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Capstone Project

IoT enabled smart switchboard to enable remote control of existing home appliances

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Chapter 1

Introduction

1.1 Introduction

In the present day scenario, Energy efficiency is the major requirement of any power device (mechanical or electrical). By the introduction of Power Electronics systems electrical systems are aiming towards higher energy efficiency. The losses in these systems are quite low and they enable the user to control the devices to a much larger extent than was possible by using the conventional approach.

This project focuses on providing automated control of the existing home appliances by adding a control circuitry to the existing devices. The devices are controlled using wireless communication over the internet by microcontrollers. An app-driven remote control is provided for user interaction. The efficiency of usage can be improved device-by-device. This will enable the user to switch off the devices when idle even remotely and also the power consumptions of devices will be lowered when appliances are not running at their full intensities. Cumulatively, an energy efficient household can be achieved by using such smart switches for controlling appliances used in the house.

A smart switchboard is an upgrade to the conventional switches, they use novel Internet of Things (IoT) enabling them to be accessible remotely over the internet. The switches are designed in a modular fashion providing scope for scalability of the project. Based upon the monetary capability of the user and upon introduction of new devices in the household at later stages, the sockets can be easily added or removed at any time in the smart switch. This will enhance the viability and long term relevance of the project.

1.2 Need Analysis

The currently available solution and research exhibit these features

- The existing market solutions provide on/off switching of the devices. The available solutions provide comparatively lower energy efficiency and also require human intervention to achieve desired conditioning of the environment.
- Some of them also use unsuitable technologies like Bluetooth, Ethernet etc. From the present analysis of the existing solutions for automating a room environment, the technologies used suffer from a number of drawbacks. So, these protocols are limited in functionalities when used by an end user in real life.

1.3 Aim

The project aims to manage and control existing devices through a smart switchboard accessible over the internet.

1.4 Objectives

- To develop driver circuits for controlling the devices inside a room
- To develop software programs for the microcontroller to operate the driver circuits.
- To design mobile applications for users to control the devices over the internet.

1.5 Problem Formulation

In the present day scenario, user comfort and convenience is the main target for the product developers. The present conventional devices installed and their manual control does not provide benefit for monitoring and controlling them, when a person is away from home. This leads to large power losses due to unnecessary operation of the devices. This can even cause major damages to life and property if not handled properly. Also, existing commercial solutions in the market provide entire new smart devices which requires users to replace the existing devices incurring huge costs.

1.6 Deliverables

- A compact and efficient Smart Switch Board is developed.
- A user-friendly mobile application is developed for operating different appliances installed inside the room.

1.7 Novelty of work

Devices can be controlled over the internet through mobile or desktop applications. Due to the use of Power Electronics devices for the voltage control, there are negligible losses incurred. The switches are formed in a modular fashion providing user to add new devices over time. Higher levels of controllability could be achieved through individual device level control.

Chapter 2

Theory, Standards and Constraints

2.1 Theory

2.1.1 Phase Angle Control

Phase angle control is a simple AC-AC conversion technique used to convert an input AC RMS Voltage to a reduced RMS value. It uses a low frequency switch to chop the AC sine wave. The reduced output voltage is controlled using a quantity known as the Firing Angle. The firing angle controls the output of the sine wave using delayed firing of the switching elements (triac, SCR etc.) ensuring the magnitude of AC rms signal is reduced. The output voltage is calculated by the determining the area under the curve, the subsequent increase in the firing angle leads to decrease in value of rms and hence the brightness of light or speed of fan can be controlled.

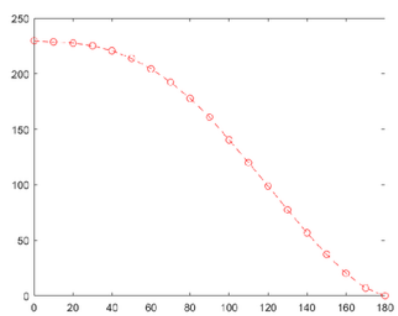

Figure 2.1: Variation in RMS Voltage Output with the Firing Angle

There are a variety of **advantages** of this approach:

- It uses simple voltage control to operate the devices at varied brightness and speeds.
- This allows the use of a low frequency switch, in our case a Triac. These low frequency switches have much higher ratings and can be applied directly to the power circuit.
- This allows for a very fine control over the voltage values and thus numerous steps for variation in device parameters can be provided.

Disadvantages of the approach can be:

- Harmonic inclusion in the AC waveform leading to shortening of life of devices.

- Reliability of the controlling switches is reduced as the switching does not occur at zero voltages and currents.

The following graphs show the variation in Output Voltage waveform with subsequent increase in firing angle. The following data is represented from the above graphs:

