Industrial Energy Monitoring System based on the Internet of Things (IoT)

by

Hemanand Ramasamy

15730

Dissertation submitted in partial fulfilment of
the requirement for the
Bachelor of Engineering (Hons)
(Electrical and Electronics Engineering)

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Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved by,

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(IR DR PERUMAL NALLAGOWNDEN)
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
September 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except in the references and acknowledgements, and that the original work contained herein have been undertaken or done by unspecified sources or persons.

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HEMANAND RAMASAMY

ABSTRACT

Energy monitoring system has long been utilized for basic functionalities such as process scheduling and billing purposes in the industrial scenario. However the use of energy monitoring for improving energy efficiency and the monitoring of degradation in power quality parameters that provides important insights into process degradation and fault diagnosis as long been ignored due to lack of ability of the current energy monitoring systems to acquire and process both energy and power quality data in real-time. The advent of technologies such as the Internet of Things (IoT), Cloud computing and Big Data has made real time acquisition and analysis of data possible. This paper discusses on use of these technologies for developing an integrated real-time power monitoring system and its possible application in fault cause-effect diagnosis. This project focusses on the technologies that would enable the development of the an real-time energy monitoring system and its implementation developing an development of the an real-time energy monitoring system

ACKNOWLEDGEMENT

I would like to take this opportunity to express my gratitude toward my supervisor, Ir. Dr. Perumal Nallagownden for this great supervision, continuous support, previous guidance and understanding which truly helped me throughout completing this project. His experience has offered me better insight and understanding on my project and helped me to enhance the current solution in the industry.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1. BACKGROUND

Electrical energy forms the backbone of the global economy with per capita consumption increasing by 14.3 % from 2005 to 2011 [1]. The Manufacturing Industry that dominates the global economy accounts for about 42.3 % of the world electricity consumption [2]. This increasing trend in the demand for electrical energy had resulted in increasing prices in electricity. Traditionally, energy cost constituted a small portion of the total production cost receiving relatively less attention. The increase in energy prices is forcing the industries to shift towards treating energy as a resource, which requires to be planned and managed for their plants as a variable input. Reduction in energy consumption for the industries requires energy efficient operation. Energy efficient manufacturing provides several advantages such as cost-savings, fulfillment of environmental regulations and adapting to consumer preference for green products. Green product is defined by as those that are manufactured consuming as little energy as possible - not just products that consume less energy when used [3]. ISO 50001 identifies energy monitoring and analysis as the critical activities to be performed to improve energy efficiency. Hu et al. claims that the efficiency of many machine tools are below 30 % [4].

Absence of sub-metering is considered as one of the main barriers for improving energy efficiency in both energy intensive and non-energy-intensive industries [5, 6]. With the introduction of sub-metering, the benefits of implementation of energy efficiency practices can be quantified in terms of cost reduction which motivates investments into energy efficiency programmes.

According to Herrmann et al. [7] understanding and characterization of energy consumption in machine tools and manufacturing systems is considered as the first step towards reduction in energy consumption. Energy saving opportunities such as load balancing and proactive maintenance depends on the availability of near-real-time data of the energy consumption pattern [8].

One of the challenges in energy management rises due to the variety of energy usage across processes, each one having a unique characteristics of energy consumption. The integration of energy management along with production management is the key in enhancing energy efficiency [9].

2. PROBLEM STATEMENT

Energy efficient operation and proactive maintenance based on power analysis data requires energy consumption pattern in individual equipment or processing/manufacturing. This requires the collection of sufficient data for analysis which requires real-time acquisition and transfer of data from multiple sources; high processing power and storage of huge sets of data

3. OBJECTIVES

To design an energy monitoring system that can

i. acquire and transfer real-time energy and power quality data to server
ii. process and store huge sets of data in real-time
iii. communicate with other intelligent devices

CHAPTER 2

LITERATURE REVIEW AND THEORY

1. LITERATURE REVIEW

The 1973 Oil Crisis resulted debate on appropriate usage of the energy and led to intensive discussion on energy efficiency ever since the late 70s. Bunse and Vodicka [9] lists three reasons improving energy efficiency in the industry: energy prices, environmental regulations and customer awareness on environmentally benign products.

Rodhin and Thollander [6] and Tiranni et al [5] lists and discusses on various barriers for energy efficiency in non-energy intensive and energy intensive industries, respectively. Garetti and Taisch [3] suggests that there is an absence of the required level of control in energy usage. This shortcoming has led to research into methods of estimating energy consumption patterns: use of data on machine tools to simulate energy profiles [10], “EnergyBlocks” Methodology for predicting energy consumption in production operations [11]. The forecasting models used for estimating energy consumption are classified into two categories [8]. The first is based on driving factors and the other is based on historical data. However, the estimated energy consumption are inaccurate and available at large time intervals. Therefore, use of an energy monitoring system to assess energy performance with improved accuracy in real-time is essential.

The concept of energy monitoring systems has long been used solely for identifying the energy consumed by the equipment in an industry. The metering for an energy monitoring system has been classified into three levels [12]; and O’Driscoll and O’Donnel [13]: Facility Level, Process Chain Level and Machine Level. The benefits of metering at different levels is shown in Table 1 [12].

TABLE 1. Levels of Metering and its Benefits

Level	Benefits
Factory Level	• Process rescheduling • Supply contract for electricity
Departmental Level	• Quantify improvement measures • Scheduling energy intensive process • Savings benchmarking, quantify energy savings
Machine Level	• Energy forecasting in product design • Energy labeling • Proactive maintenance • Power Quality Data

The frequencies of data acquisition and analysis required for the different levels of energy monitoring are days for production planning, hours for macroplanning, and seconds for microplanning and microseconds for process control [10].

The use of power analysis is key in recognizing process degradation over time. The use of energy, load and power quality data will allow industries to develop insights into issues that could lead to machine failure. The financial consequences due to the degradation in the power quality is been stressed [14]. The real-time processing of the power quality data enables detection of disturbances in the system and analysis of correlated events that could have caused the disturbances.

The current approaches of energy monitoring systems lack the ability for the real-time analysis of power quality data. Power quality analyzers like Fluke Power Quality Analyzers provide built-in processing for calculating various power quality data and is designed for temporary metering [15]. A proper implementation of energy monitoring system with real-time processing power will aid in identifying degrading trends in electrical systems allowing the focus on inspection and proactive maintenance to a specific equipment

Shrouf and Miragliotta [8] have presented the benefits due to adoption of IoT and related practices. The authors considered the following features could be enabled using an IoT based Energy Monitoring System with real-time data:

- Monitoring Power Quality

- Process design integrating energy data to reduce energy consumption
- Energy consumption adjusted based on energy price information
- Efficient use of renewable energy by adjusting production schedules
- Evaluating power generation processes

The following benefits are considered to be enhanced:

- Calculation of operational costs
- Energy efficiency of production processes increased based on real-time energy data
- Proactive maintenance based on power quality data reducing maintenance cost

2. THEORY

2.1 Data Transfer

The real-time data acquisition and transfer of data from multiple sources is enabled IoT paradigm. The IoT paradigm is defined as the combination of smart object and smart communication networks [16]. A smart object is considered to possess some mandatory functionalities such as Self-Awareness with unique digital identity, Self-Diagnosis and location awareness, communication with other smart objects or with central acquisition system and that of a smart network are open and standard protocols, object addressability, multi-functionality [16]. The benefits of adoption of IoT and related practices for energy monitoring system are highlighted by Shrouf and Miragliotta [8] and Haller et al [17]. The wide scale adoption of the IoT-based systems has been limited due to the security concerns related to transferring of critical data through the internet and sharing of corporate network for internet access.

