

**DESIGN AND DEVELOPMENT OF A VOLTAGE OPTIMISATION DEVICE**Abunku M<sup>1</sup>, Anande T.J<sup>2</sup>, Genger .K<sup>3</sup><sup>1</sup>Electrical & Electronics Engineering, College of Engineering, University of Agriculture, Makurdi<sup>2</sup>Electrical & Electronics Engineering, College of Engineering, University of Agriculture, Makurdi<sup>3</sup>Electrical & Electronics Engineering, College of Engineering, University of Agriculture, Makurdi

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**Abstract** - The research is carried out to design and develop a voltage optimization device. Critical analysis of related research is carried out to know what has been done and current works been done. With advancement in power electronics devices, electromechanical switching devices are gradually been phased out giving way for the power electronics devices.

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**Keywords:** Voltage optimization; voltage power optimization; conservation voltage regulation; voltage correction, Power Electronics, Nominal voltage.

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**I. INTRODUCTION**

Most consumer electrical appliances are designed to operate within a standardized voltage band of  $\pm 10\%$  of the nominal 230V which meets the approved limits in the UK [1]. Efficient operation of these appliances requires they operate at the nominal voltage. However, the challenge of above or below nominal voltage supply creates a less efficient usage of these appliances. Operating these electrical devices above the required optimum voltage for example, does not increase the performance but rather causes increase in losses leading to higher bills and carbon emissions. These losses are generally in the form of heat and contribute to insulation breakdown and shortened lifespan of the appliance.

The quality of supply voltage is a function of the power quality. A fairly constant voltage output is desired for the optimum operation of electrical appliances in homes and industries. The European Union's directive on low voltage stipulates a tolerable range of voltage fluctuations acceptable for normal system operation.

**II. LITERATURE REVIEW**

Voltage optimization devices have been developed by some companies to either reduce the voltage band or eliminate the band entirely thus giving the nominal voltage required. The iVolt [2] develops voltage optimization devices giving voltage reduction as well as energy savings.

Several techniques have been made known in publications as well as in real time designs. In publications, [3] have presented in their paper a design of Constant Voltage Transformers (CVT) founded on the Ferroresonance theorem. Reference [4] have also published a report using power electronics in the regulating of transformer voltage and highlighted its advantage over mechanical tap changers. Other publications supporting electronic approach in tap changing are; [5], [6] and [7]. An AC-AC converter based on the buck-boost topology reported on by [8] served as an insight in advancement of power electronics in power management.

In real life applications, [9] shows a typical use of the fixed tap changing system.

The major benefit to the society is the conservation of energy through reduction in the voltage to the nominal value giving a reduction in bills [10].

Based on the studies carried out on published works, the use of power electronics in tap switching proved to be a leader in that regard. Thus a power electronic operated tap design was chosen for this research work.

Tap changing transformers, installed at substations, have been developed in an attempt to control the fluctuations in voltage levels experienced at the consumer end. However, their contribution to the solution gave a reduced voltage band. Voltage optimization devices have also been developed for domestic and industrial applications to control the voltage level to a relatively stable level.

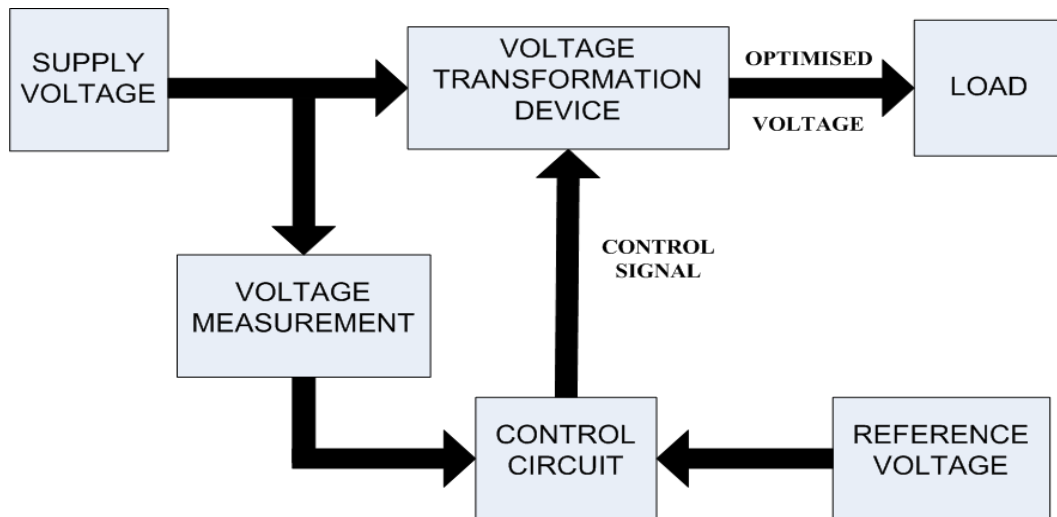
Voltage optimization is a term most often used to describe the technology used to give an optimal output voltage level for domestic use. Other terms used to describe this same technology include; Voltage Power Optimization, Supply Voltage Optimization, Conservation Voltage Reduction, Voltage Correction among others. In [11], automatic voltage stabilizers

were grouped into the types; Electro-mechanical, Ferro resonant or Constant voltage transformer, Electronic step regulators, Saturable reactors and Electronic Voltage Stabilizer.