1. Input Voltage Waveform
2. Zero Cross Detection
3. Firing Pulse
4. Output Voltage Waveform

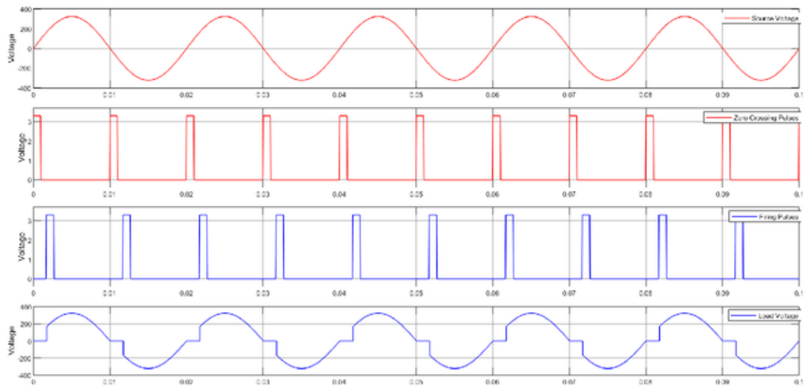

Figure 2.2: Variation in voltage waveforms for $\alpha = 30°$

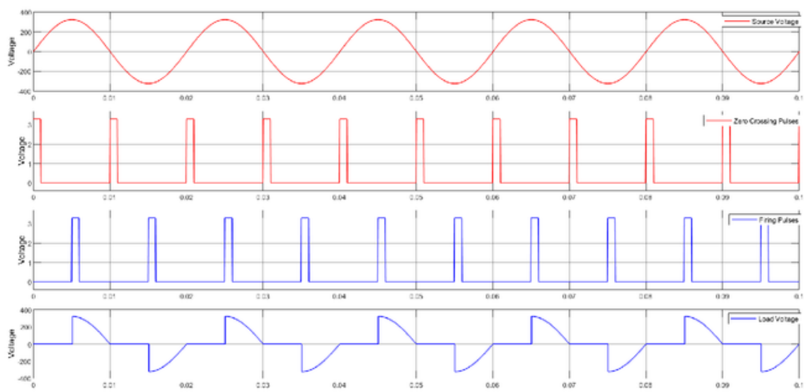

Figure 2.3: Variation in voltage waveforms for $\alpha = 90°$

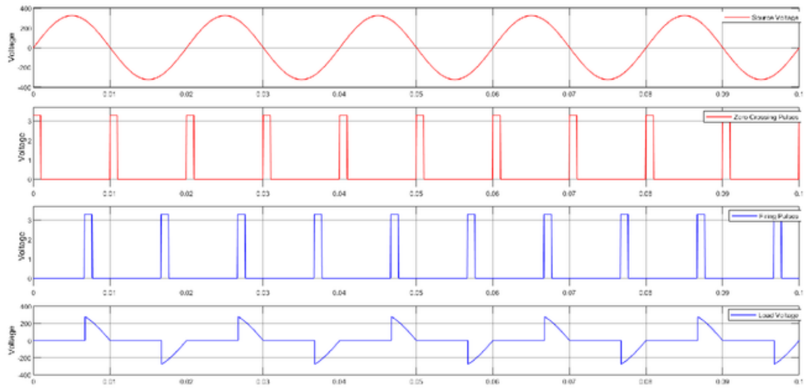

Figure 2.4: Variation in voltage waveforms for $\alpha = 120°$

2.1.2 5V Power Supply

A 5V Power supply is designed to provide uninterrupted mains supply to the microcontroller.
The 230V AC Mains is converted to a 13V AC signal using a Step Down Transformer. The transformer also provides isolation to the circuit. This stepped down voltage is passed through a bridge rectifier to convert it into a pulsating DC output. This DC supply cannot be reliably without converting removing ripples from the output and thereafter regulating the output. Hence, this output is connected to a LM7805 5V Voltage Regulator in parallel with 2200 µf and a 470 µf capacitors. This stabilises the output and reduces the input ripples to almost zero.

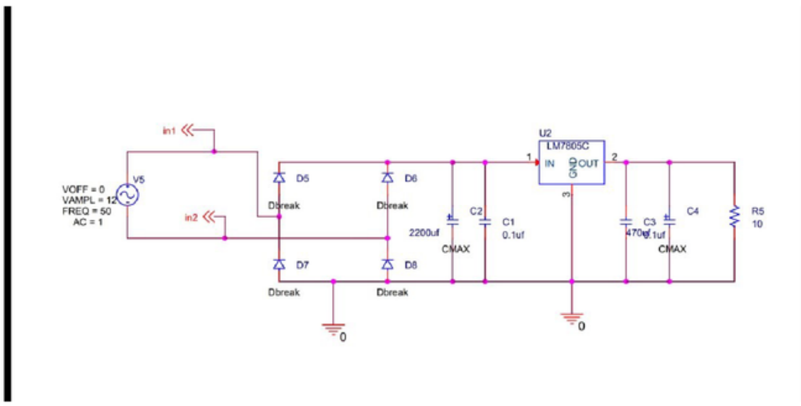

Figure 2.5: 5V DC Power Supply

2.1.3 Zero Crossing Detection Circuit

A zero cross detection circuit is a type of voltage comparator which locates point of zero voltage. In this circuit, a transistor based opto-isolator IC (4N25) is used with rectifier voltage pulse of 100 Hz provided at the input pins. The location of zero point is necessary for following the rectified voltage waveform of the circuit in order to fire the triac at required phase angles. The microcontroller (ESP8266) fires interrupts upon receiving signals from the zero crossing circuit marking the starting point of the counter timer. Now, by calculating the time corresponding to the input firing angle the pulse is fired providing gate signal to the triac, thereby turning it ON.

2.1.4 ESP8266

The ESP8266 WiFi Module has a self contained SoC with an integrated TCP/IP protocol stack which provides it access to a Wi-Fi network. The ESP8266 has the potential of either hosting an application or offloading all Wi-Fi networking functions from another application processor. The ESP8266 module is an extremely cost effective board with a huge, and ever growing, community.

This module has a powerful on-board 32-bit processor with storage capability that allows it to be integrated in various applications. Its high degree of on-chip integration allows for minimal external circuitry, including the front-end module.

Figure 2.6: ESP8266 Wifi Microcontroller

2.1.5 Triac

The Triac is a power electronic device that is used in AC switching application. Since it consists of two thyristors connected back-to-back (in other words, anti-parallel) but on the single piece of silicon so it controls the flow of current in both half cycle of alternating current.

Similar to that of the thyristor, the TRIAC also have three terminals namely MT1, MT2 and gate terminal. For the first half cycle MT1 act as anode terminal and MT2 terminal act as cathode terminal and for the next half cycle reverse is the case. However, the gate terminal is fixed and it receives the gating pulse for the TRIAC in both half cycle thus making it capable of controlling the flow of current.

Just like thyristor, the TRIAC also needs a minimum value of gate current called as latching current. So the gating pulse must be applied till the anode current go beyond latching current after which the pulse can be removed in order to reduce losses.

Figure 2.7: Triac BT136

The TRIAC turns off automatically when the current in the circuit goes below holding current and when the gating pulse is again given in the next half cycle, TRIAC start conducting. This process keeps on going. And thus, the RMS value of output voltage is controlled by changing the delay angle or firing angle of the TRIAC. Here in our project, the TRIAC is used in Controlling the brightness of lamp and speed of the fan.

2.1.6 Optocouplers

Figure 2.8: Optocoupler MOC3021

Optocoupler is an electronic component that is used to isolate circuits on PCB. It consists of two parts: an LED which receives the pulse and emits the Infrared light and the other is a photosensitive TRIAC which senses the radiation from LED and undergoes conduction. Thus, in turn, it produces a gating signal for the TRIAC of the main power circuit. As soon as the main TRIAC receives this signal it starts conducting. Now the firing pulse given to the TRIAC can be controlled by controlling the pulse firing delay given to the diode of the optocoupler.
When the pulse is removed, the currents flowing through the LED of optocoupler becomes zero and the photosensitive device i.e. TRIAC inside the optocoupler stops conducting thus making the whole circuit inoperative.
There are further other benefits of using an optocoupler which includes the removal of electrical noise. It also isolates the low-voltage side from the high-voltage side in the circuits.
Here in our project we have used two different optocoupler namely MOC3021, which is used to generate the firing pulse for TRIAC which in turn help in controlling the AC output waveform and the other one is MOC3041 which contains a Zero-Crossing Circuit inside it thus making it suitable for ON/OFF application as it generates the firing pulse at the instant when AC signal crosses the zero instant thus reducing the chances of a sudden large rise in current.
We also have to take care of the maximum amount of current that the LED inside optocoupler will withstand and hence a proper calculation is made to find out the value of limiting resistor as the peak value input pulse at the terminal of the diode is 3.3v which will be given by the microcontroller in our application.

