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Preliminary Report

MA, DARYL(DM2913)
00754071
BBOXX LTD

Executive Summary

BBOXX is a start-up that has gone from strength to strength having initially started in March 2010 as a company designing and manufacturing solar systems that are distributed in Africa. Having finally asserted their market position in Kenya and Rwanda, and also having achieved Series C funding[1] of £15m pounds worth of investment, BBOXX is now seeking to push towards new frontiers and develop new technologies.

Having sensed an opening in the scalable AC smart metering market in Africa and other locations around the world, BBOXX aims to expand their business by creating a new product termed the BBOXX Hub. The Hub is a product designed to support existing BBOXX infrastructure including the GSM connectivity and remote monitoring of products, and to also be able for interfacing with additional sensors such as the AC metering.

My role for this 6-month placement period would be to drive the implementation of the AC Smart meter, and I will be responsible for the standard and quality of its measurements. The implementation of the AC Smart Meter will be separated into distinct and manageable phases. The final product would also be able to communicate with existing BBOXX systems as well.

This project will require application of my technical skills in the area of instrumentation design, firmware design and also the ability to speak to fellow co-workers regarding the current technologies involved in the implementation of previous BBOXX products.

[1] Series C Funding: Third Phase of Investment Capital meant for company fast scaling and business expansion

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1.Company Overview

BBOXX was founded by three alumni from the Electrical and Electronics Engineering Department in Imperial College London in 2010. The company aims to provide 20 million people with electricity by 2020, and intends to do so by using a financing structure that relies heavily on technologically advanced products and appliance. Recently, BBOXX hit its highest ever cash collection in March 2016, with £81,000 collected. With this, BBOXX is now looking to expand its business, by looking into the metering market, and also by selling its technology to third parties.

1.1 Department

BBOXX has offices in the UK, China, and Africa. The engineering team is located in London, while the manufacturing team is located in China. The team in Africa is mainly focused on the sale of BBOXX products. The engineering team in London is split into 2 main departments. The first department is the Smart Solar team, which works on the current BBOXX products, and mainly involves the hardware, software, and firmware required for the BBOXX Home[2] and Hub[3] lines to run smoothly. The second department is the software department, which focuses on the web interface and payment collection for customers around the world.

[2] BBOXX Home: Plug and Play product that includes a 50W roof mounted solar panel, with DC outputs for powering lights, TVs and phones.
[3] BBOXX Hub: New product that aims to be able to contain multiple sensors that can be modularized to suit individual customers.

1.2 Role and Responsibility

My role would be based in the smart solar team, where I would be in charge of designing and implementing an AC Smart Meter that is capable of being integrated into current BBOXX technologies. I would take charge of the design conception, prototyping, the testing, and the integration of the product. This would be done in phases as will be covered in greater detail in **Section 2.3.**

2. Project Description

2.1 Application

This product would enter the Rwandan markets as a smart meter for current on-grid systems for accurate electricity metering. Currently, Rwandan electricity customers are billed inaccurately by the grid operators, as there is no clear metering system in place. BBOXX aims to provide this smart metering in order to allow customers to receive an accurate reading of their electricity usage through text messages. This product would also be sold to third party customers as a fully independent AC Smart Meter for off-grid locations for use with inverters or large scale appliances.

2.2 Deliverables

The deliverables would be for the product to be competitively priced in comparison to current market options, and be scalable for large scale manufacturing. This product would also have to be capable of measuring both AC and DC voltage and currents, while finally it has to be able to integrated with the current BBOXX hub system, which is GSM enabled to work in off-grid locations.

2.3 Approach

The project can be divided into 5 different phases as seen in **Figure 1** below.

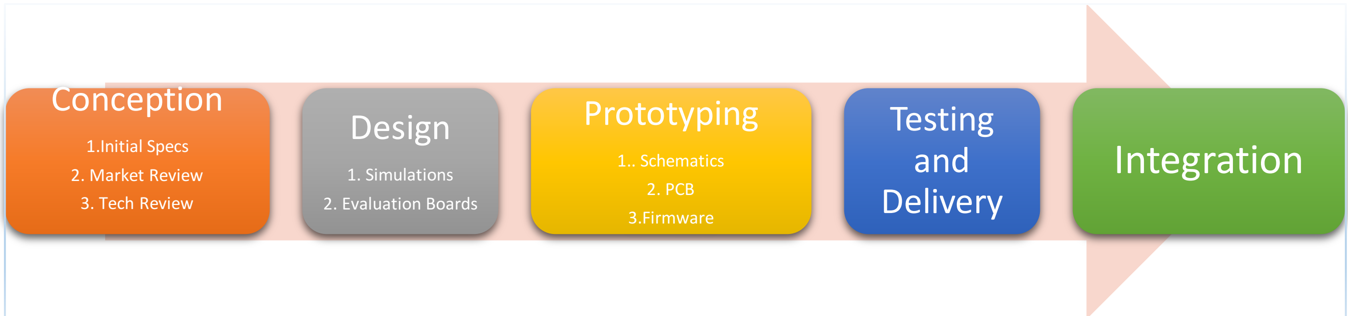

Figure 1: Project Phases

The **conception** stage involves applying the initial specifications that would be used to provide the direction for the project. A quick review into the current competitors in the AC smart meter market for both the local market in Africa and western options such as the smart meter market in Europe and the US will be done. This information on the market for smart meters would show the possible costs involved in selling and prototyping these meters. The different methods of AC mains monitoring would also be explored, and the best method would then be evaluated and used in the initial prototype.