### III. SYSTEM BLOCK DIAGRAM

Focus was drawn to the analysis of the basic components and subsystems that made up the voltage optimization device.

The system block diagram is shown in Figure 1



**Figure Error! No text of specified style in document.. System block diagram showing the various components within the system**

Based on the system block diagram in Figure 1, the analysis of the entire system requirements was made. These requirements are discussed in the subsequent sections.

#### 3.1. Supply Voltage

The supply voltage was thought of as the problem or cause that gave rise to the need for a voltage optimization device as highlighted in the literature review.

This was the primary input to the system. For the purpose of the research, it was imperative to consider the supply as a controllable voltage source in order to achieve a fluctuating voltage source. A fluctuating voltage was needed to act as the benchmark from which an optimized voltage could be referenced to. The magnitude of the supply voltage did not play a significant role in the performance of the optimization device therefore, safety was a deciding factor in choosing voltage magnitude to act as the supply voltage for the system. For this reason, a maximum of 50VAC was selected as the maximum supply voltage and 25VAC as the minimum voltage with 40VAC as the nominal system voltage. These voltages complied with safety rules in the lab.

The most likely source of controllable voltage supply was the variac, hence for the purpose of controlling the voltage, a variac was used.

#### 3.2. Voltage Sensing and Measurement

Since the aim was to obtain an optimized voltage from a supply voltage which varied, there was a justified reason to have a measurement of the supply voltage and output voltage. The measured voltage was necessary for control operations.

#### 3.3. Control Circuitry

A control circuitry was the component in the system charged with the responsibility of monitoring and controlling the working of the voltage transformation device to achieve the optimized voltage. The control circuitry was made to accept a reference voltage value upon which control and corrective actions were taken.

### **3.4. Voltage Transformation Device**

The transformation of the input voltage into an optimized output voltage was an important element in the system. The transformation of the supply voltage at a minimum loss level was considered a major factor owing to the fact that, an efficient system gave a better result. Major losses in power systems are due to heat hence the transformation device had to operate at specified ratings with minimal heat dissipation.

### **3.5. Optimised Output Voltage**

The need to monitor the output voltage was due to the fact that the measure of the output voltage gave an indication of whether the research work was successful or not.

## **IV. VOLTAGE MEASUREMENT**

Measurement of the input voltage was for logic decision by the control circuitry. Also, the measurement of the input voltage served as a raw data used to compare with the output voltage. Solution to the voltage measurement was to first of all, rectify the voltage and filter before it was fed into the control circuit.

### **4.1. Control Circuitry**

A control circuit, the core of the system, was tasked with the responsibility of;

- Comparing measured input or supply voltage with a reference voltage.
- Sending control signals to the voltage transformation device.

In the light of the logic operation of the control circuitry, it was imperative that a microcontroller played the role of monitoring and controlling the process.

**4.1.1 Microcontrollers.** In size, they are much smaller than the components they control. This makes microcontrollers very powerful in terms of their control capabilities and they are found in modern day industrial and domestic applications.

Possible microcontrollers considered included;

- PIC Microcontroller
- MBED
- BS2

Prior to the selection of a microcontroller, research into the factors that affect the choice of a microcontroller was carried out [12]. Some of the factors included;

- ❖ Required Hardware Interfaces: these were generally grouped into two categories; the communications and the digital and analogue inputs and outputs. In the communications category, some common peripherals are UART (Universal Asynchronous Receiver/ Transmitter), USB (Universal Serial Bus), SPI (Serial Peripheral Interface), among others. A combination of these two categories gave insight into the number of pins required.
- ❖ Cost and Power Consumption: Minimal power consumption at an attractive price appeared a more reasonable option in this regard since the project was not focused on a highly specialised high-end processing.
- ❖ Memory: A critical concern was not to run out of RAM (Random Access Memory) and Flash memories. A safer approach was to have far more larger capacities to cater for future needs but from an engineering perspective, cost proved the limiting factor.
- ❖ Development tools and compilers: Availability and ease of development tools was also considered. Some microcontrollers come with complete Integrated Development Environment (IDE) packages making them most preferable to designers.

The PIC microcontroller was selected as the microcontroller for this research work. In the family of the PIC microcontroller, there were the 12, 16, 18, 24 and 32 series to choose from. A compromise between the cost and functionality had to be reached. The selected PIC was the 28 pin, 16F876A.

**4.1.2. Source of DC supply.** Power supply to the control circuitry to carry out its functions was considered. For a DC supply, the first source of power was from rectification of the control voltage, filtered and regulated to give a fairly constant supply voltage. An alternative dc supply to act as a backup in the event of AC failure was adopted. Limit on the magnitude of the dc voltage to be used was dependent on other electronic components in the circuit such as the microcontroller. A 5VDC was used since the selected microcontroller PIC16F876A microcontroller operated well at this voltage.

## **4.2. Circuit Design**

The possible solutions are now presented.

**4.2.1. PCB Design Layout.** Modern design trends have shifted to the use of Printed Circuit Boards (PCB), replacing the use of Breadboards and Vero boards. The disadvantage of the older methods was made evident with increasing circuit complexity. A more complex circuit required several conductors and hence made it difficult to troubleshoot in the event of a fault. Modern designs also take into account, the impact of Electromagnetic Interference (EMI) and with the older methods they offered little or no solution to this problem.