2.1.7 L7805 Voltage Regulator

The Voltage regulator is used to regulate the input voltage to it to a fixed value. Thus it maintains fixed and hence smooth output voltage regardless of the input voltage.
The voltage equivalent to the difference of input and output is released as heat. So the greater is the difference, the more will be the heat that is released. Now in order to dissipate the heat, and to prevent the thermal breakdown of the material used inside the voltage regulator, we do use a heat sink. Thus the heat sink helps in ensuring the proper operation of the voltage regulator.

Figure 2.9: 5V Voltage Regulator LM7805

There are further other benefits of the voltage regulator as it shields and protects the electronic circuitry from any potential damage.
Here in our project, we have used voltage regulator 7805 as we need a smooth 5v dc output in order to power up the microcontroller. Also, we need to take care of the input voltage appearing at the terminal of voltage regulator so that the difference in voltage must not be very large. Also, the input voltage must be greater than 7v as according to the datasheet of 7805, the minimum voltage needed at the input terminal to regulate it to 5v is 7v.

7805 Rating

- Input voltage range 7V- 35V
- Current rating Ic = 1A
- Output voltage range Vmax=5.2V ,Vmin=4.8V

2.1.8 Snubber Circuit

Due to various conditions that generally occurs in electrical and electronics circuits like overcurrent, overvoltage, a large change in the difference of voltage etc., the components in the circuits may get fails. Now we need to protect our circuit from such anomalies. So for the protection against overcurrent, we do use fuse, heat sinks are used to dissipate the heat generated due to an excessive change in voltage.

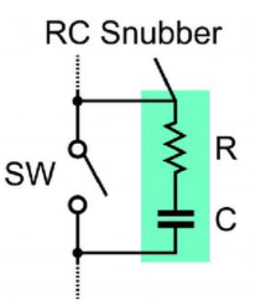

Figure 2.10: A RC Snubber Circuit

Now there appear some cases where there is a sudden rise in current(di/dt) and a sudden rise in voltage(dv/dt). These spikes are very dangerous and can burn the semiconductor devices connected in the circuit. So in order to protect the circuit against these two conditions of sudden rise we do use snubber circuit.
Snubber circuit basically has an inductor in series and capacitor in parallel along with a series resistance. The series inductor protects the circuit against the sudden rise in voltage. This is because of the property of the property of inductor which opposes the sudden rise in current. Also, the capacitor helps in protecting the circuit against the sudden rise in voltage. This is because of the property of capacitor which opposes the sudden rise in the voltage. Also, a series resistance is connected in series with the capacitor to limit the discharging current of the capacitor so that the current in the switch due to capacitor do not lead to an overcurrent condition in through the switch when it is operated.

2.2 Realistic Constraints

- Although the project will be designed with a modular approach with scope of future expansibility, it will be demonstrated on a much smaller scale, due to a lack of infrastructure and budget.
- Plug and Play modules with fine level of control will be developed only for Lights, Fans due to lack of budget and time. Rest of the devices will be controlled in only an On/Off state.
- Testing of the modules will be limited to the devices available in the institute.

2.3 Technical Standards Used

IEEE802.11 Standard for Wi-Fi

P2413 Standard for an Architectural Framework for the Internet of Things (IoT)

2755-2017 IEEE guide for terms and concepts in Intelligent Process Automation.

IEEE 61850-9-3-2016 International Standard for communication networks and systems for power utility automation

IEEE 802.15.4 Wireless sensor/control networks.

IEEE 1016 Software design description.

Chapter 3

Design Methodology

3.1 Methodology

A. Development of driver circuit

To introduce software based control, microcontroller based actuators modules are to be attached in the power supply lines of the devices (fan and lighting system control).

A.1. Study of control methodology The development of actuator modules designed for each device to be automated will be using plug and play methods so as to convert existing devices into smart ones. The actuators will operate and automate the appliances based on the commands received from the microprocessor.

A.2. Actuator circuit design

- **Incandescent Lamp** The use of pulse width modulated signals that drives a bidirectional control switch i.e., Triac which is connected to the Lamp and thereby with the AC mains. As the width of the PWM is altered the voltage across the lamp will be varied and hence the brightness of the lamp will be controlled.

- **Fans** Speed regulation of fans will be done using the Triac to reduce the energy losses that were occurring by the use of conventional voltage controller. A snubber circuit is connected in parallel with the triac in order to protect it against reverse breakdown.

  Now the designed circuit of actuator modules is designed in such a way that there would be no need to interfere with the existing circuitry of the appliances. The existing switches will be simply upgraded by the smart switch boards providing automated control of each appliance over the internet.

B. Design of the software for the Smart Switch Board

The smart switch board needs a central hub for their communication and management. It will receive the inputs from the zero crossing detection circuit and give an optimized output pulse to the switch after processing it using the aforementioned algorithms.

The microcontroller ESP8266 is programmed on NodeMCU platform. The coding is done in C++ language for the microcontroller in order to generate the firing pulses accordingly to operate the driver circuits.

C. Development of a user interface to enable user interaction with the system

Applications will be developed for the most common mobile platforms, iOS and Android. A cloud-based web app will also be deployed for users to operate from laptops and desktops. The user will be able to use these apps to connect directly to the server hosted on the Home Automation Unit in their homes without any middleware services ensuring their security and privacy.

The programming of the Android Application is done in Java XML. The MQTT broker (CloudMQTT.com) is being used for machine-to-machine internet of things connectivity. It works on a publish/subscribe methodology, and is a lightweight messaging protocol developed on top of the HTTP.