Use of Wi-Fi for the communication network provides data transfer speed of about 10 Mbps and can easily be implemented over existing infrastructure. A lightweight protocol for data transfer over the network is required to be implemented on a terminal unit with limited resources to spare.

2.2 Data Processing

Computers in energy monitoring systems have been traditionally used for monitoring and logging while the data processing is embedded in remote energy meters. This limits the processing power required for power quality analysis and also to implement IoT functionalities. The use of energy meters as terminal units with minimum processing power implementing the functionalities of a smart object while the required processing power for data analysis is provided by a centralized system that can be operated on demand. The advancements in networking technology has given rise to cloud computing which uses a network of computers on the internet for processing the data.

2.3 Data Storage

The storage of data is key for predicting failures in a system based on the analysis of the real-time data acquired. The advent of technologies such as Big Data has made it easier for storing data on remote servers with easier access. The establishment of data servers with Big Data capability can be done in the cloud. The implementation of data storage and analysis on the same cloud platform reduces the latency in accessing the data for analysis.

2.4 Signal Processing

High sampling rate is required to detect anomalies in the power quality data. The detection of transient over-voltage at different sampling rates is shown in Figure 1. The real magnitude of the transient over-voltage is not detected at the lower sampling rate and the same is identified with higher sampling rates.

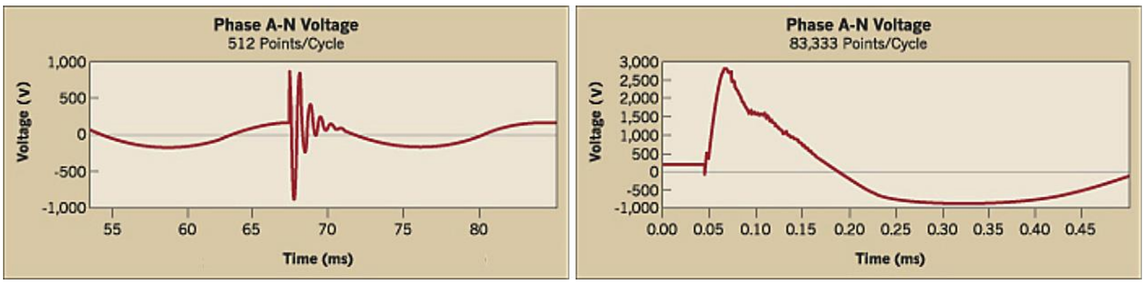

FIGURE 1. Transient Over-Voltage Interpretation [18]

The signals from both the voltage and current sensors are to be acquired at the same time to ensure there is no lead or lag error which would lead to error in the measured values. Use of di/dt sensors such as a Rogowski Coil results in a 20 dB per decade gain. A digital integrator is required to recover the current signals from the sensor's output.

Digital Signal Processing (DSP) of the signals from the transducers enables the acquisition of data at the required sampling rate. The algorithms of detecting abnormalities that occur for a very short period of time are to be implemented on a DSP System on an Application Specific Integrated Circuit (ASIC).

2.5 Power Quality Analysis

The anomalies in the power quality can be classified into different types. The main anomalies with an adverse effect on the equipment are unbalanced voltage or current and harmonics [19].

2.5.1 Unbalanced voltage or current

The magnitude or phase deviation of the phase current and phase voltages from their rated values is called unbalance. Voltage unbalance occurs when voltages of a three-phase system are not identical or the phase difference is not exactly 120º.

Unbalance current between the three phases can be calculated using

$$\frac{I - i}{I} \times 100\% \qquad (1)$$

where, I is the rated current and i is the actual current

Similarly unbalanced voltage can be calculated using

$$\frac{V - v}{V} \times 100\% \qquad (2)$$

where, V is the rated voltage and v is the actual voltage

Usually caused by single-phase loading in a three phase system or blown-out fuse in one phase of a three-phase capacitor bank. The effects of unbalanced voltage or current are (i) excessive drawl of reactive power, (ii) shortening of life span of certain appliances, (iii) degradation of FACTs controller performance, (iv) unequal losses/heating in phases, (iv) neutral shifting in ungrounded systems affecting operation of relays and circuit breakers.

2.5.2 Harmonics

Caused due to magnetization nonlinearities of transformers, rotating machines, arcing devices, semiconductor based power supplies, reactors controlled by thyristors, phase controllers and AC regulators. Its effects are stator and copper losses in motors, stray, hysteresis losses, mal-tripping in relays, increase in reactive power in capacitor banks and noise in transmitted signals.

The other common power quality anomalies are interruptions, transient under-voltage, transient over-voltage, sag and swell. The anomaly detection algorithms are to be implemented at different levels of the energy monitoring system based on the time period an anomaly would occur.

CHAPTER 3

KEY MILESTONES

1. KEY MILESTONES

The project should achieved certain milestones to achieve the required objectives and are discussed below

- Acquisition of sensors and microcontroller – The acquisition of the energy metering IC – ADE7880, microcontroller for control and data transfer – CC3200, Current Transducers
- Interfacing the sensors with microcontroller – To design the filter signal and to communicate with the energy metering IC from the microcontroller for data transfer
- Design microcontroller to process acquired measurements - buffering of the data and detection of an event
- Data Transfer – to enable the communication between the server and the meter and transfer of data
- PCB Fabrication – Design PCB to incorporate the various subsystems onto a single board
- GUI Design – Design of graphical user interface for basic configurations and to view data
- Testing – acquisition of data and check its processing
- Documentation and Reporting – The specific details of the project will be discussed and reported. Recommendations and suggestions will ensure further study in the topic

2. GANTT CHART FOR FINAL YEAR PROJECT I

No		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Project Selection and Research Work														
2	Literature Review														
3	Extended Proposal														
4	Research on Required Components														
5	Proposal Defense														
6	Lab Setup for Development and Testing														
7	Acquiring Voltage and Current Sensors														
8	Simulation and Circuit Design														
9	Interim Report Submission														

3. GANTT CHART FOR FINAL YEAR PROJECT II

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<tr><th>No</th><th></th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th></tr>
<tr><td>1</td><td>Build circuit design on breadboard</td><td bgcolor="#FFC000"></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td>8</td><td>System Unit Testing</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td bgcolor="#FFC000"></td><td bgcolor="#FFC000"></td><td></td></tr>
<tr><td>9</td><td>Complete System Test</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td bgcolor="#FFC000"></td></tr>
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CHAPTER 4
METHODOLOGY

The design of a real-time industrial energy monitoring system would enable better insights into the energy and power quality data in the industries. This will lead to reduced down time of equipment in an industry leading to financial benefits. The functionalities and constrains considered in the proposed industrial energy monitoring system are discussed in detail.

1. SIGNAL ACQUISITION AND PROCESSING

The signal acquisition and processing part of the system uses ADE7880, a poly-phase multifunction energy metering integrated circuit (IC) from Analog Devices [20].

This IC provides the digital signal processing core for acquiring signals from voltage and current transducers and calculating various power quality parameters. It also provides the function to monitor the calculated parameters and cause an interrupt when a value crosses a preset threshold value. The reading from the IC conforms with IEC 61000-4-7 Class I and Class II specifications. The readings provided by the IC are active, reactive and apparent powers; power factor; total harmonic distortion and harmonics within the 2.8 kHz pass band in all phases. The IC incorporates second-order-sigma-delta Analog to Digital converters (ADCs) for high accuracy and contains a digital integrator on the phase and neutral current data paths. The harmonics engine that analyzes one phase at a time can analyze up to the 63rd harmonic and provides data for up to three harmonics. These values are updated at a rate of 8000 samples per second.