Having justified the use of PCB, the software for the design of the PCB was considered. Proteus comes with its package, a PCB layout design tool, ARES. This made Proteus ISIS the preferred software for schematic capture and PCB layout.

## **4.3. Voltage transformation Device**

This device served as the link between the supply voltage and the optimized output voltage. Though other methods or techniques exist for the transformation of the supply voltage, for example, the use of power electronic AC-AC topologies such as the Buck-Boost converter, this research work was centered on transformers.

A transformer with taps was used for the transformation of the supply voltage into the desired output. For the number of taps, the voltage band of the input voltage of -37.5% and +25% of the nominal 40VAC was factored into the computation.

After the choice of a transformer with taps as the transformation device was made, there was the issue of the choice of the tap switching mechanism or device. Some possible switching mechanisms were;

- Power electronics such as transistors and thyristors
- Servo motors
- Relays

Power electronic switches provide fast static switching compared to slow and motion controlled switching in mechanical switches such as the servo-controlled tap changers. The relay tap changers also have the disadvantage of the inability to control the time of switching, which means, at above or below zero crossing, dangers of sparks were inevitable. Also, momentarily loss of current to load were some initial challenges associated with mechanical tap switches.

Both the transistor and thyristor families of semiconductor devices are used in many switching applications due to reasons such as efficiency (Lower on-state resistance), low cost, maintenance-free and small size. Both are three-terminal devices, and provide a good control range of current with a small amount of controlling current (typical values in mA). One major advantage of the thyristor over the transistor is the triggering method used. The transistors employ the use of continuous gate while the thyristors use pulses. Once the thyristor is triggered, it remains in conduction even in the absence of the trigger current [13]. The family of thyristors was selected based on this reason.

Within the thyristor family, selection of the switching device was made by considering the electrical characteristics, availability and cost. GTO (Gate Turn-Off) and IGCT (Insulated Gate Commutated Thyristor) are high current conducting devices (kA) hence their use in this project will be underutilized. The choice of the appropriate thyristor was settled on the grounds that, the implementation of a switch would require more SCRs (Silicon Controlled Rectifiers) arranged anti-parallel (back to back) while the triac is capable of conducting in both cycles. Additional factor was that the triac can be made conductive (switched on) by the application of either positive or negative gate pulse but SCR requires only positive pulses.

## **V. HARDWARE DESIGN**

The hardware aspect of the design dealt with;

- ❖ The transformer design

❖ Printed Circuit Board (PCB)

### 5.1. Transformer Design

Upon completing a literature review on transformers, the shell type was selected for implementation. Pre-existing laminated iron sheets were used for the construction. This also gave maximum allowable power rating for the transformer.

**5.1.1. Calculating the turns per volt.** The turns per volt was calculated from the formula:

$$= \frac{1}{4.44 \times 10^{-4} \times C_A \times B \times F}$$

B is the flux density and F is the supply frequency (50Hz). The flux density is dependent on the material used for the core. Typical value for normal steel is 1 wb/m<sup>2</sup>. Based on the above assumptions, the turns per volt were calculated by;

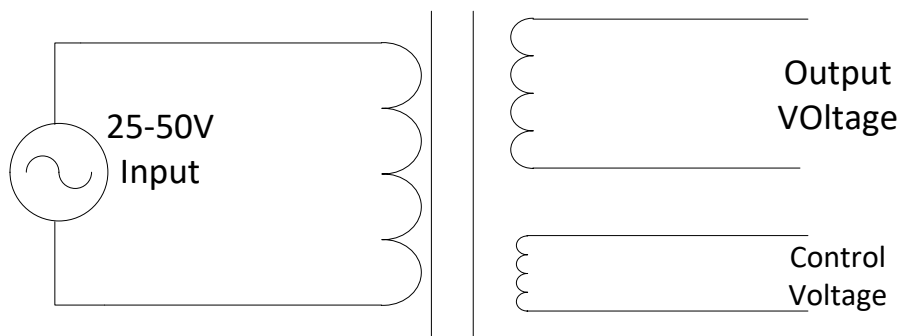
$$= \frac{1}{4.44 \times 10^{-4} \times 11.20 \times 1 \times 50} = 4.02 \text{ turns per volt}$$

For primary winding; 50V = 50 x 4.02 = 201 turns

For secondary, 40V = 40 x 4.02 = 161 turns

For control circuit winding, 12V = 12 x 4.02 = 48 turns

**5.1.2. Choice of Tap Positioning.** The main choice of tap changer positioning in transformers is based on current. The side with the higher voltage will have the least current and hence most suitable for the placement of the taps at that side. Supply voltage to the control circuit was incorporated into the design and as such, there was the need to keep the transformer energized at all times. This reason eliminated the option to put the taps on the primary side of the transformer. The proposed model of the transformer model is shown in Figure 1.



**Figure 1. Transformer Model Used**

The purpose of the control voltage winding was to supply rectified voltage to the control circuit for DC power supply.