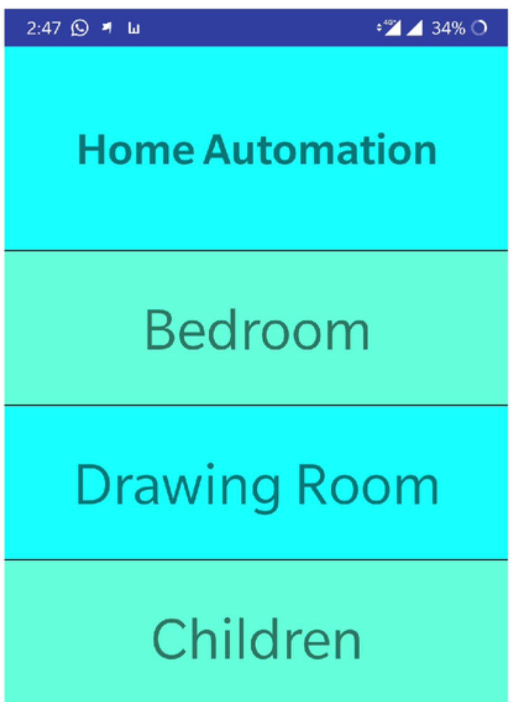

Figure 3.1: Room Selection Screen

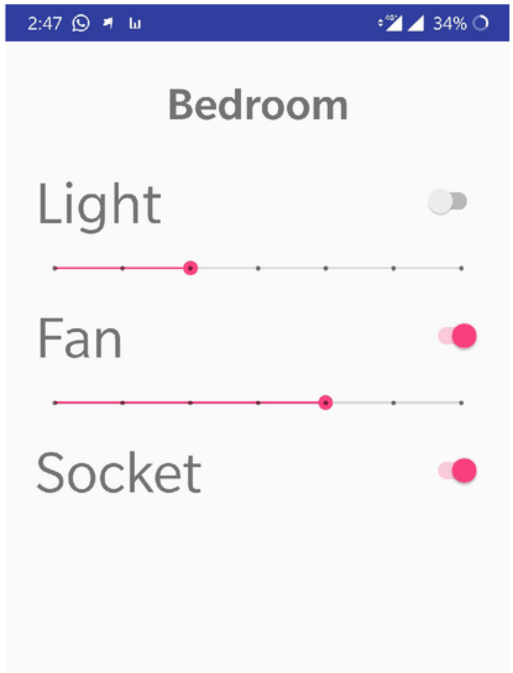

Figure 3.2: Device Control Screen

3.2 Flow Chart

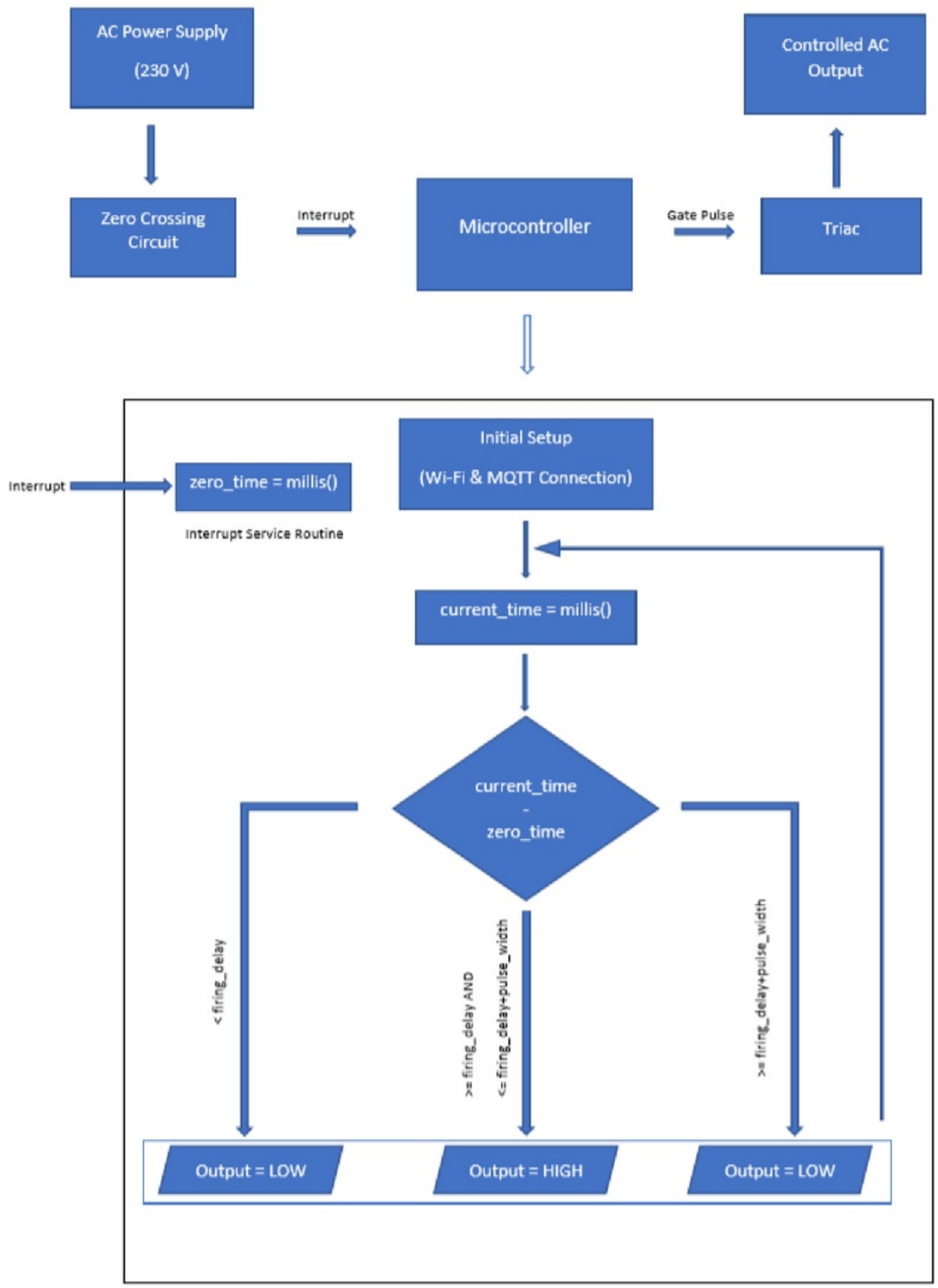

Figure 3.3: Logic flow for operation of the Smart Switchboard

3.3 Mathematical analysis and calculations

3.3.1 Power Supply

$$V_{inp} = 230V = V_{\mathrm{p}}(primary\,voltage)$$

$$V_s(secondary\,voltage) = 13.74V$$

$$V_{cp}(peak\,capacitor\,voltage) = 13.74 * \sqrt{2} - 2 * 0.7 = 18.03V \tag{3.1}$$

From the data sheet(attached) of Voltage Regulator(7805), the minimum voltage at the Input Terminal must be above 7V.
As we know the discharging equation of capacitor is :

$$V = V_{cp} * e^{\frac{-t}{T}} \tag{3.2}$$

$$7 = 18.03 * e^{\frac{-5*10^{-3}}{T}} \tag{3.3}$$

By Solving,

$$T = 5.28ms$$

$$R * C = 5.28ms$$

From Diode Bridge Rectifier,

$$V(drop) = 1.4V = I * R$$

$$I = 500mA_{(load\,current)}$$

By solving,

$$R = 2.8\Omega \tag{3.4}$$

Putting in eqn 3.7,

$$C = 1880\mu F \tag{3.5}$$

So, we have used slightly larger value of capacitor i.e. 2200µF.