The next phase would be the **design** stage, where the specifications for the product would be much more detailed in order to satisfy all the requirements for BBOXX. Having clearer specifications would allow a basic circuit to be built up in LTSpice[4]

[4] LTSpice: Free software for circuit simulations.

for simulations, and this will be done in tandem with evaluation board[5] tests using existing circuitry for sensing mains. Doing so gives an understanding of the safety standards required for mains electricity sensing, and to slowly build up a test bench to the levels required for personal safety during the testing of these sensors.

The **prototyping** stage would then follow, whereby the schematic, PCB and the firmware of the initial prototype would be built up. Designing the schematic of the sensor would require a thorough investigation of the components available in the market and understanding their pros and cons. Once the basic schematic is done, the PCB design would begin. Both of these would be done in the Altium Designer[6], and hence it is important to properly learn the functions and capabilities of the software. Once the PCB design is complete, the manufacturing of the PCB design would take roughly around 2 weeks. This would allow time to focus on the firmware required for programming the microprocessors and the sensor required. Calibration of the sensor to accurately measure the values required would be done in software, and doing so is hence related to the firmware design as well. Lastly, the firmware must be integrated into existing BBOXX technologies, with the sensor microcontroller able to accurately send data to the main microcontroller.

The **Testing and Delivery** Stage would then involve extensive testing and debugging, with the accuracy of the device to be determined, including its dynamic range. This would be important in ensuring that the quality of the product meets a minimum standard before it goes into production. Once the product reaches an acceptable standard, the next step would be to modifying the design processes to make it suitable for large scale manufacturing processes. This would require understanding the manufacturing process of the PCBs in China, and to find a method that would be appropriate with the tools they currently employ for manufacturing. Once this final design is done, this would be the final prototype of the AC Sensor.

The **Integration** Stage involves the big data analysis of the information that is capable of being sent by the sensor. The data obtained by the sensor would be sent via GSM to a server, where the data analysis for the user occurs. All data analysis would optimally be done on the server in order to reduce the amount of data required to be sent by GSM.

2.4 Technical and Soft Skills Required

As mentioned previously, the **conception** stage involves having to look into fellow competitors and understanding the current products in the market. Having to obtain information from these companies requires the ability to communicate with these firms in order to comprehend their products. This often involved emails with the CEOs of these companies, as they were mostly startups as well. An understanding of power electronics is also required in order to accurately assess various AC sensoring techniques.

The **design** stage requires increased power electronics understanding, and also an ability to utilize LTSpice to run simulations. For this case, it is far more important as dealing with mains voltage implies that any circuit mistakes could ruin the components or even hurt the user.

The **prototyping** stage involves a keen understanding of the concepts behind instrumentation. As learnt previously from the course, there is no perfect component for a certain circuit. Finding the component suitable for the circuit involves trying to find the right balance between the different trade-offs. The PCB layout would also have to be done, and this would involve understanding the software in order to utilize all the electrical connections correctly. For the firmware, a certain amount of

[5] Evaluation Boards: Boards provided by chip manufacturers that allows the user to test the functions of the chip with a pre-built circuit.
[6] Altium Designer: PCB Design software that contains schematic and 3D CAD elements that allows the user to build highly customizable PCBs.

software engineering in embedded systems is required, as was done in the Year 3 course for real time digital signal processing.

The other stages involve an extension of the previously mentioned technical skills, and would have to be applied further in order to complete the device. Having to integrate the firmware with the current BBOXX system would also involve communication with the employees both in the London office and in the China office, and hence would require extensive soft skills as well.

3. Details of Work

3.1 Conception Stage

3.1.1 Initial Specifications

An AC Smart meter implies a meter capable of metering the AC voltages, currents and power, while sending this information to a server. This can then be obtained by the customer for either further analysis, or to calculate their electricity usage.

