5: Power at different frequency

4.5 Load shedding by demand response algorithm

To demonstrate load shedding scheme in laboratory, a test rig was set-up using light lamps to represent residential loads. These loads are classified into three types. They are controllable, differ-able and non-differ-able loads. The priorities were set as per the control algorithm discussed in previous chapter. The frequency is varied in three steps 49.3Hz, 49.0Hz and 48.5Hz. The frequency level for the load shedding is 49.3Hz at which the controllable loads were shed first. Then, the frequency was stepped down to 49.0Hz at which both controllable and differ-able loads were shed. Further when the frequency reached

48.5Hz, non-differ-able and all other types of loads were shed. Then the frequency was increased in steps again and the loads were connected in the same set priority. From the experimental results a three dimensional plot as shown in Figure 4.6. It shows the power demand of the loads at different frequencies when measured at different time intervals. The maximum permissible frequency variations occurring the system is 47Hz in this algorithm. This test shows that demand side control using smart meters can instantly disconnect the loads for residential customers. This will help the utility companies in implementing a real time pricing tariff and incentive based tariff programs in future.

S.no	frequency(Hz)	Power(W)	Time(hours)
1	49.5	839.673	2
2	49.6	856.017	4
3	49.7	872.361	6
4	49.8	882.756	8
5	49.9	907.092	10
6	50.0	931.608	12
7	50.1	949.878	14
8	50.3	969.975	16
9	50.4	984.15	18
10	50.5	1002.375	20