3.3.2 Zero Crossing Circuit

From data sheet(attached) of A4N25 Transistor based Octocoupler: For internal Diode to turn ON -

$$I(max.\,permissible\,limit) = 60mA \tag{3.6}$$

$$Rectified\,Voltage, V = 5.21V \tag{3.7}$$

$$R_{connected} = 165\Omega \tag{3.8}$$

$$I_{actual} = \frac{V}{R_{connected}} = 31.57mA \tag{3.9}$$

3.3.3 Triac Circuit

From the Triac Circuit,

$$V_{0rms} = \sqrt{\frac{1}{2\pi}(\int_{\alpha}^{\pi} (V_m sin\theta)^2 d\theta + \int_{\alpha+\pi}^{2\pi} (V_m sin\theta)^2 d\theta} \tag{3.10}$$

On solving, the output rms voltage of Triac is:

$$V_{0rms} = \frac{V_m}{\sqrt{2}}[\sqrt{\frac{1}{\pi}((\pi - \alpha) + \frac{sin2\alpha}{2})}] \tag{3.11}$$

Now, for different firing angle, the output voltage across load would be different as: for α=0°

$$V_{orms} = \frac{V_m}{\sqrt{2}}$$

for α=30°

$$V_{orms} = \frac{V_m}{\sqrt{2}} * 0.98$$

& so on...

3.3.4 Optocoupler

From datasheet of MOC3041 Optocoupler:

$$I(max.\,permissible\,limit) = 60mA \tag{3.12}$$

Now,

$$Voltage\,applied, V = 3.3V \tag{3.13}$$

Hence,

$$R_{reqd.} = \frac{V}{I} = \frac{3.3V}{60mA} = 55\Omega \tag{3.14}$$

3.3.5 AC Fan

From datasheet(attached) of ac axial fan:

$$L = 3H,\ R = 1.67K\Omega$$

So,

$$X_L = w * L = 3 * 2\pi * 50 = 942.477 \tag{3.15}$$

$$tan\theta = \frac{X_L}{R}$$

$$\theta = tan^{-1}(\frac{X_L}{R})$$

$$\theta = tan^{-1}(\frac{94204777}{1.67 * 1000})$$

$$\theta = 29.43^\circ \tag{3.16}$$

Now, for the circuit to start operating-

$$Firing\, angle(\alpha) >= \theta$$

Hence,

$$\alpha > 29.43^\circ \tag{3.17}$$

3.3.6 Power Rating of the Smart Switchboard

Keeping in mind the trace widths used for the high power component of our PCB, the following maximum ratings for the Smart Switchboard have been calculated.
Trace Width for High Power side,

$$t = 1.5mm$$

By referring to a professional PCB manufacturer, BITTELE (www.7pcb.com), the following maximum current limit was determined using their Trace Width Calculator.

$$I = 5.3A$$

Our circuit operates at a rated RMS voltage of 230V. Hence,

$$P_{max} = 5.3A * 230V$$

$$P_{max} = 1219W \tag{3.18}$$

3.4 Circuit Diagram

Following are the schematics prepared on the Autodesk Eagle schematic and PCB design software. The simulation for same was performed using OrCAD (PSpice).