3.1.2 Market Research

The smart meters produced by western metering companies such as Ikstra, Rexel and Elster cost in the range of £140 to £200 for a GSM enabled single-phase AC measurement. For a non-GSM enabled meter, the cost reduces to around the range of £30. Lower accuracy smart meters could be purchased on Amazon for around £50. However, these meters are purely WIFI enabled for homes in the western world, and not capable of GSM connectivity for use in rural areas. For more information, a table is available in **Annex C.**

For companies currently in the solar industry, 2 companies appear the closest to the implementation of a smart AC meter. The first company, Lumeter, has a product for both 240V AC and 120V AC for low-power AC grid monitoring. However, the max current rating for their products is limited to 5A. A SMS/Web enabled platform allows Lumeter to track the individual and aggregate usage, while using load-management features. The other company, Powerhive, has a centralized metering system that tracks the usage of customers via their output from the main generator. Data analytics is also performed on the data currently used for consumption patterns.

Hence, for a production cost of around £20, the sale of a single AC smart meter could be quite lucrative. This means that the product is definitely viable, and hence the project was given the go-ahead.

3.1.3 AC Sensing Methods

4 different sensoring methods were considered. Using a RMS to DC converter, Bridge Rectifier, Differential Amplifier and using an application specific integrated circuit(ASIC) for AC measurements. The method chosen was eventually the ASIC, due to its low track usage, and also because it automatically calculated all the values required while being able to transmit the data using 3 types of communication protocols[7].

The RMS to DC converter converts the RMS voltage of an input voltage into a DC value that can be read by the microcontroller. This would be suitable for the voltage, and is also of relatively low costs. The main drawback for this method was an inability to read AC current.

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[7] Communication Protocols: Protocols that define the way information is transmitted between two or more devices. Examples include SPI, UART, RS485 and I^2C.

The bridge rectifier circuit was considered to fully rectify the AC signal, before a smoothing capacitor is used to obtain a DC value from the circuit. This circuit was the cheapest among the methods. However, a large number of components was required, and more importantly, the smoothing capacitor did not necessarily generate a smooth DC signal.

The differential amplifier was also considered to be used with a gain and a bias, that reduced the AC signal to a value low enough. This method would reduce the AC signal to the required range for the microcontroller input, and would also bias the signal such that the signal is above DC. This would be useful for measuring the input signal as well. However, this circuit is unable to be used for current measurements.

All these methods were chosen before the ASIC was used. This was the best method in terms of the cost (£6 for all components required) and also simplicity, since the AC measurement IC allowed the current and voltage to be measured simultaneously. Furthermore, the power and energy could also be metered separately, and the communication protocol drivers were all included in the IC.

3.2 Design Stage

The design stage involved the use of LTSpice models to determine whether the circuit would work safely, and that the voltages involved were not too high. An example of the circuits tested can be seen in **Annex A**. The simulations allowed us to further determine that the differential amplifier and the bridge rectifier circuits were not so suitable, and this led us to use the ASIC to determine the voltage and current.

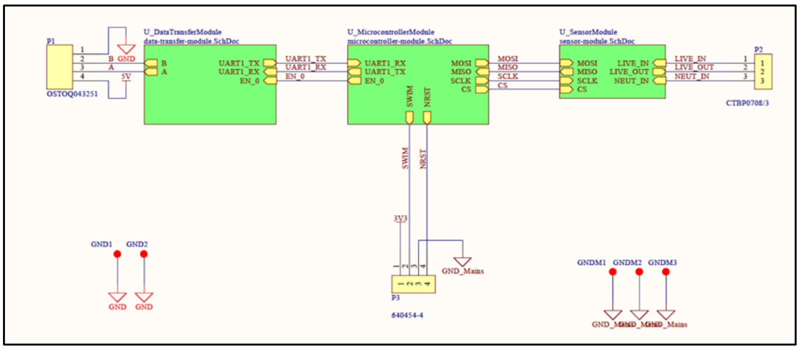

Figure 2: Parent Schematic of the AC Sensor, with the green blocks representing the 3 modules, and the yellow blocks representing the connectors to all outputs/inputs.

The evaluation board used was useful in having a circuit that was already pre-built. This allowed the testing to be done safely considering the high voltages involved, and to also be able to have an idea of what the circuit should look like when using the ASIC. The evaluation board used was the EVAL-ADE7953, and a picture of this could be seen in **Annex B** as well.

3.3 Prototyping Stage

3.3.1 Schematic

The overall schematic involves 3 main modules. The sensor module, which deals with measuring the voltage and current from the mains input, the microcontroller module, which deals with the transmission of the sensor information, and the data transfer module, which involves the communications hardware and the isolation devices for the different protocols required.