The energy metering IC uses either an Inter-Integrated Circuit (I2C) or Serial Peripheral Interface (SPI) for communication to enable configuration and data transfer. A High Speed Data Capture (HSDC) port can be used with I2C to provide direct access to the ADC outputs and power information in real-time. The IC can be operated in three different low power modes to save energy when operated using battery power.

2. CONTROL AND DATA TRANSFER

The energy metering IC requires a host microprocessor for configuration and acquiring data. Texas Instruments CC3200, a single chip wireless microcontroller unit (MCU) doubles as a Wi-Fi enabled device allowing data transfer and also contains an ARM Cortex M4 processor running at 80MHz. The Wi-Fi internet on chip supports enterprise security and WPS 2.0 for secured communication and includes embedded TCP/IP protocol stacks. This MCU provides the required control and forms the bridge for the data between the ADE7880 and the cloud. The integrated processor enables the MCU to perform the intermediate data processing required before it is transferred to the server which ensures that the data transferred is at its minimum and thus reducing the load on the central processing system. The Universal Asynchronous Receiver/Transmitter (UART) interface of the MCU provides access to the ADE7880 for system configuration and calibration without the need for network connectivity. The requirement of physical access to the energy meter for configuration improves the security of the system. The availability of General Purpose Input Output (GPIO) pins on the MCU can be used for controlling relays or switches in response to an abnormality in the power supply system.

The data transfer should be done using a very light weight protocol implementation in a format that enables portability between different systems allowing the use of the data for various analysis. The data transfer from the MCU to the server is to be done over MQ Telemetry Transport (MQTT) Protocol, a “light weight” messaging protocol on top of TCP/IP designed for machine-to-machine communication and the IoT [21]. It’s a broker-based publish/subscribe protocol designed to be lightweight to run on limited resources and limited bandwidth. The format of the data to be transferred will be in JavaScript Object Notation (JSON), a light weight data-interchange format which would offer high interoperability for the data between multiple systems [22].

The MCU should be able to ensure that an abnormality is notified to the server and in the event of a communication failure able to stack the events occurred that can be transferred later. The transfer and storage of the key data parameters at a frequency of 8000 samples per second is required for better data analysis. However the data of just 13 key parameters transferred at that rate will result in 1.5 GB of data every hour and 13 TB every year which can be overcome by transferring and storing data at a much lower frequency.

The MCU will use a circular buffer to store the key parameters on an on-chip memory of 256KB SRAM which will provide high frequency data for 0.61 seconds. The use of external memory using Direct Memory Access (DMA) will provide much longer periods of data storage. In the event of an abnormality the data from the circular buffer will be made available for analysis.

The energy metering system is to operate the energy metering IC at low power modes during equipment idle time to avoid energy usage and data transfer during an idle state.

3. DATA PROCESSING AND STORAGE

The use of a cloud platform which provides Platform as a Service (PaaS) enables a reliable system with a load based costing model. The data storage and processing is to be present on the same premise to avoid latency in accessing data for analysis. Microsoft Azure, a cloud computing platform provides an end-to-end solution for IoT, big data processing, storage and analytics.

The end point that receives data from the terminal units for analysis is to be provided by Event Hubs PaaS which can handle data ingress from multiple units in real-time while the data transfer from the server to the energy meter is enabled by using the Service Bus Topics PaaS. The data received from the energy meters are in MQTT protocol which is to be converted into Advanced Message Queuing Protocol (AMQP) for processing in the cloud.

The events are analyzed in real-time using Stream Analytics and the data is stored for Machine Learning algorithms for prediction based fault detection.

The data flow of the proposed Energy Monitoring System is depicted in Figure 2. The data transferred from the energy meters to the cloud can be classified into measurements and abnormality event.

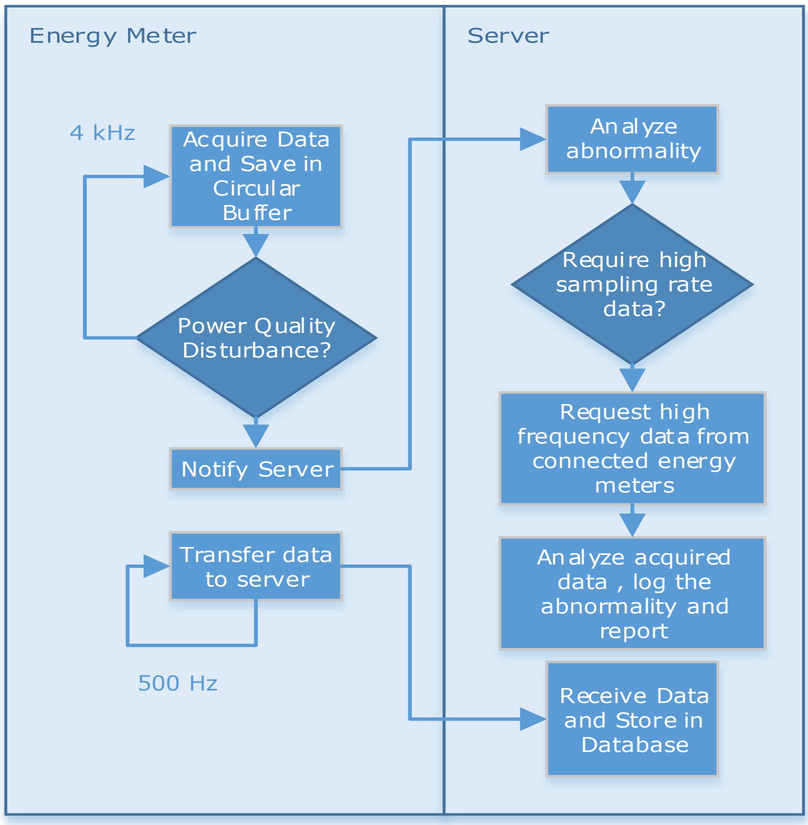

FIGURE 2. Flow chart of the proposed Energy Monitoring System

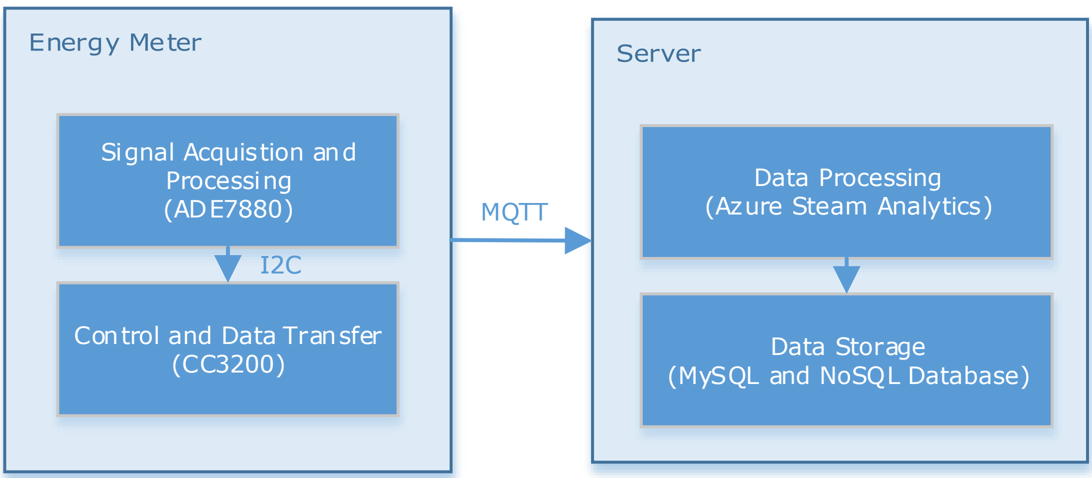

FIGURE 3: System Fabric Design

The general methodology for the project flow is given in Figure 4. The details of the flow chart are as follows:

- The Development and Testing of the meter requires laboratory power source with variable voltage and current settings. Multimeter and Oscilloscope would be required for calibration and to test the accuracy of the system
- Voltage and Current sensors are to be selected to provide the required accuracy for the calculation of Power Quality parameters
- The interfacing of the sensors to the energy measuring IC requires the conditioning of the output signal and required isolation
- The algorithms for calculating the required data from the measured values are to be deployed and optimized to achieve the required processing rate
- The communication platform based on Ethernet/Wi-Fi is to be developed on the microcontroller to enable transferring of the data to the storage media.
- The development of a Graphical User Interface is to be developed to enable the configuration of the metering device

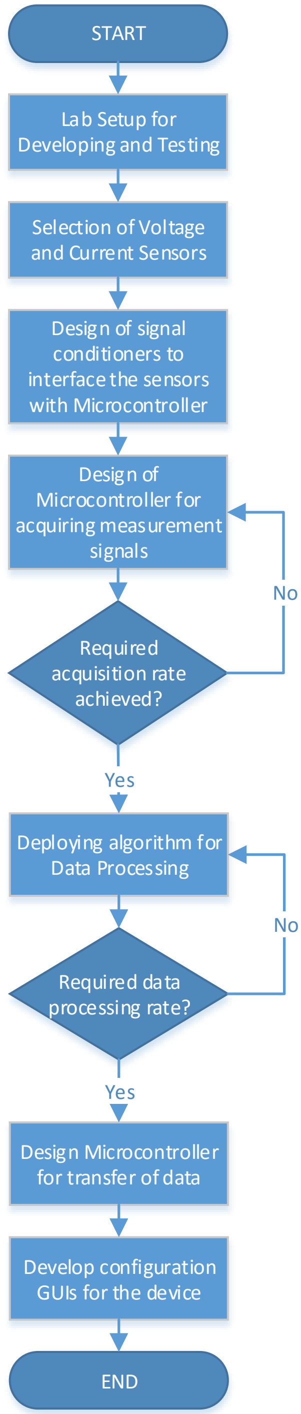

FIGURE 4. Flow Chart of the Research Methodology

CHAPTER 5
RESULTS AND DISCUSSION

The principles and the outcomes of the Energy Monitoring System designed are discussed.

1. SENSORS INTERFACING WITH ADE7880

The Analog to Digital Converters (ADCs) of the Energy Measuring IC ADE7880 has a limitation of a full-scale input of 0.5V differential input. The real power signals should be converted to this range to ensure accurate reading without damaging the Energy Meter IC. The design of the voltage divider and that of the current sensing circuits were simulated and tested for integration with ADE7880. The simulations were performed in LT Spice IV.

1.1 Voltage Sensing

The line voltage source will be stepped down using a voltage divider and connected directly to the voltage input of the ADE7880. A simple resistor divider network is used for attenuating of the line voltage before connecting to the voltage input of ADE7880. The attenuation circuit is designed for a 3 dB corner frequency to match that of the current channel inputs. Figure 5 shows the circuit used for the voltage source. The resistors R1 and R2 are used for the resistor divider and the R2 in parallel with the Capacitor provides the antialiasing filter. Figure 6 shows the simulation with an input voltage of 240 V at 50 Hz with an output voltage of ±250 mV. The maximum voltage to be measured is set to 600 V. However the resistor R1 can be modified to change the voltage input limit. The analog input can withstand a voltage of ±2 V without the risk of permanent damage.

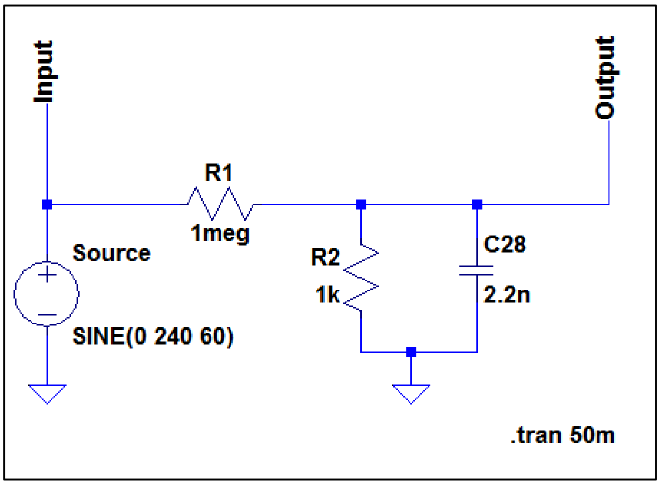

FIGURE 5. Voltage Attenuator with Anti-Aliasing Filter

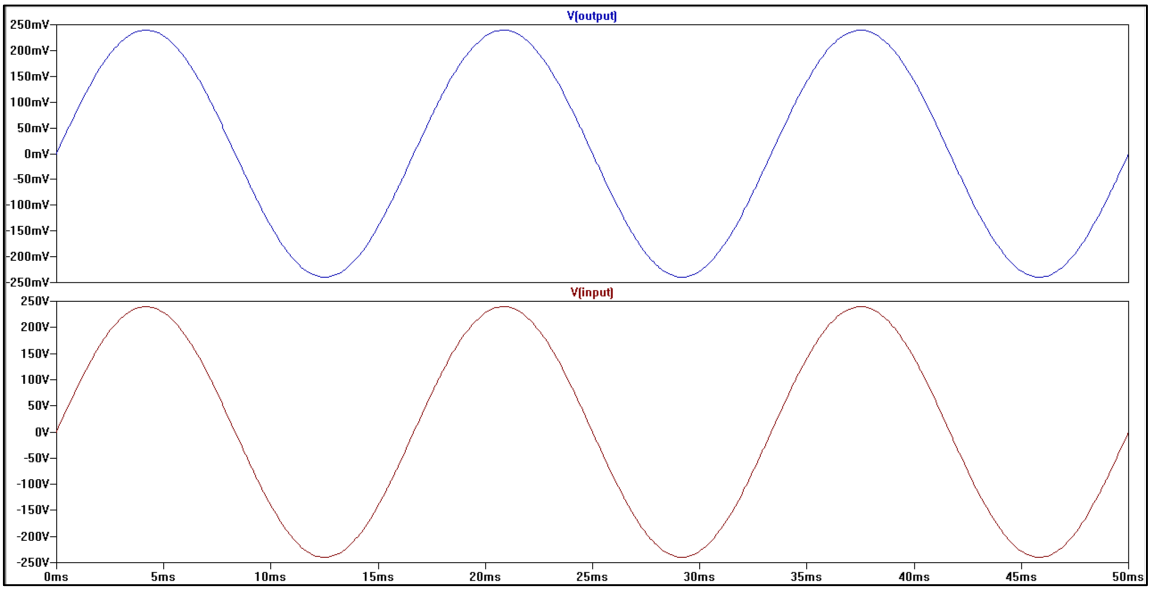

FIGURE 6.Voltage Attenuator with Anti-Aliasing filter Output

1.2 Current Sensing

The current sense input requires a current transformer to measure the current. The circuit design is shown in Figure 7. The resistors R1 and R2 are the burden resistors used to convert the secondary current of the transformer to a voltage. Resistors R4 and C3 acts as an antialiasing filter with a corner frequency of 72 kHz. The Figure 8 shows the simulation with an input current of 8 mA (Transformer's Secondary).