**5.1.3. Size of Winding Conductor.** The main factor in the choice of conductor size was the maximum current delivered by the transformer. A maximum of 8A was used to arrive at the size of the conductor. A 140m enameled copper wire, 22 SWG (Standard Wire Gauge) and diameter of 0.710mm was used (Farnel, 2013).

**5.1.4. Formwork Design.** The formwork or transformer bobbin used was selected based on the dimensions of the iron sheets and the calculated core area.

### 5.2. PCB Design

The system control PCB was divided into three main individual but interdependent boards;

- Rectification
- Main Control

➤ Switching

The logic in this approach was to simplify the overall circuitry for easy analysis and troubleshooting. Also, the effect of Electromagnetic Interference (EMI) was taken into account to arrive at this approach. The system design approach is shown in Figure 3.

**5.2.1. Rectification Circuit.** The purpose of this PCB was to rectify the transformer input, output and control winding voltages to be used by the main control PCB. The rectified primary voltage served as the input to the logic operation of the microcontroller in the control PCB. The rectified output voltage was for measurement and display purposes via the microcontroller. The rectified control winding voltage was the primary supply DC voltage for the control circuit. The 3D visualization of the PCB is shown in Figure 4 and the completed PCB with assembled components shown in Figure Error! No text of specified style in document...

**5.2.2. Switching PCB.** The switching of the transformer taps was implemented with triacs mounted on the switching PCB. The 3D visualization of the PCB is shown in Figure 6. The terminal blocks on the PCB served as a link between the PCB and the main control PCB. A set of six (6) terminal blocks was also included for the termination of the transformer tap windings. Due to budget constraints, an improvise was made on the heat sink; an aluminum strip was fabricated in the lab rather than costly off-shelf ones.

**5.2.3. Main Control PCB.** This was the core of the control circuitry. With main inputs from the rectification circuit, the main control PCB handled the logic operation and control switching of the triacs on the switching PCB. Figure 7 shows the 3D visualization of the PCB.

The main component on the PCB was the PIC16F876A microcontroller, responsible for the logic operations and control switching of the triacs. In the switching of the triacs, a zero-crossing optocoupler was used to drive the triacs. The optocouplers served as isolation of the power circuit from the control circuit. The isolation was required to prevent or minimize electrical noises in the switching circuits from influencing the control circuit. The zero-cross functionality allowed the safe switching of the triacs by eliminating potential sparks and thereby protecting the triacs.

Also embedded in the implementation of the PCB were serial communication and LCD display. For serial communication, FTDI's MM232R was used to implement communication between a computer and the microcontroller [14]. The LCD was used to give a visual observation of the measured voltages (input and output).

Power supply for the main control PCB was also implemented. In the implementation, use was made of relay with NO (Normally opened) and NC (Normally Closed) contacts. In the absence of rectified voltage from the transformer, a back-up battery supplied the control PCB with DC voltage.