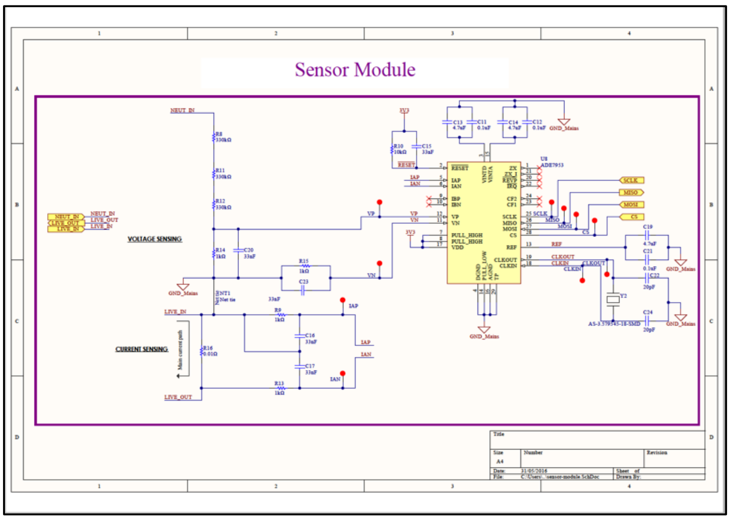

Figure 3: Sensor Module containing the ASIC, voltage sensing and current sensing circuits

Sensor Module

Different measurement ICs were considered before the ADE7953 was chosen for it being the lowest cost IC capable of I^2C[8] communication. This communication was compared with Serial-Parallel Interface(SPI) and Universal Asynchronous Transmission(UART) communication interfaces before being chosen for its daisy-chaining capabilities.

The ADE7953 measures the active, reactive and apparent energy/power, allows the sampling of input waveforms, and is also able to measure the RMS current and voltage. Programmable gain amplifiers at the input to the IC improves the resolution of the input signals into sigma-delta ADCs, thus increasing the accuracy of the readings.

The potential divider resistors had to be specifically chosen to ensure the max power rating was met. Considering an input voltage of 220V AC, the voltages are particularly high, and hence the resistors chosen had a voltage rating of 200V. These potential dividers formed the voltage sensing component of the circuit.

The current sensor chosen was a shunt resistor with a value of 0.01Ω, assuming a max current rating of 15A flowing in from the mains. The power rating of the resistor had to be carefully chosen such that the power rating was less than the power across the resistor. The shunt resistor was also chosen ahead of hall sensors or Rogowski Coils[9] due to the low costs involved.

Microcontroller Module

The microcontroller module involves a STM8 value line microcontroller, that was chosen for its cost. This microcontroller was added after initial tests showed that the ADE7953 IC had identical addresses, which gave rise to the issue of data collisions when adding multiple sensors to the same data bus using the I^2C interface. Hence, for scalability purposes, this microcontroller would allow the user to actively modify the address of the sensor.

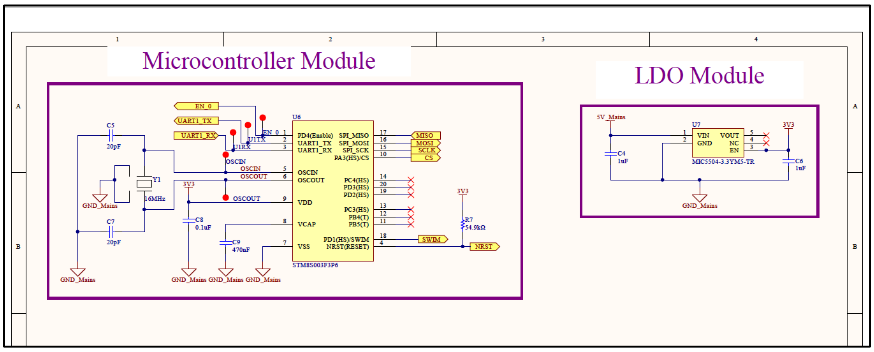

Figure 4: Microcontroller Module and the LDO Module

The low dropout regulator is used to drop the 5V supply voltage to a 3.3V supply for the microcontroller and the IC.

Data Transfer Module

For safety and isolation purposes, the decision was made to isolate the mains input side and the data transmission side in order to prevent any high currents from damaging the board.

This isolation is done by using a DC-DC converter in order to convert the 5V supply voltage from the BBOXX Hub to a 5V supply voltage referenced to the ground of the mains input. The transmission of the

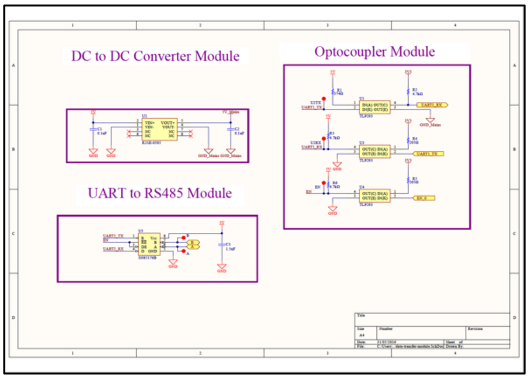

Figure 5: Data Transfer Module

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[8] I^2C(Inter-Integrated Circuit) is a communication protocol that utilizes 2 lines for data transmission. It is capable of daisy-chaining, where there are multiple master and multiple slaves attached to the same data bus. This protocol has the advantage of reduced tracks and ports required, considering it only needs 2 lines for all communications.