$$Cutoff\ Frequency, f_c = \frac{1}{2\pi RC} \qquad (3)$$

$$Burden\ Resistor, R = \frac{1}{2} \times \frac{0.5}{\sqrt{2}} \times \frac{N}{I_{FS}} \qquad (4)$$

where N is the input to output ratio,

$\frac{0.5}{\sqrt{2}}$ *is the rms value of full scale ADC input voltage*

I_{FS} *is the maximum rms current to be measured*

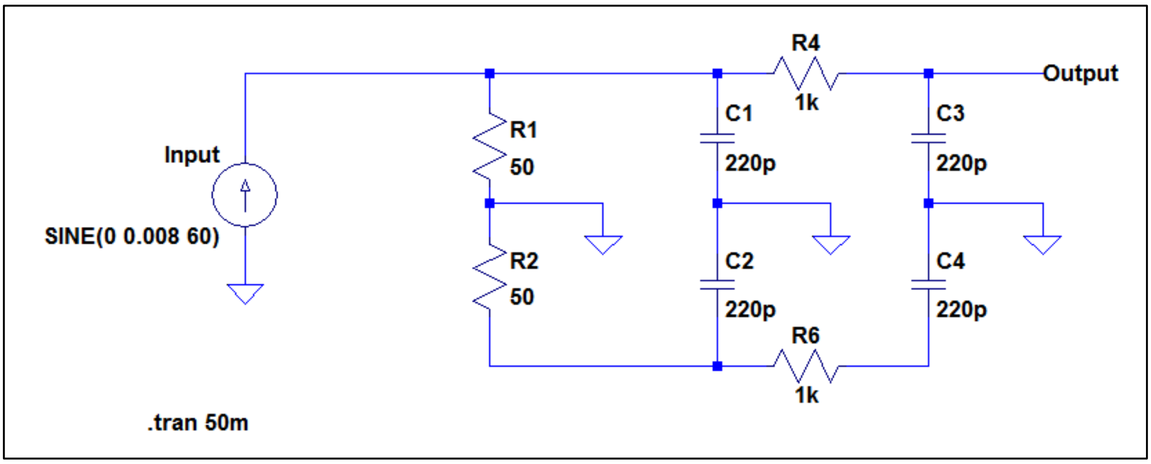

FIGURE 7. Current Transformer Circuit

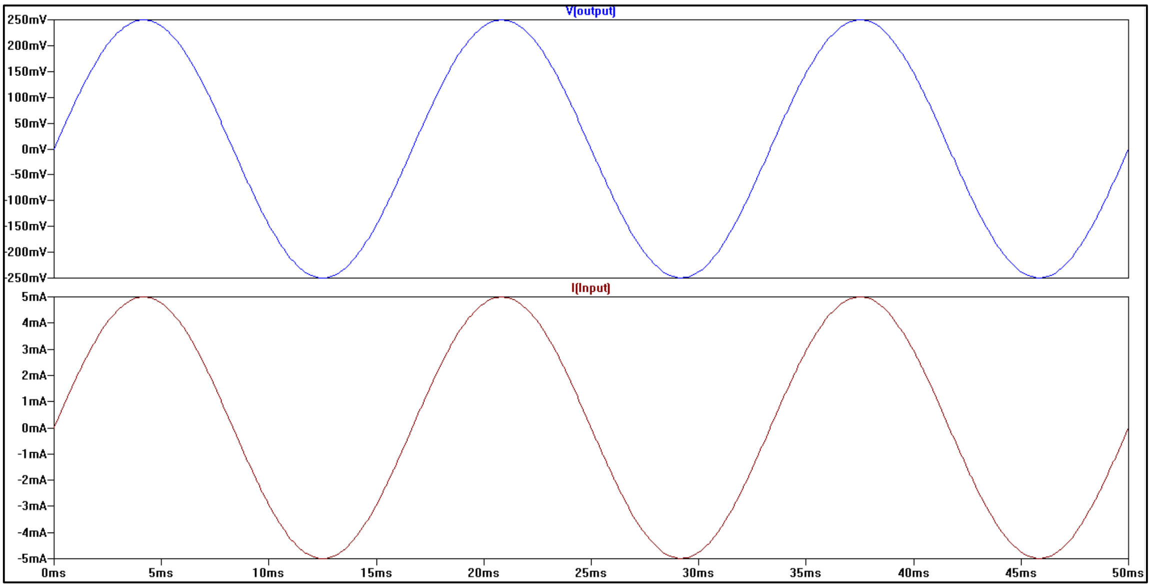

FIGURE 8. Current Transformer Circuit Output

2. Inter IC Communication

The interface between the Energy Metering IC and the main Microcontroller is essential to develop the system this was implemented using the Inter-Integrated Circuit (I^2C) communication protocol. It was established by Philips Semiconductor as a multi-master, multi-slave protocol. Used to connect lower speed peripheral ICs to microcontrollers. The I2C communication is made up of two bidirectional open-drain lines – Serial Data Line (SDA) and Serial Clock Line (SCL) with pulled up resistors. Neither the mater nor the slave drives the signal High enabling different voltage signals to interface without level-shifting circuits by pulling up the signal line to the lowest voltage in the transmission. The I2C systems have a 7-bit address space and operates on three different speeds low-speed mode (10 Kbits/s), standard mode (100 Kbits/s) and fast mode (400 Kbits/s).

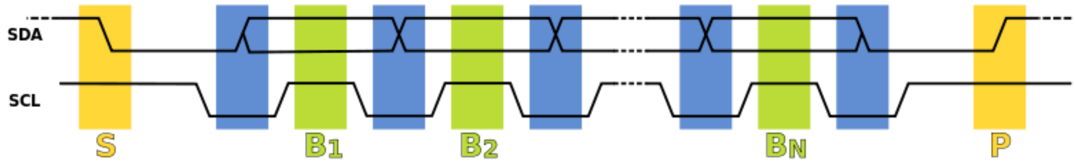

FIGURE 9. I2C Timing Diagram

The timing diagram of a I2C data transfer is shown in Figure 9. The flow of the data transfer is,

- A START bit is signaled by pulling SDA Low when SCL is High
- The first data bit is set in SDA while maintaining the SCL Low
- The received data is sampled when the SCL rises (green)
- The process repeats, SDA transitions while SCL is low and the data is read when SCL is High
- A STOP bit is sent when the SDA is pulled High when the SCL is high

The I2C standards varies from devices to devices based on the number of data to be transmitted in a single transmission. The different standards for reading and writing data from and to the ADE7880 are discussed in detail.

The ADE7880 I2C system supports a clock frequency of maximum 400 kHz. The master device CC3200 initiates the data transmission by generating a START condition. The master transmits the address of the slave device and the direction of the data transfer in the initial data transfer. If the slave send an Acknowledgment Signal the transaction continues until a STOP the maters issues a stop condition.