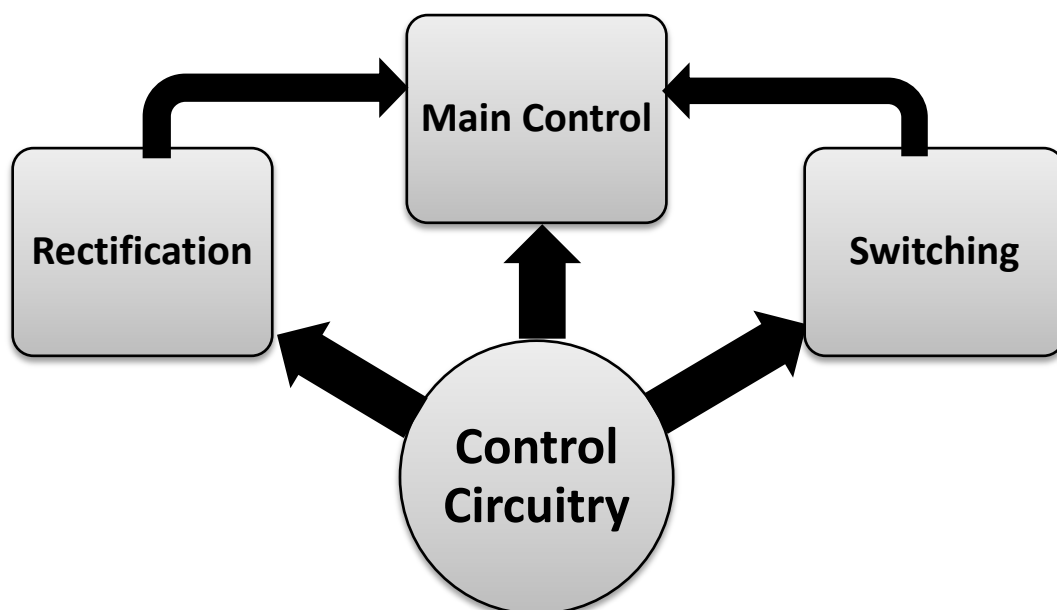


Figure 3. Block diagram of PCB design

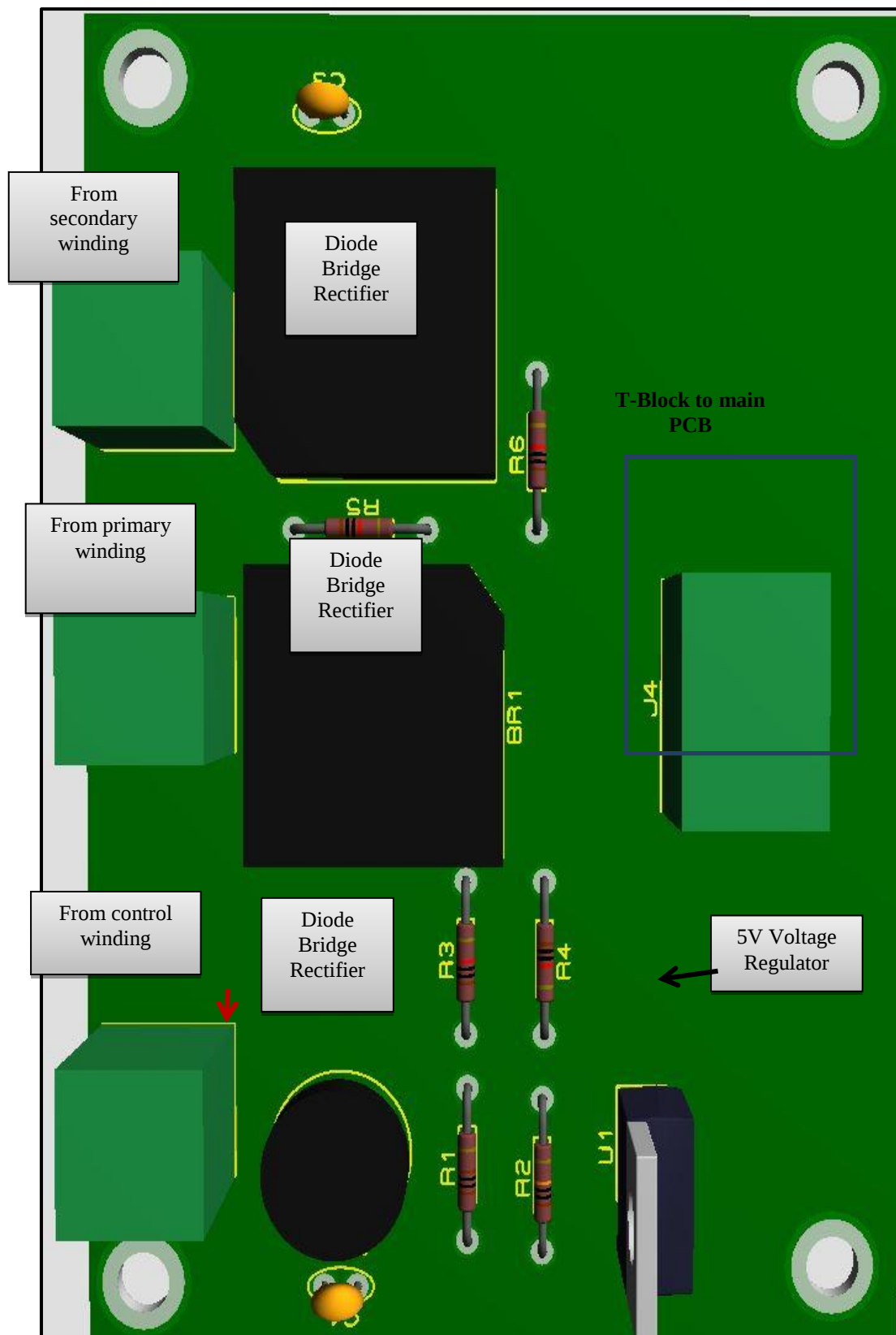
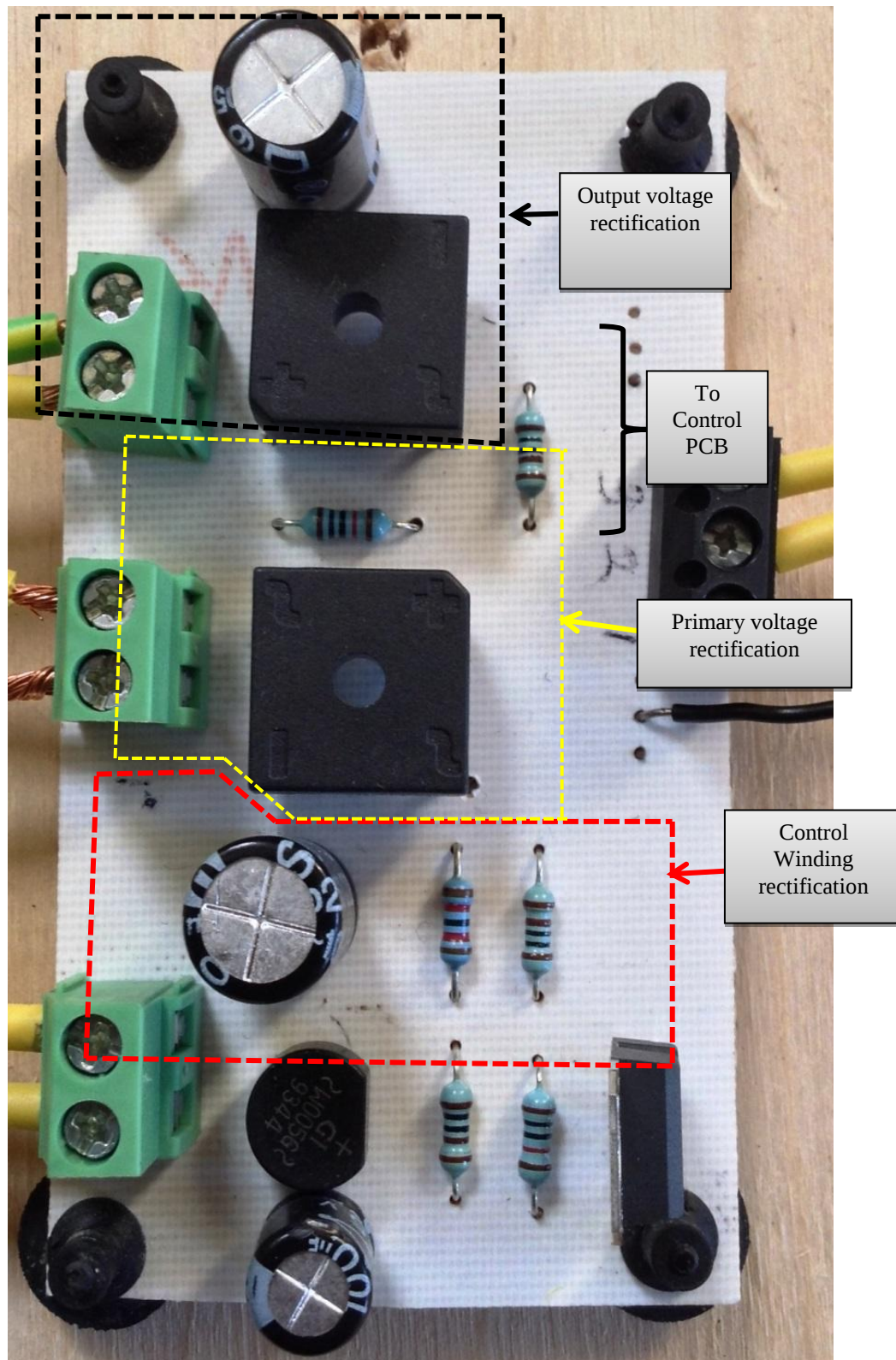
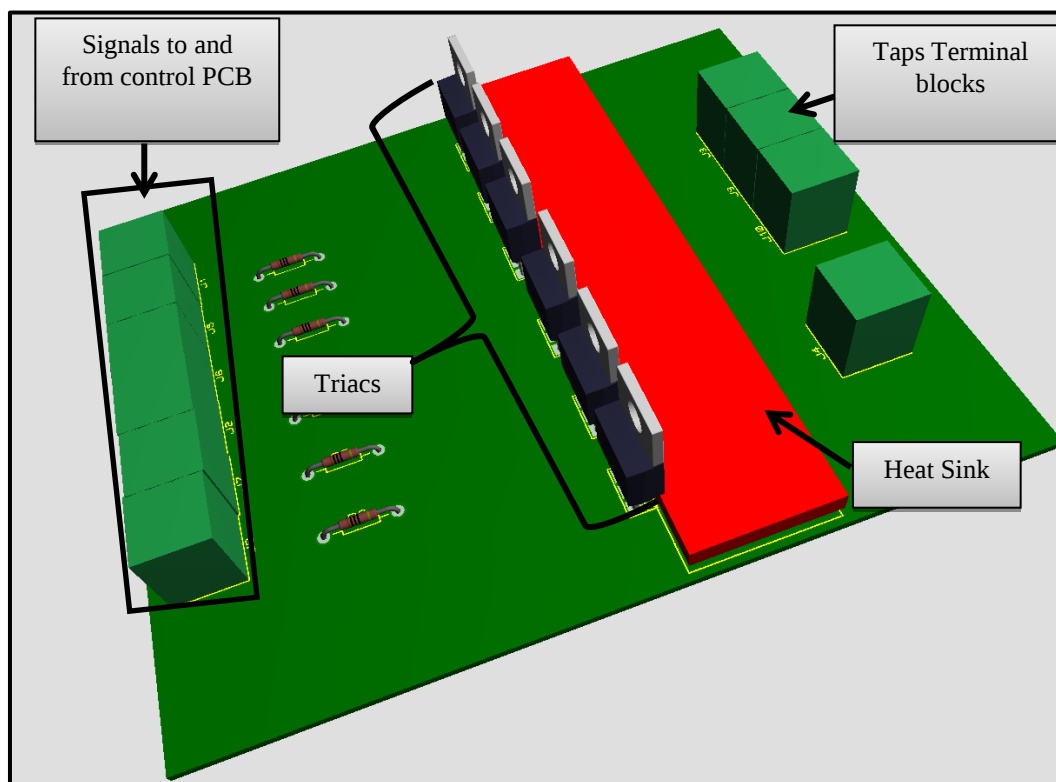