[9] Rogowski Coils: Device used to measure AC current by using the rate of change of current is proportional to the voltage.

UART data is also through optocouplers, that allow the signal to be isolated from the mains. Finally, a UART to RS485 driver IC is used to convert the UART signals to a RS485 protocol signal.

3.3.2 PCB Design

The PCB was designed based on the schematic as shown in **Figure 6**, with the 3D model shown in **Figure 7**. The size and the layout of all the components chosen were based on their datasheets.

The components were first placed as close as possible to reduce the amount of tracks required. Mounting ports and isolation barriers were then added as "keep out zones". The routing was then done manually such that each track was placed as carefully as possible. This was a time-consuming process, but the end result was that the tracks were as compact as could be. Finally, the silkscreen layer was added, with the name of the firm and its logo, and warnings for the high voltages involved added to the PCB.

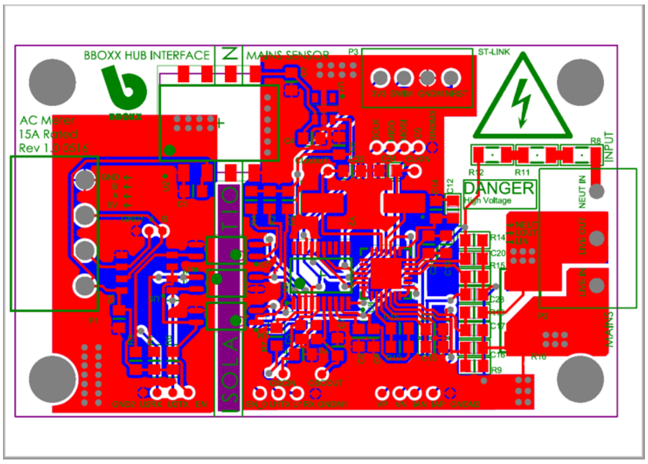

Figure 6: PCB Design, with the red representing the top layer, blue representing the bottom layer, and green representing the silkscreen layer

It is interesting to note that after choosing some components, I realized that they were not suitable for the PCB layout either due to their tracks or their size, and ended up changing them a few times. This was an eye-opener into the fact that the schematic is only one facet of the product design. Designing the PCB requires experience, and there were many things I could not foresee beforehand. One example was the size of the isolation barrier required. My initial design had a 5mm large barrier, but this was much larger than the size of the optocouplers. This led to a redo of the entire layout.

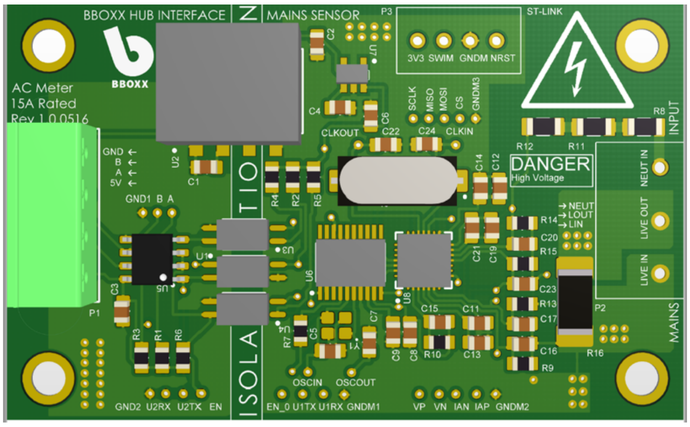

Figure 7: PCB Design using the 3D viewer

The PCB design was completed in about 2 weeks, and after numerous checks with the datasheets to ensure that the sizes were correct, and with fellow co-workers to ensure that there were no errors, it was sent for manufacturing.

3.3.3 Firmware

The firmware for the STM8 was tricky to obtain. One issue faced was the fact that the STM8 compiler was no longer freeware, as advertised on the STMicroelectronics site. This was an issue as I did not want additional software costs being added to the product. Hence, this led to a search for open source compilers, and a suitable version was found in the Small Device C Compiler(SDCC) developed by Sandeep Dutta. This allowed the compilation of C code into a hex format, that could be uploaded into the STM8 microcontroller by the ST-Link software provided by STMicroelectronics. The compiling was done using windows command line as shown in **Figure 8**, which took a while to get used to as there was no console window.

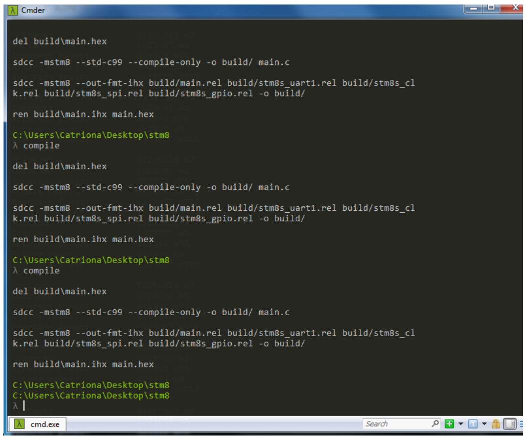

Figure 8:Windows Command Line Compilation of Code

The data obtained from the sensor was tested, and the following readings were sent via UART to the PC. This allowed us to obtain the following readings as shown in **Figure 9**. This showed that the sensor was working after calibration was done.