2.1 I2C Write Operation

Write operation to ADE7880 is initiated when a START condition is generated by the master and consists in one byte the address of ADE7880 followed by the 16-bit address of the target register and the value of the register. The 7-MSB of the address byte consists of the ADE7880 address (0x0111000) and the Bit 0 denotes a read/write bit. After receiving one byte the ADE7880 generates an acknowledgement signal. The master generates a STOP condition when data transfer is completed. The timing diagram of I2C Write Operation of a 32-Bit Register is shown in Figure 10.

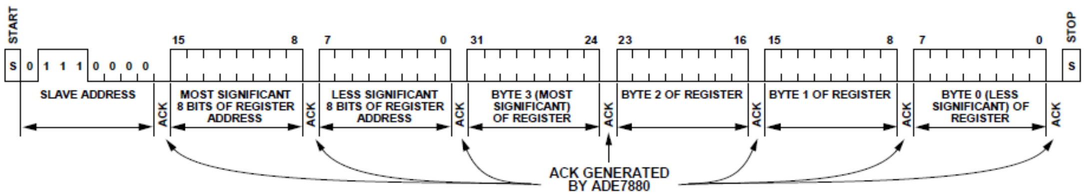

FIGURE 10. I2C Write Operation of a 32-bit Register

2.2 I2C Read Operation

The read operation to ADE7880 is done in two stages. The first stage sets the pointer to the address of the register to be read. The second stage reads the content of the register. The timing diagram can be seen in Figure 11.The Master generates the START signal and the address of the slave followed by the 16-bit address of the target register. After the last byte the target address is sent and acknowledged the second stage begins with a START signal been generated by the master followed by the address byte. After this is received the slave sends the data with the MSB first.

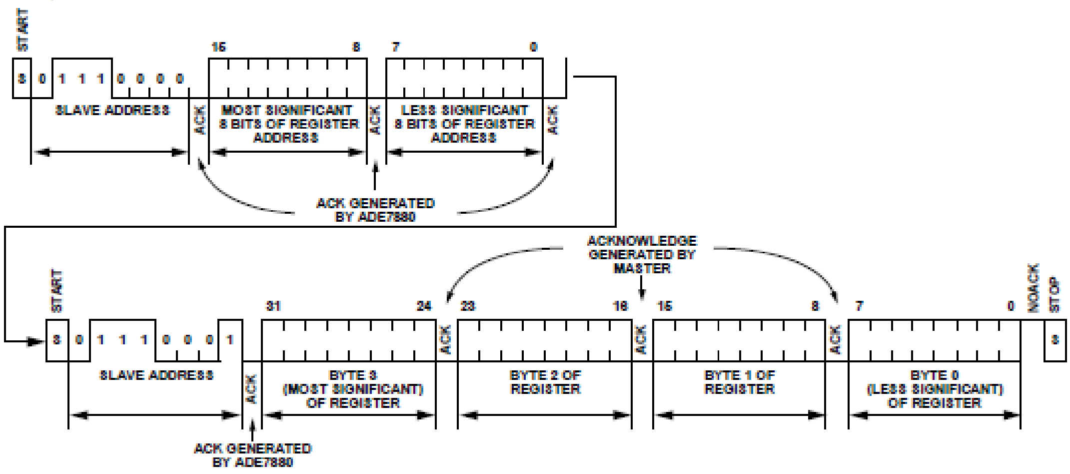

FIGURE 11. I2C Read Operation of a 32-bit Register

2.3 I2C Read Multiple Registers

The Harmonic calculations of the ADE7880 are stored in a sequence of registers and reading each register one by one would result on high overhead. ADE7880 provides access to all the Harmonics registers in a single transaction. The 32-bit width registers containing the harmonic calculation is located starting at the address 0xE880. The burst mode reading of multiple registers is show in Figure 12. The burst mode is accomplished in two stages. The first stage sets the pointer to the address. The second stage reads the content of the register. It begins with generating a START signal followed by the address. After the data of the first register is received the master acknowledges and the ADE7880 increments the pointer to the next register. The process continues until the master stop acknowledgement and generates a STOP signal.

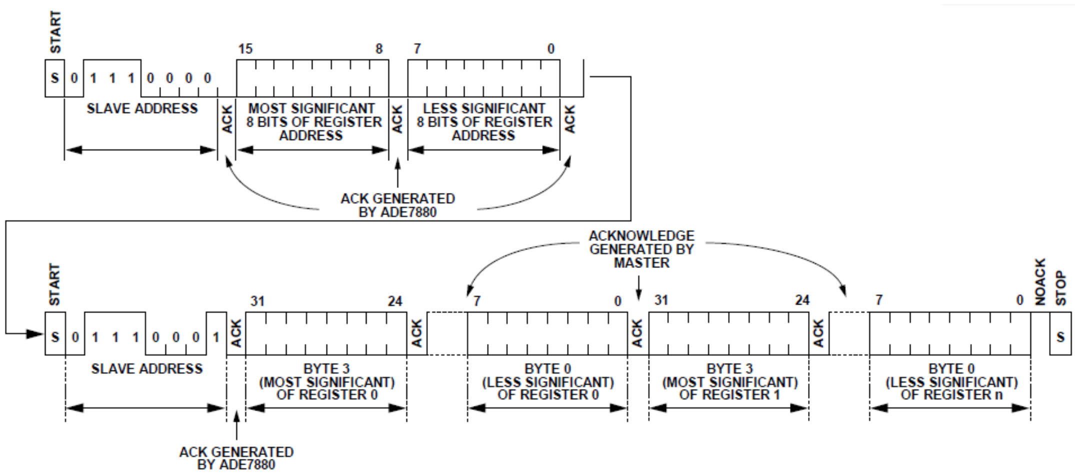

FIGURE 12. I2C Harmonics Data read operation

3. MQTT Server

The data from the Energy Meter is processed by the microcontroller and the data is transferred to the server using MQTT Protocol for further analysis. The publish-service model requires a message broker server to enable communication. The broker distributes the data to interested clients based on topics. The various methods/modules established in the MQTT Protocol are Connect, Disconnect, Subscribe, Unsubscribe and Publish. The clients use a specific topic to send data and another client subscribed to the same topic receives the data.

One of the main feature of MQTT Protocol is Quality of Service (QoS), it makes communication easier in unreliable networks because the retransmission and guarantee of message delivery is handled by the protocol. The values levels of QoS and their functions are,

QoS 0: It guarantees best effort delivery. A message won't be acknowledged by the receiver or redelivered by the sender. It can be referred to as "fire and forget".

FIGURE 13. MQTT QoS 0 Transaction

QoS 1: It guarantees that the message is delivered at least once to the receiver. However the message can be delivered more than once. The sender stores the message until an acknowledgement is received in form of a PUBACK command message. Failing to receive PUBACK in a reasonable amount of time the sender retransmits the message.

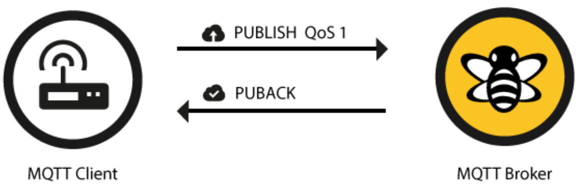

FIGURE 14. MQTT QoS 1 Transaction

QoS 2: Ensures that the message is received only once by the counterpart making it one of the safest and the slowest QoS level. When a packet gets lost in transaction, the sender takes the responsibility of resending the packet after a reasonable amount of time.