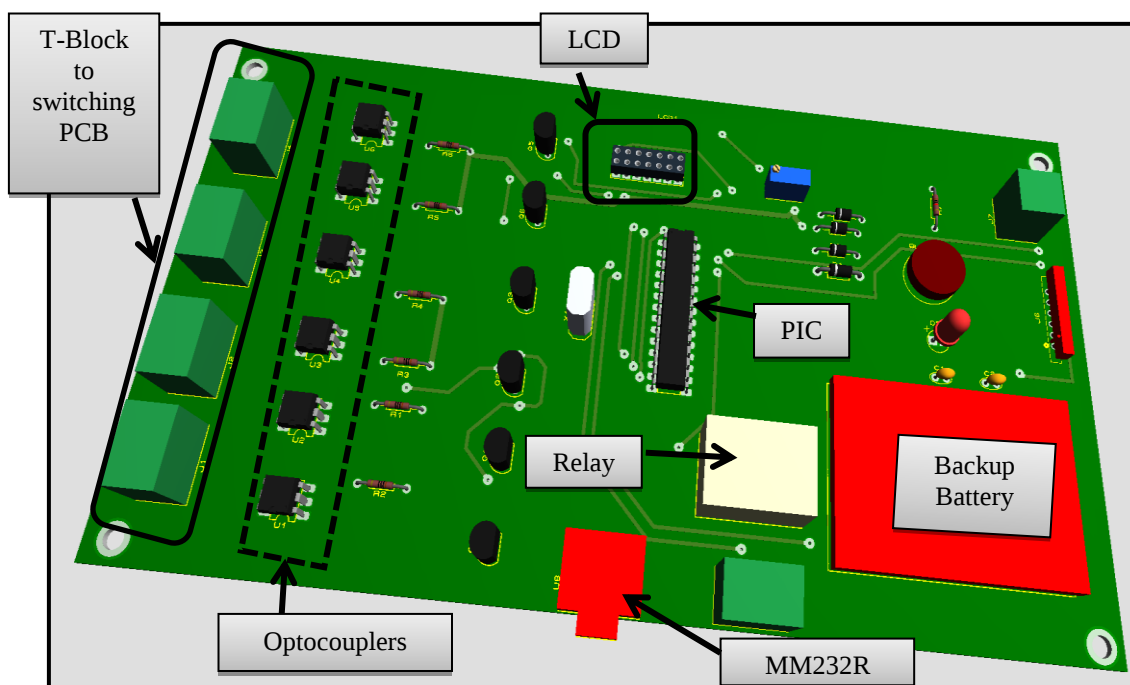
Figure 4. PCB - Rectification Circuit in 3D visualisation