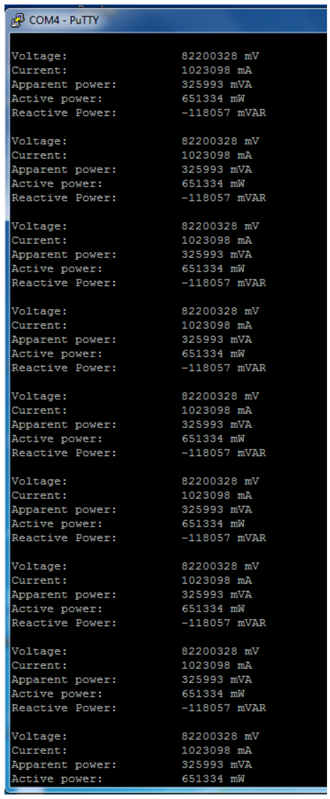

Figure 9: Readings from the Sensor

3.4 Future Stages and Contingencies

To date, the manufacturer PCB has not arrived. Hence, most of the calibration and testing is done on the evaluation board. Once the PCB arrives, the components will be soldered onto the PCB board and testing will commence.

A few possible issues I expect to face would be the accuracy of the sensor and how well it would measure the power. This involves using a reference meter that has to be of high accuracy in order to determine how accurate the sensor is. The next issue would also be the algorithm for calibrating the sensor. Considering all the sensors need to be calibrated separately, I would need to find an algorithm and write a program that allows quick calibration of all the sensors for large scale production.

Considering all these issues, I tried to push forward the PCB production and firmware production such that I could complete it within the first 2 months. This leaves me with ample time to complete the testing and debugging for the product in the future.

4.Project Timeline

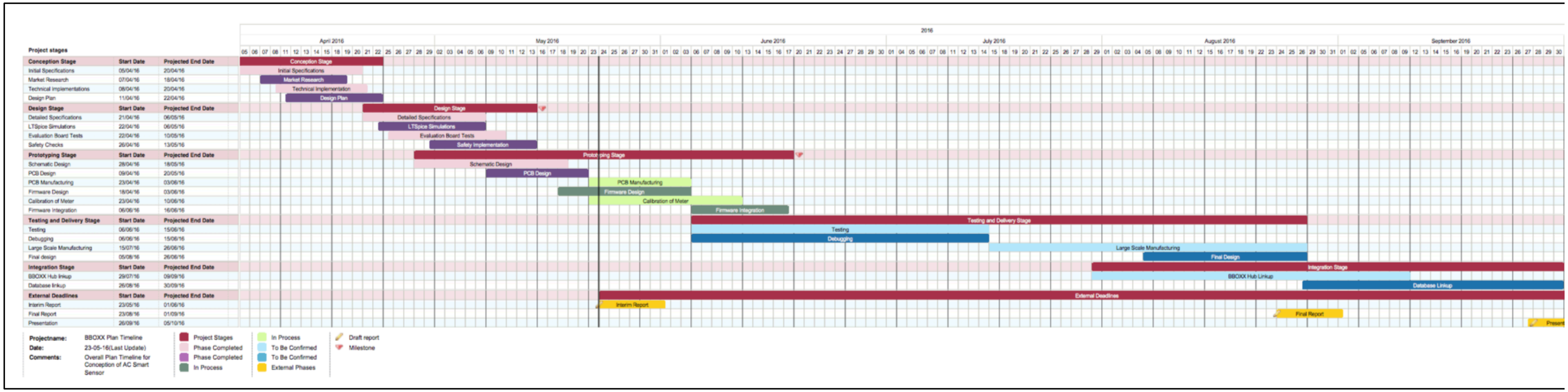

Figure 10: Gantt Chart for 6 Month Long Program

As seen from **Figure 10,** the entire process for the product lifecycle is shown. The different stages lead to each other, and hence it is important to complete the previous stages before moving to the next stages. However, certain processes can be overlapped in order to increase the efficiency, as done with the PCB manufacturing and the firmware design. Using this Gantt chart allows the maximization of my time at work, and also leaves me with more room to plan for likely mistakes made, considering this is my first time designing a circuit from scratch. Hence, the large time given for testing and delivery (12 weeks) is currently to be confirmed, whereby if I am able to accomplish the product up to an acceptable standard before then, I would be able to move on to the next stage. This is dependent both on my personal satisfaction, and also by speaking to fellow co-workers and asking them for their inputs on how to improve the product.