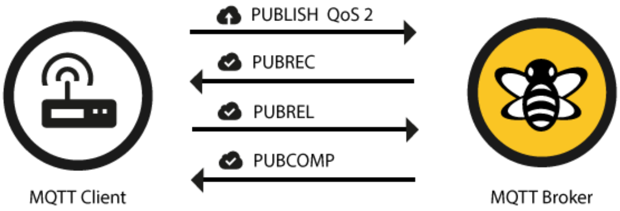

FIGURE 15. QoS 2 Transaction

The server for the MQTT broker was established locally for testing and later deployed on the Azure Cloud Platform. The various QoS levels were tested with for deciding the QoS level for the Energy Monitoring System. QoS Level 1 was used for the notification of abnormality to the server since the event should not be missed but can be repeated twice or more. However the regular transaction of historical data can be done in QoS 0 to reduce the overhead that will be resulted due to QoS 1 or QoS 2.

The JSON Data structure is used for transfer of data from the energy meter to the server. An example of transferred raw data is show in Figure 16 and 17. This enables other systems to access data and interpret it.


```
{
  "d": {
    "id": "SHOT_BLASTING_1",
    "pf": 0.94,
    "v": {
      "a": 239,
      "b": 242,
      "c": 242
    },
    "i": {
      "a": 13.2,
      "b": 13.7,
      "c": 12.9,
      "n": 13.4
    }
  },
  "ts": "2015-10-31T14:47:36+00:00"
}
```


FIGURE 16: JSON Object for a Measurement

```
{
  "d": {
    "id": "SHOT_BLASTING_1",
    "event": "V_SWELL",
    "phase": "A",
    "value": 279.5
  },
  "ts": "2015-10-31T14:47:36+00:00"
}
```


FIGURE 17. JSON Object for a Voltage Swell Event.

3.1 Local Server

A local Linux machine based on the Ubuntu flavor was established to act as an MQTT Server. The server was established using an open-source library – Mosquitto MQTT Server. The details of the MQTT Server are shown in Figure 18. The server listens to Port 1883 for the MQTT traffic. The local server enabled easier modifications before the deployment to the Cloud which would face latency.

```
kodedevil@userver: ~
Using username "kodedevil".
kodedevil@localhost's password:
Welcome to Ubuntu 15.10 (GNU/Linux 4.2.0-16-generic x86_64)

 * Documentation:  https://help.ubuntu.com/

Last login: Sun Dec 13 20:00:45 2015 from 10.0.2.2
kodedevil@userver:~$ mosquitto
1450689460: mosquitto version 1.4.5 (build date Mon, 09 Nov 2015 15:00:46 +0000)
 starting
1450689460: Using default config.
1450689460: Opening ipv4 listen socket on port 1883.
1450689460: Opening ipv6 listen socket on port 1883.
```

FIGURE 18.MQTT Server Broker

3.2 Remote Server

A virtual machine on the Azure Cloud Platform running Mosquitto MQTT Server was established the data was processed in real time and the analyzed result was sent to Android Devices using Notification Hubs. The establishment of a Cloud based server provides low latency access to storage and other computational services that can enable Machine Learning and Predictive Maintenance. The details of the Cloud end point to that acts as an MQTT broker is shown in Figure 19.

Resource group	DNS name
EnergyMonitoringSystem	mqttserver-02ft75d2.cloudapp.net
Status	Operating system
Stopped (deallocated)	Linux
Location	Size
East US	Standard DS1 (1 Core, 3.5 GB memory)
Subscription name	Virtual IP address
Pay-As-You-Go	-
Subscription ID	Virtual network/subnet
eac41746-2bef-43ae-8eb9-e76185c4fca0	MQTTServer

FIGURE 19: Cloud Server End point Details

An example of the code that analyses data for over voltage and the result of the analysed data been received and analysed in the server is shown in Figure 20.

```
kodedevil@MQTTServer:~/mqtt$ sudo python main.py
Connected with result code 0
/cc3200/regular 241.8
/cc3200/regular 241.9
/cc3200/regular 239.7
/cc3200/regular 256
Voltage Swell
/cc3200/regular 245
```

FIGURE 20. Example of MQTT Data Processes

```
import paho.mqtt.client as mqtt

def on_connect(client, userdata, flags, rc):
    print("Connected with result code "+str(rc))
    client.subscribe("/cc3200/regular")

def analyze(input):
        if(float(input) > 250.8):
                print "Voltage Swell"

def on_message(client, userdata, msg):
    print(msg.topic+" "+str(msg.payload))
    analyze(msg.payload)

client = mqtt.Client()
client.on_connect = on_connect
client.on_message = on_message

client.connect("mqttserver-02ft75d2.cloudapp.net", 1883, 60)

client.loop_forever()
```

FIGURE 21. Code for the above results

4. Energy Meter Design

The Printed Circuit Board (PCB) Design is to be done based on the required standards and parameters to avoid disturbance in ADC signals and I2C communication signals. The circuit schematic and the PCB layout is shown in Figure 22, 23 and Figure 24 respectively.