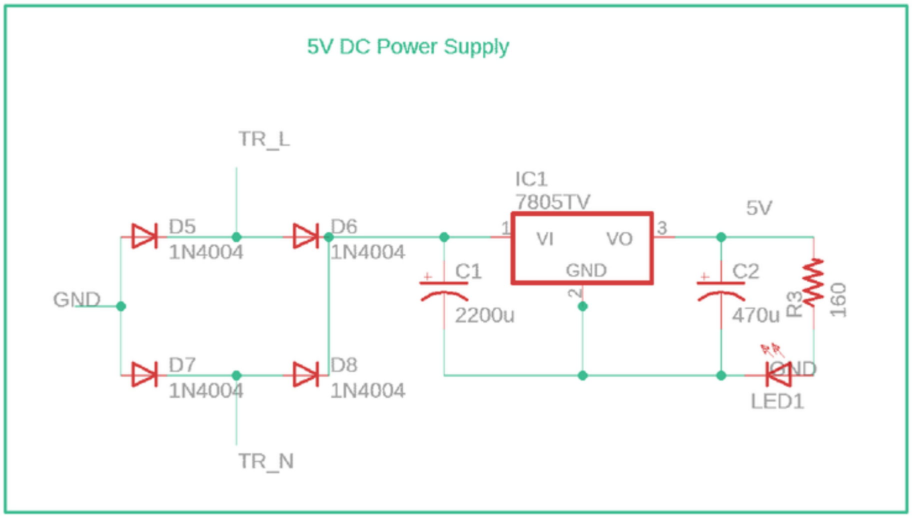

Figure 3.4: 5V DC Power Supply

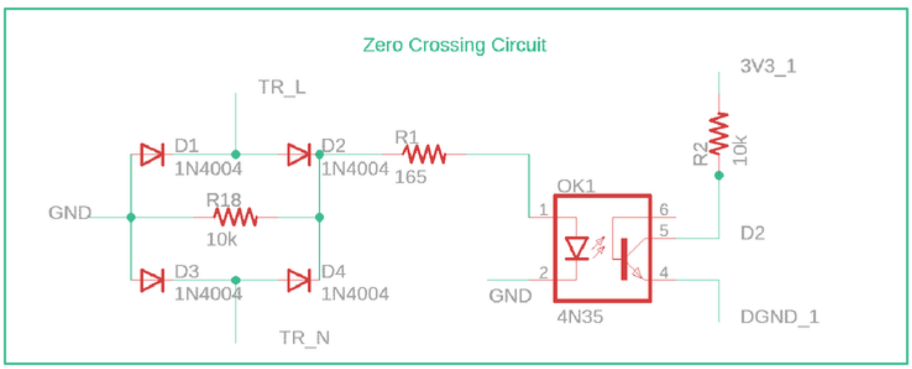

Figure 3.5: Zero Crossing Detection Circuit

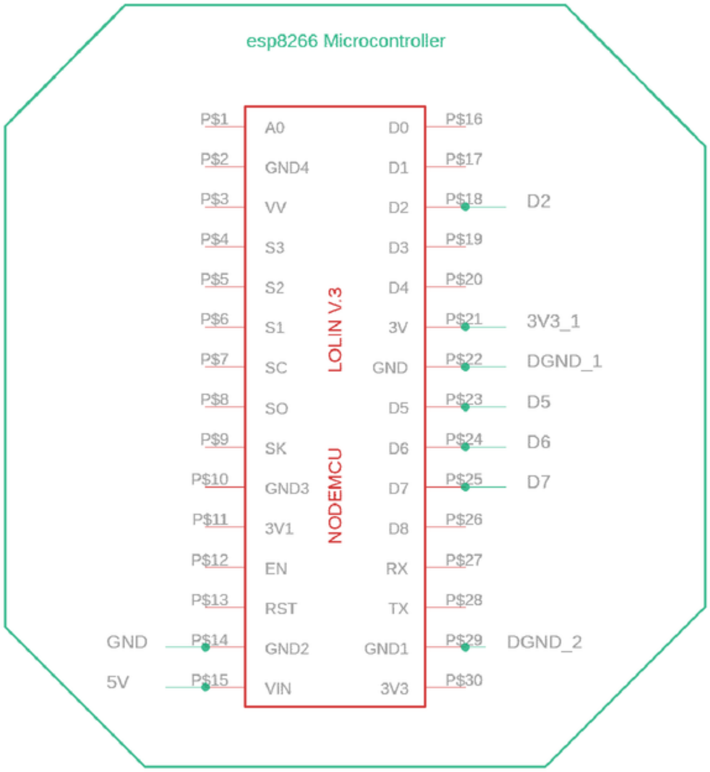

Figure 3.6: The esp8266 Microcontroller

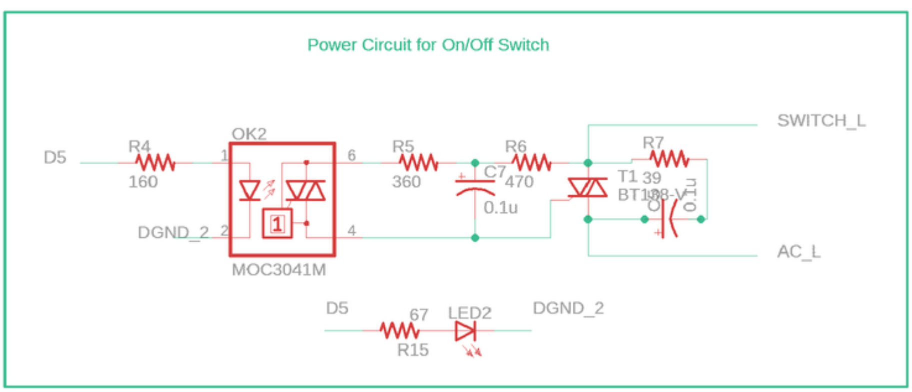

Figure 3.7: Power Circuit for On/Off Switch

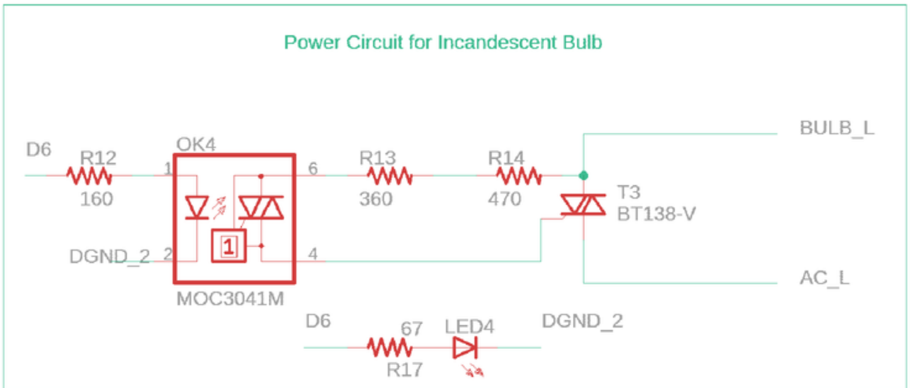

Figure 3.8: Power Circuit for Incadescent Bulb

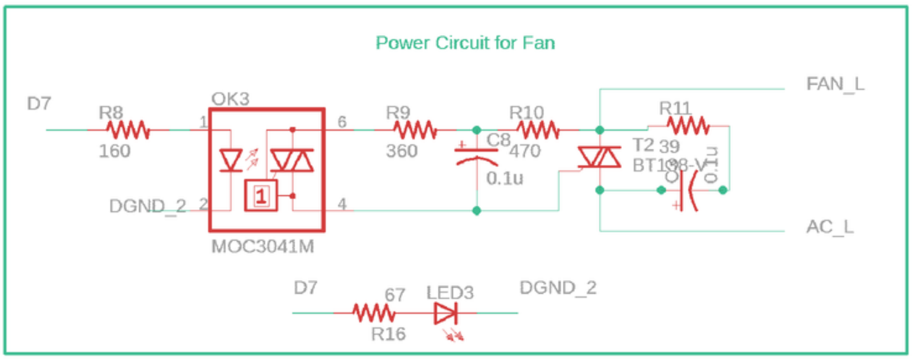

Figure 3.9: Power Circuit for Fan

3.5 Hardware Design

The prepared schematics after verification of results in the sofftware simulations were laid out on a PCB using Eagle CAD. This enabled us to minimise an otherwise complex and cumbersome circuit into a simplified design which could be installed inside a small enclosure resembling a switchboard in everyday homes.