5. Conclusion

This is one of the best chances for me to learn and expose myself to the life of an electrical engineer. In 2 months, I have delved into software and hardware, learnt new programs and had the opportunity to buy new products for testing. Working in a startup is also much more efficient, with buying and sourcing for components being much quicker as I would only have to go through my manager. Most importantly, with many of my fellow co-workers graduates from Imperial, its been a joy to learn and understand their point of views. I have enjoyed myself thoroughly these 2 months and I would be looking forward to the next 4 months for a fulfilling and enriching placement.

Annex A: Spice Models

The Spice Models shown were used in the simulation of the possible AC sensing circuits. These circuits were eventually not used in the final schematic.

Bridge Rectifier Circuit

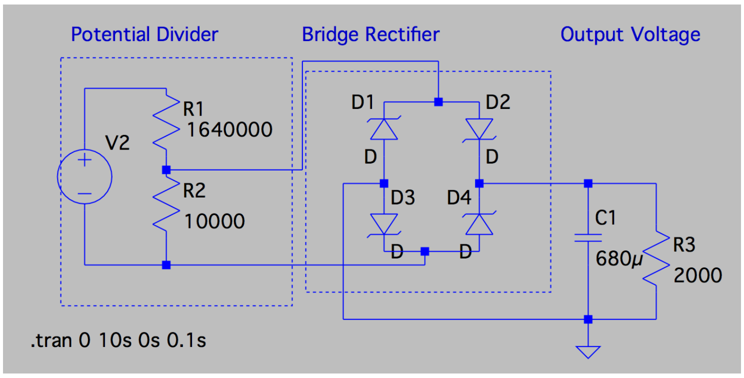

Figure A1: Bridge Rectifier Circuit Spice Model

Differential Amplifier Circuit

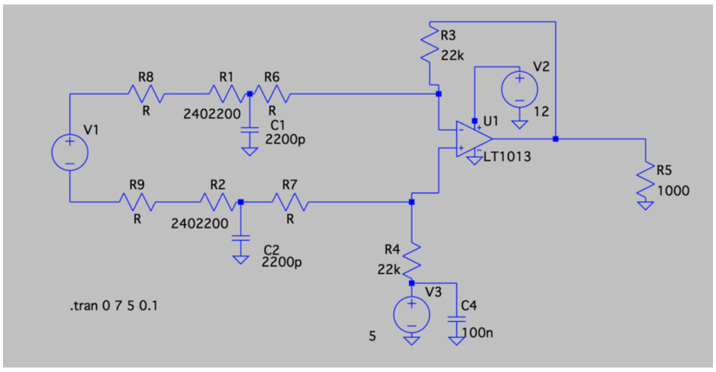

Figure A2: Different Amplifier Circuit Spice Model

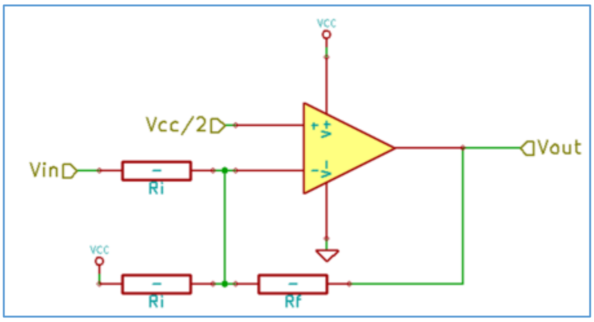

Figure A3: Differential Amplifier Circuit Example

Annex B: Evaluation Board

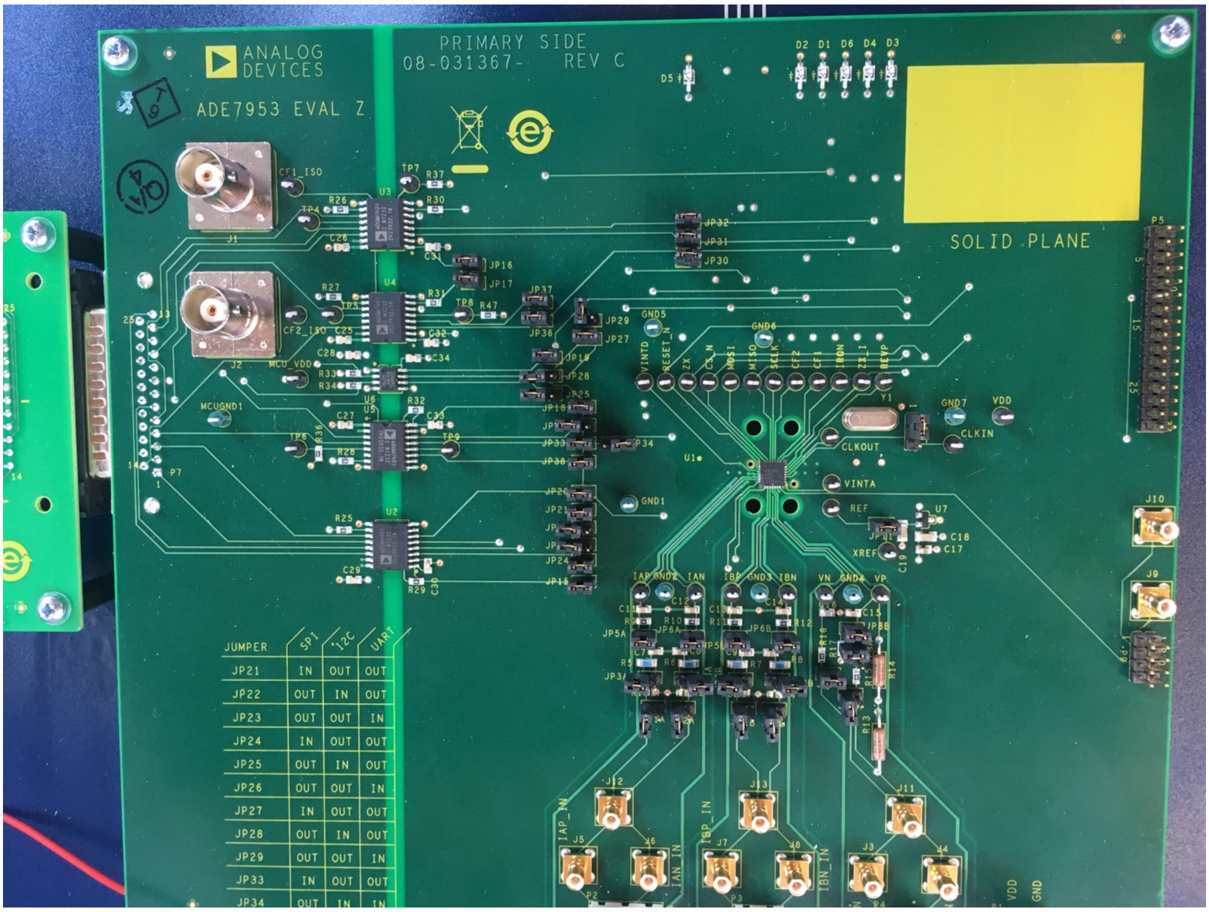

Figure B1: Evaluation Board Used in the project

Annex C: Table of AC Smart Meters

Name of Product	Power	Operating Temperature	Accuracy/ Standard	Link to Product	Price (ex. VAT)
Elster 100A MT375	Nominal Current- 5/6 A Nominal Voltage- 3x230/400 V	-25°C to +60°C	Accuracy class 2 or 1 IEC 62052-11 IEC 62053-21 ISO 9001	http://www.rexelenergysolutions.co.uk/product/2500497983/Elster-100A-Three-Phase-Smart-Meter-with-Sim-Card	1-4.... £235.71 5-9... £211.54 10+... £181.32