**Figure Error! No text of specified style in document.. Top view of the completed rectification PCB**



**Figure 6. 3D Visualisation of the Switching PCB**



**Figure 7. Control PCB in 3D visualisation**

## **VI. RESULTS AND DISCUSSION**

Results obtained from tests carried out on the transformer and the PCBs are now presented.

### **6.1. Transformer Tests**

Upon completion of the transformer design, insulation resistance test as well as voltage tests were carried out.

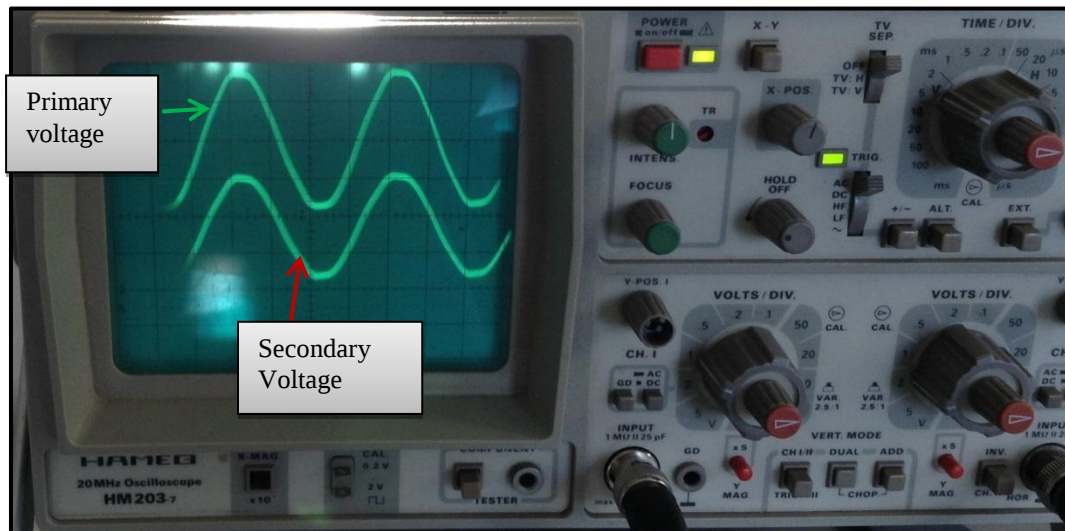


Figure 8. Oscilloscope reading of the primary and secondary voltages

A digital oscilloscope was used to measure the waveforms of the input and output voltages of the transformer. From Figure 8, it can be seen that the waveforms are not distorted but are pure sine waves indicating the the transformer is functioning properly.