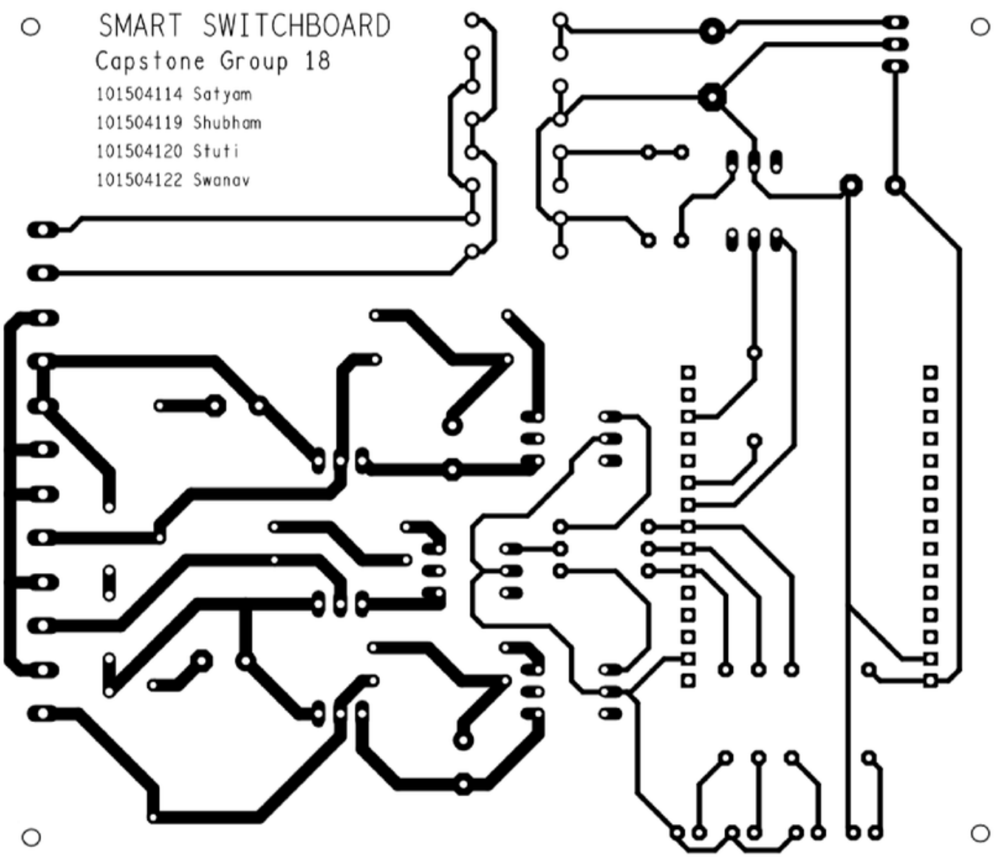

Figure 3.10: PCB Layout for the design

3.6 Hardware System

The prepared PCB was designed and ordered using a PCB prototyping facility. The components were acquired from a local retailer and soldered to create a working prototype of our concept.

The prototype went through repeated tests, and after numerous occasions of failure and fine-tuning, a working prototype was prepared for demonstration.