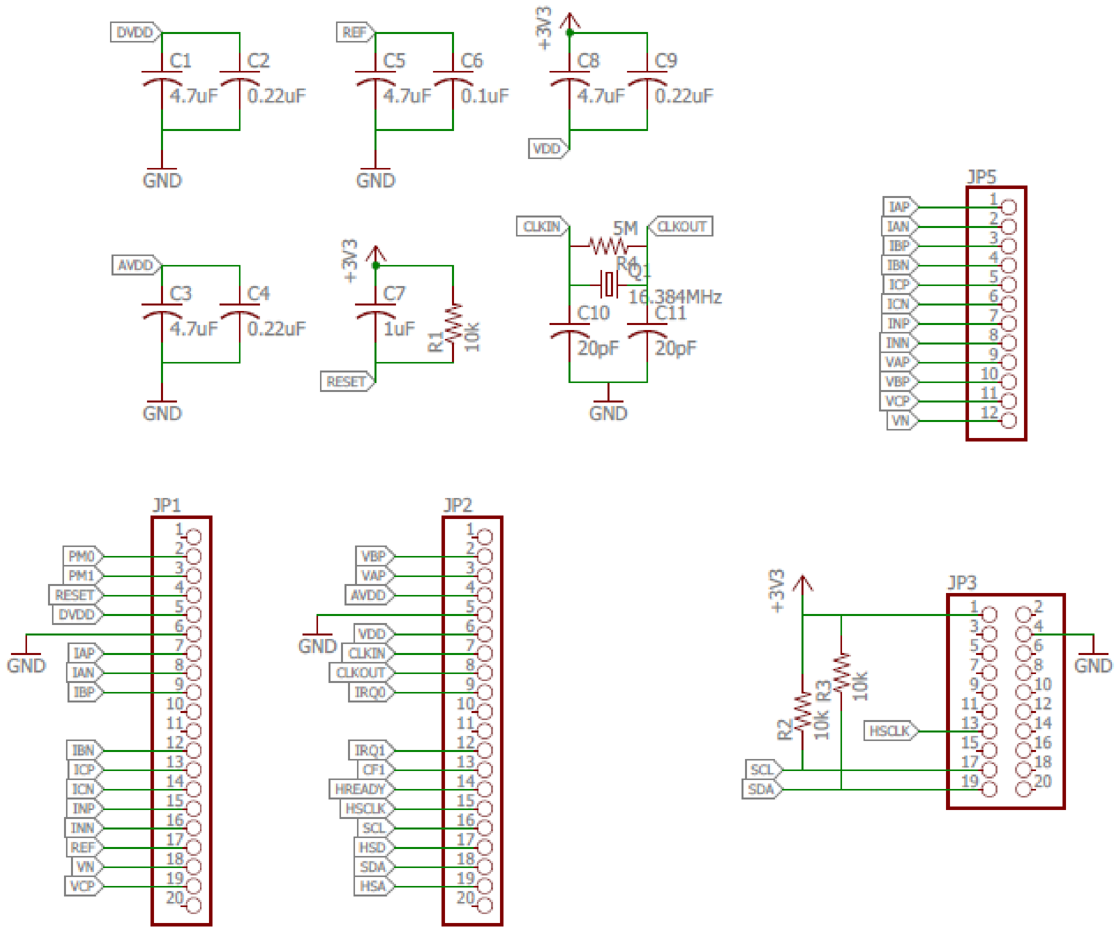

FIGURE 22. Energy Meter Schematic

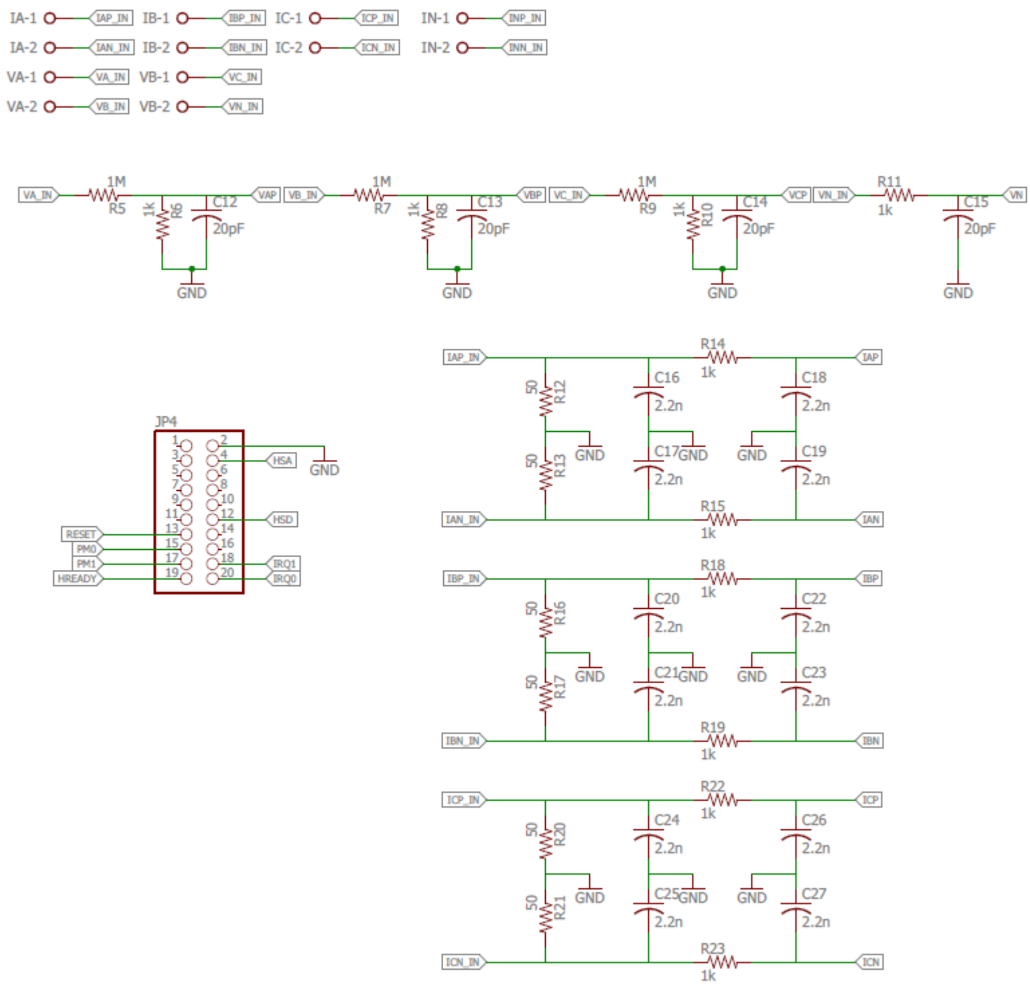

FIGURE 23. Energy Meter Schematic

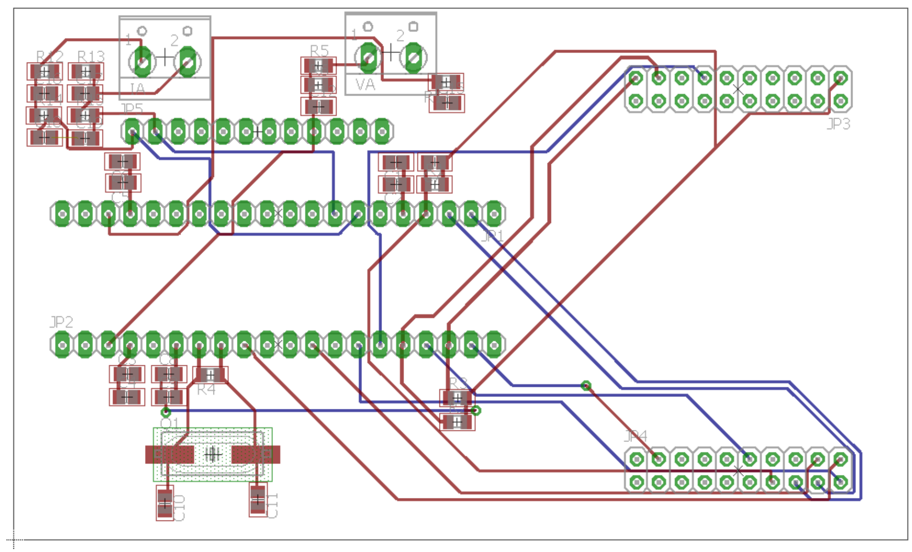

FIGURE 24. Energy Meter PCB Design

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

1. CONCLUSION

The development of an energy monitoring system with the ability to acquire, process and store data in real-time is required for improving energy efficiency operations of the manufacturing industries and to enable proactive maintenance.

The real-time data acquisition was done using a dedicated Energy Metering with a fixed function DSP. The chip level design of ADE7880 for metering enabled real-time acquisition of data. The used of a powerful processor based on ARM Cortex platform provided headroom for complex data filtering and also the ability to connect to a Wi-Fi network. The use of low level MQTT Protocol on top of well-established TCP/IP Protocol resulted in lower overhead for data transfer, which is essential for real-time data transfer in limited bandwidth.

The high computing performance required for processing huge sets of data is achieved by establishing Virtual Machines on Microsoft Azure Cloud platform. That enables faster scaling and low latency access to historical data. Virtual Machines as a Platform as a Service (PaaS) ensures that the server is not paid for when not used making implementation of the system cheaper for huge scale adaption.

A smart object communicated between each other and the server this enables better integration and varied use for the data. The used of standard and open-source protocol such as MQTT and data standard such as JSON ensures the ability for other systems to make use of the data from the Energy Monitoring System without further modification. The ability for multiple Energy Meters to talk between each other enables further development

2. RECOMMENDATIONS

The availability of real-time energy and power quality data on a cloud platform along with access to low latency historical data enables energy saving algorithms and proactive maintenance possible. The further development is to be done on Machine Learning algorithms that will make use of the real-time data to ensure prediction of machine failure using power quality data and ways to improve energy efficient process.

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