Landis & Gyr E470	**0.22VA @ 20A; 17.5W 2.2Va max @230V**	-25°C to +55°C	BS EN 61036 1996, BS EN 62056-21, BS EN 61000-4-5 **Accuracy Class A or B**	http://www.jsgsolutions.co.uk/pre-pay-meters/view-all-pre-pay-meters/landis-and-gyr-e470-tokenless-prepayment-100a-single-phase-meter.html	£125.00
Secure iCredit 500	Voltage range: 230 V Burden Voltage Circuit: < 1 W, 1.5 VA per Phase. Current Circuit: < 0.1 VA per Phase	-	Accuracy Class 1.0, MID Class B IP53 in accordance		£120.00
Iskra ME382 Single Phase	Max. current: 85A or 100A Reference voltage: 230V	-25°C to + 60°C	Accuracy class: 2 or 1	http://www.jsgsolutions.co.uk/smart-meters/view-all-smart-meters/iskra-me382-single-phase-100a-direct-connected-smart-meter-with-modem.html;limit;100	£169.00
Iskra - MT382 CT Three Phase	Max. current: 6A (5A ct operated) Reference voltage: 3x230/400V	-25°C to + 60°C	Accuracy class: 2 or 1	http://www.jsgsolutions.co.uk/smart-meters/view-all-smart-meters/iskra-mt382-ct-operated-smart-meter-with-gsm-modem-three-phase.html;limit;100	£195.00
Iskra - P2G Data Logger	Lithium battery 3.9V size D	**-25°C to + 60°C**	BS EN 60079 compliant	http://www.jsgsolutions.co.uk/remote-monitoring/remote-monitoring-by-iskra/iskra-p2g-data-logger.html	£249.00
JSG1P-RMB with GSM Wireless Datalogger	No data given	**-**	-	http://www.jsgsolutions.co.uk/remote-monitoring/remote-monitoring-by-jsg/jsg1p-rmb-with-gsm-wireless-datalogger.html	£149.99

Table C: Table of all the AC smart meters available in the market which are GSM enabled