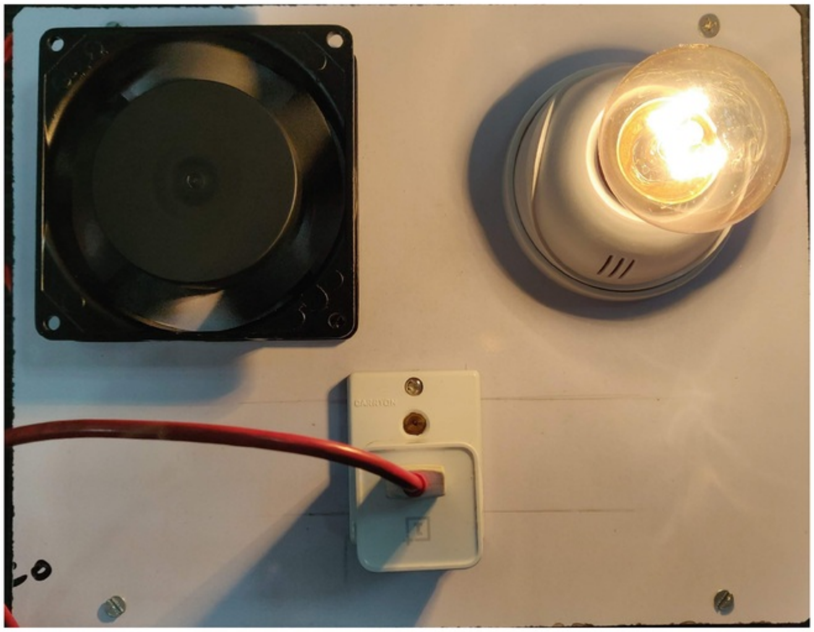

Figure 3.11: Demonstration of the complete project

Figure 3.12: Demonstration of the complete project

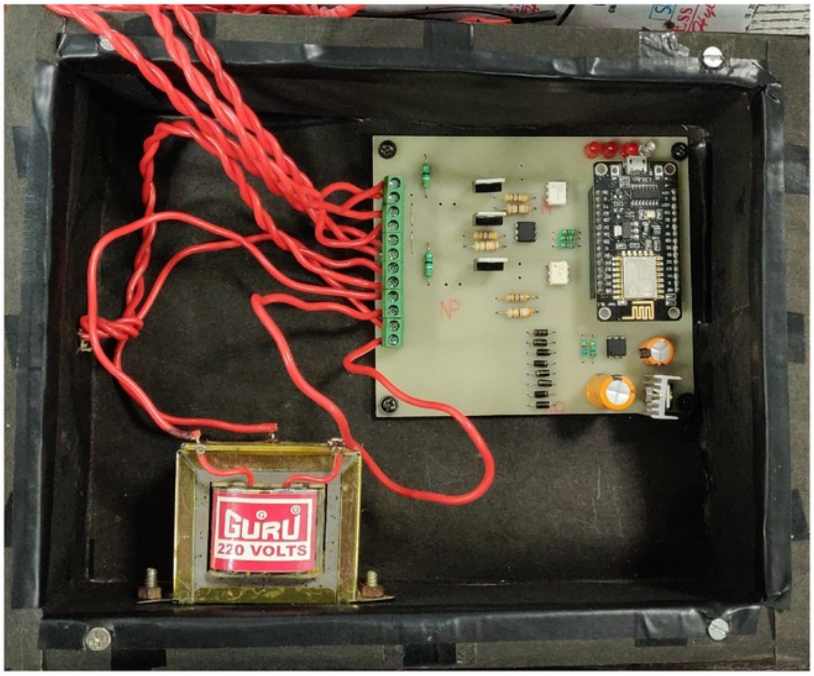

Figure 3.13: Demonstration of the complete project

Chapter 4

Results and Discussion

4.1 Results and Discussion

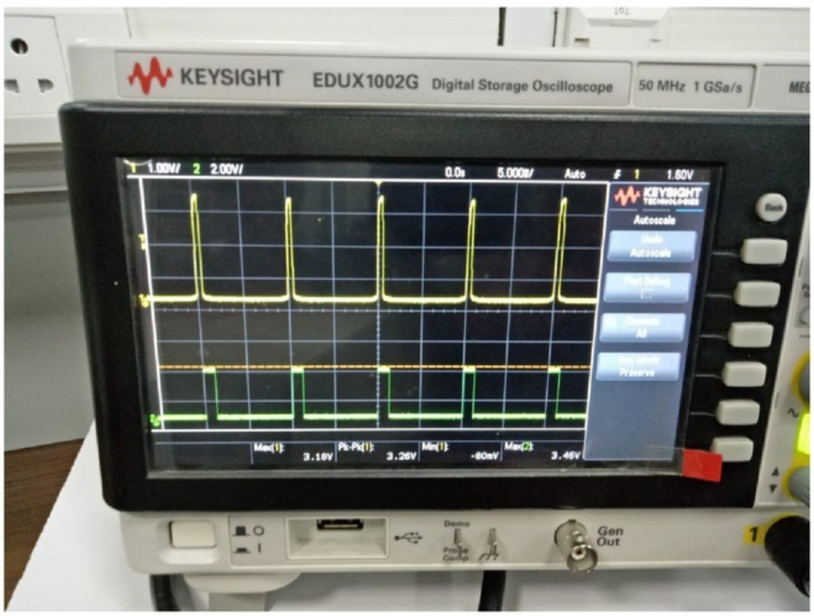

Figure 4.1: Gate signal for the driver circuit

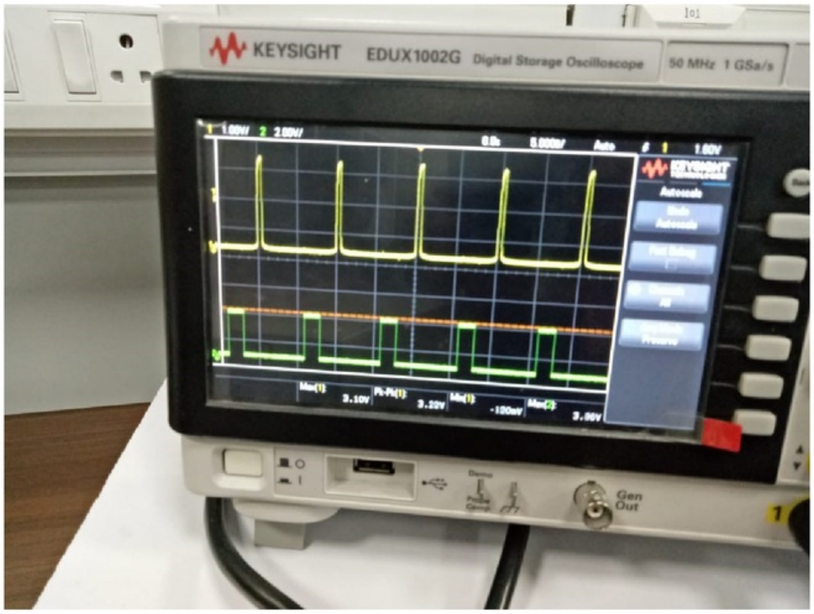

Figure 4.2: Shifted Firing pulses lead to reduced apparent voltage

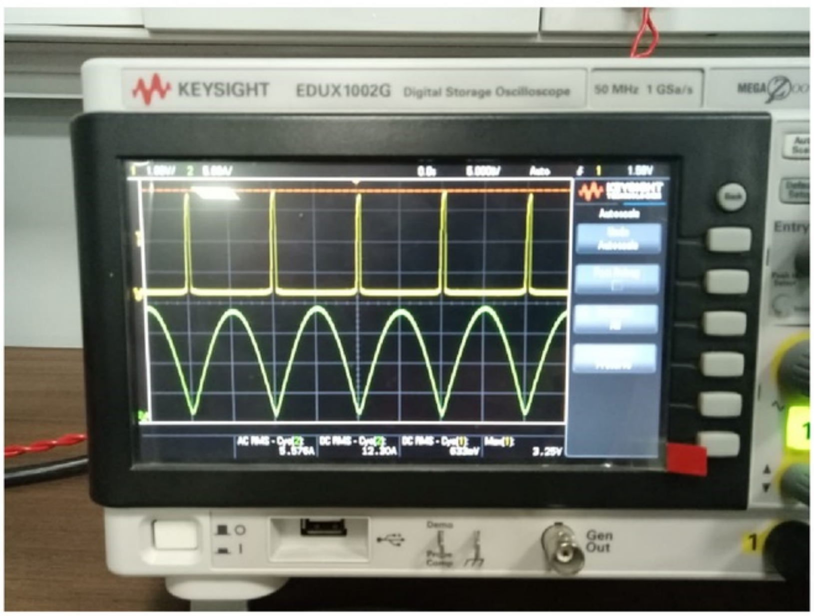

Figure 4.3: Rectified Output for Zero Detection

4.2 Justification of objectives achieved

1. With the help of power electronics devices such as triac, optocoupler etc., we designed the control circuitry for controlling the speed of fan, brightness of lights etc. We have also provided socket (Switch On/Off) for external device connection. A ripple free constant power supply of 5V for power supply of the microcontroller is designed using full bridge rectifier and smoothing capacitors. A zero cross detection circuit is also designed for detection of zero instant of the AC mains so that a reliable firing pulse can be generated from microcontroller in order to control the appliances.

2. Programming of the microcontroller is done on NodeMCU platform. The coding of the microcontroller is done in C++ language. The program formed allows the microcontroller to generate PWM gating pulses based on the user input to achieve the desired output by the user.

3. For the user interaction mobile applications enlisting rooms of each household. The rooms are further divided into lists of appliances which provides control over the devices to the user over the internet. The application is made simple and handy for the user to access easily.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

We successfully completed the following work areas, including their simulations and hardware representation:

1. 5V Supply for Microcontroller Power Supply.
2. Zero Crossing Circuit for detection of Zero Voltage instant of AC supply.
3. Firing pulse generation based on Zero Crossing Circuit fed as input to microcontroller.
4. On/Off and dimming control of lamp and fan using Optoisolators and Triac.
5. Android application for managing and control of lamp.

5.2 Future Work

The project can involve further development of-

- Plug and Play modules for AC and other household appliances.
- Machine Learning based autonomy algorithms.
- A centralised Home Automation Software to coordinate between various switchboard modules and house the machine learning algorithms.
- Sensor Aggregator Modules to provide environmental parameters to the device

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