Table 4.6: Power demand at differnt interval of time

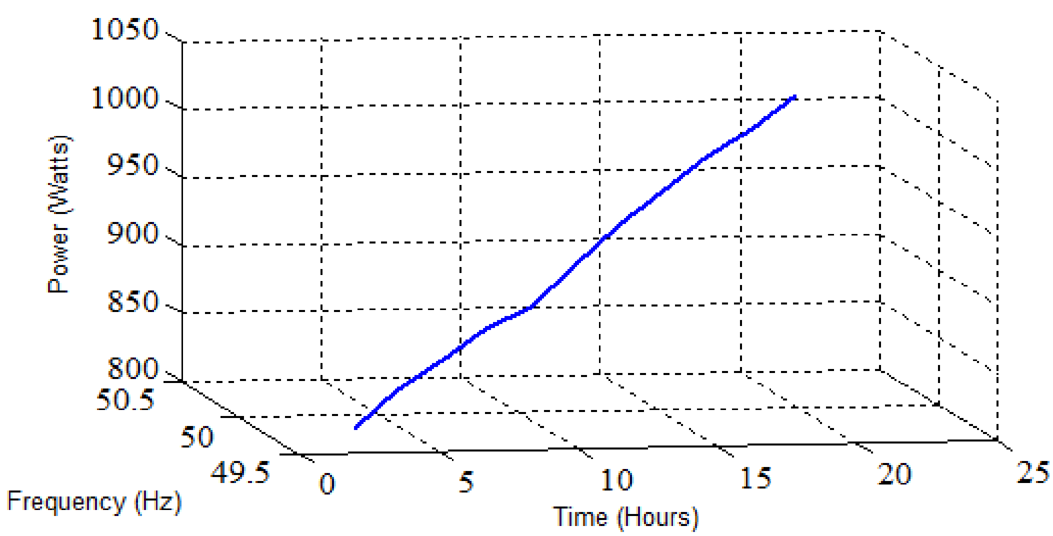

Figure 4.6: Power at different frequency

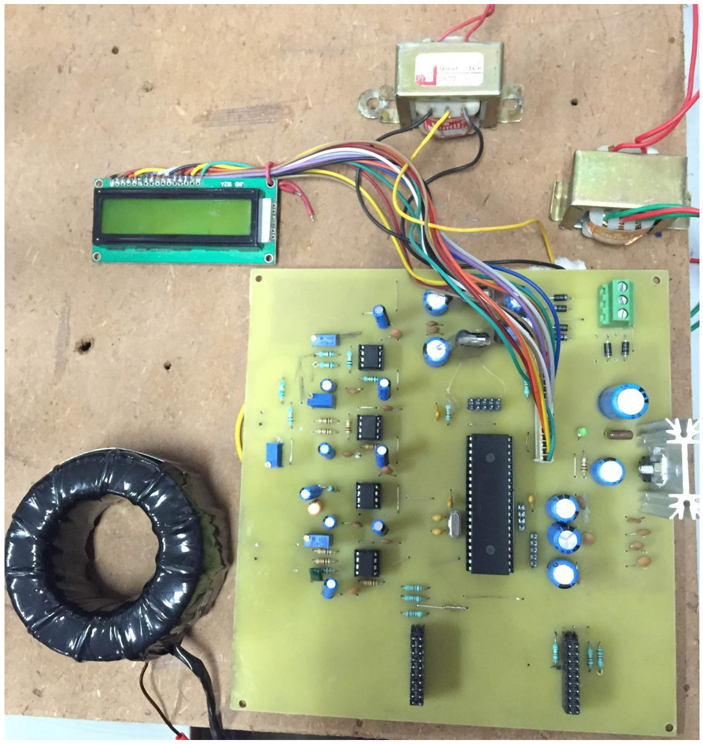

Figure 4.7: Hardware design of Smart Meter

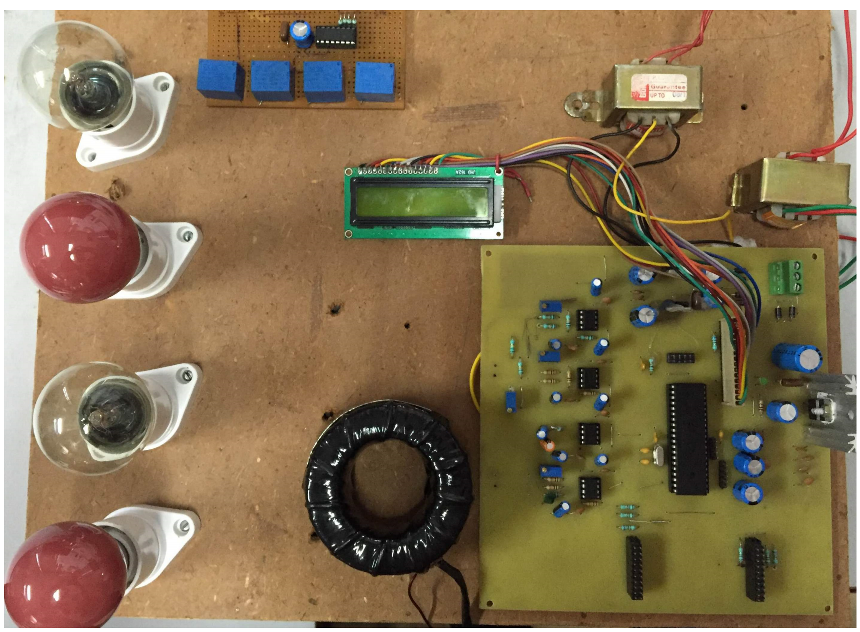

Figure 4.8: Experimental Rig for demand response

Chapter 5

Conculsion and Future Work

The instantaneous change of load demand at the customer end and degree of randomness in under-frequency relays results in frequency variations of the power system. To resolve this issue, automatic load shedding program using smart meters is considered in this work. In another words, the novelty of this work lies in designing the smart meter, developing demand response algorithm and the controllers at the smart meter itself. The hardware design proposed for smart meter measures the same amplitude at variable frequency and has an accuracy of 10mHz for its frequency measurement. The meter further connects and disconnects the load depending upon the frequency of the grid. It is validated by developing a test bench and the results showed that smart meter can efficiently help to shed the load instantaneously and rate of measure of frequency variation is improved.

The future work will include a communication module in the smart meter which will help to develop an I.o.T platform for advanced metering system. This will help the utility companies to automatically control the load at the individual residential home helping to implement incentive based programs billing systems and real time billing systems in future. The net metering concept can also be developed using this smart meter to implement a zero energy consumption building objectives. At the hardware design level a temperature control of the IC and the tamper protection using an accelerometer can also be developed.

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