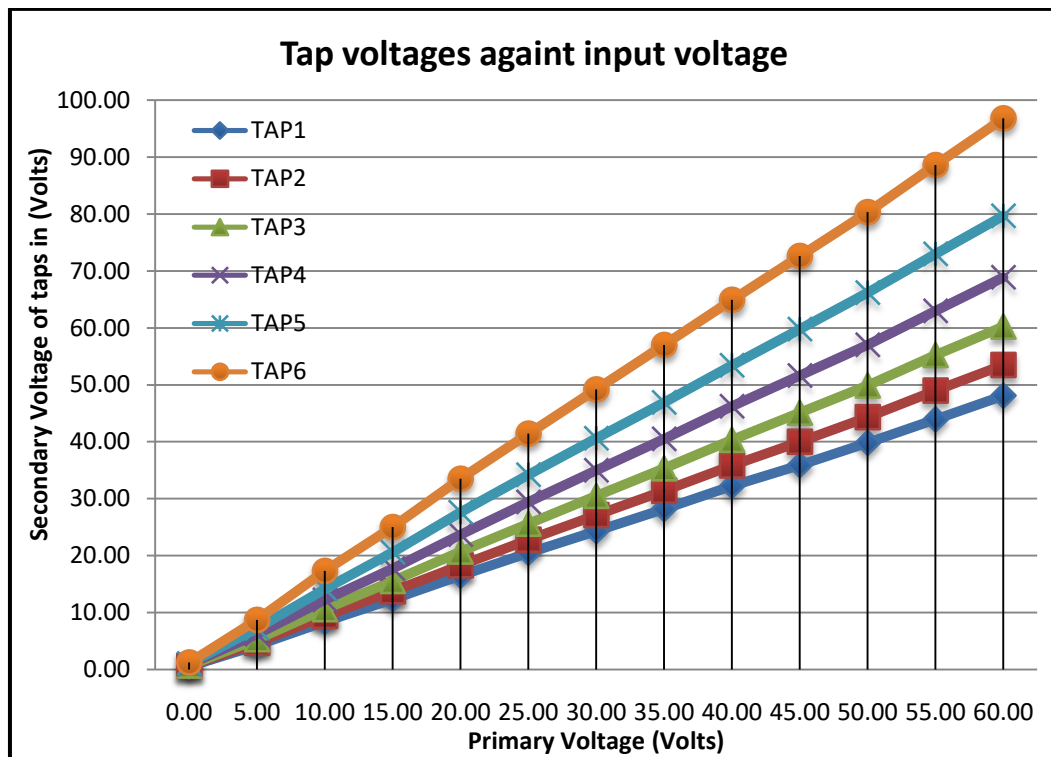


Figure2. Supply voltage compared with the secondary tap voltages

The tap voltages were seen to be as expected in Figure2 with each tap giving the expected value for tap switching. For example, at 25V input, the tap 6 must be switched on (based on the programming) to give a 40V.

## 6.2. PCB testing

**6.2.1. Rectification PCB.** The graph in Figure 10 showed a constant voltage of 5V DC given by LM7805 voltage regulator when the control winding voltage measures 8.10VAC at 35VAC supply. Overall results met expectations.

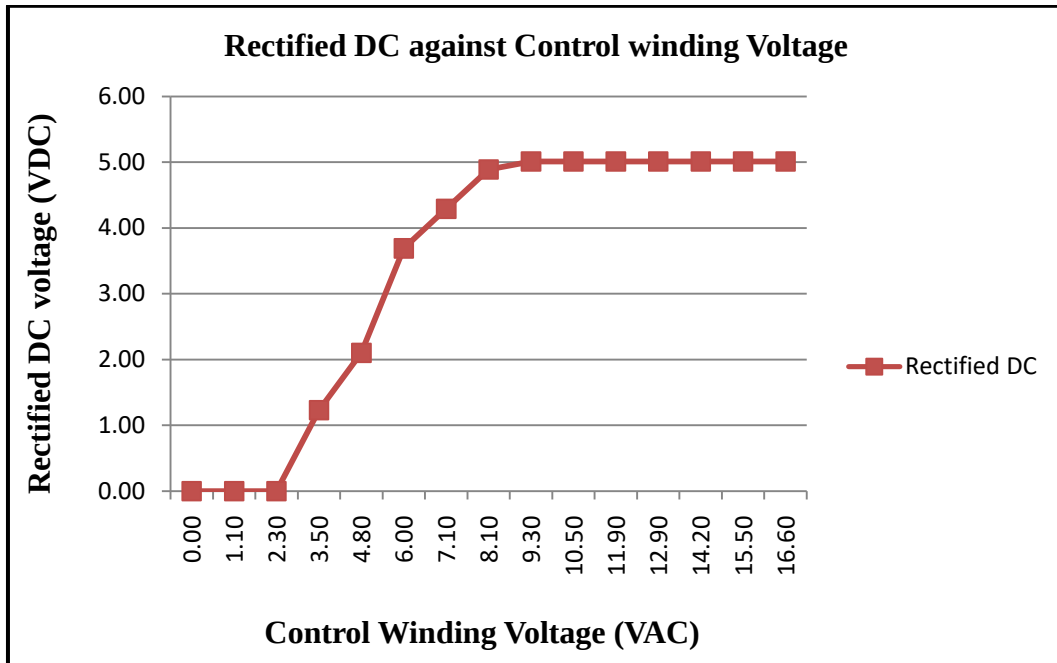


Figure 10. Graph of rectified DC voltage against Control winding AC Voltage

6.2.2. Control PCB and Switching PCB. The testing of the switching PCB could not be done in isolation or independent of the control PCB hence the testing was done simultaneously.

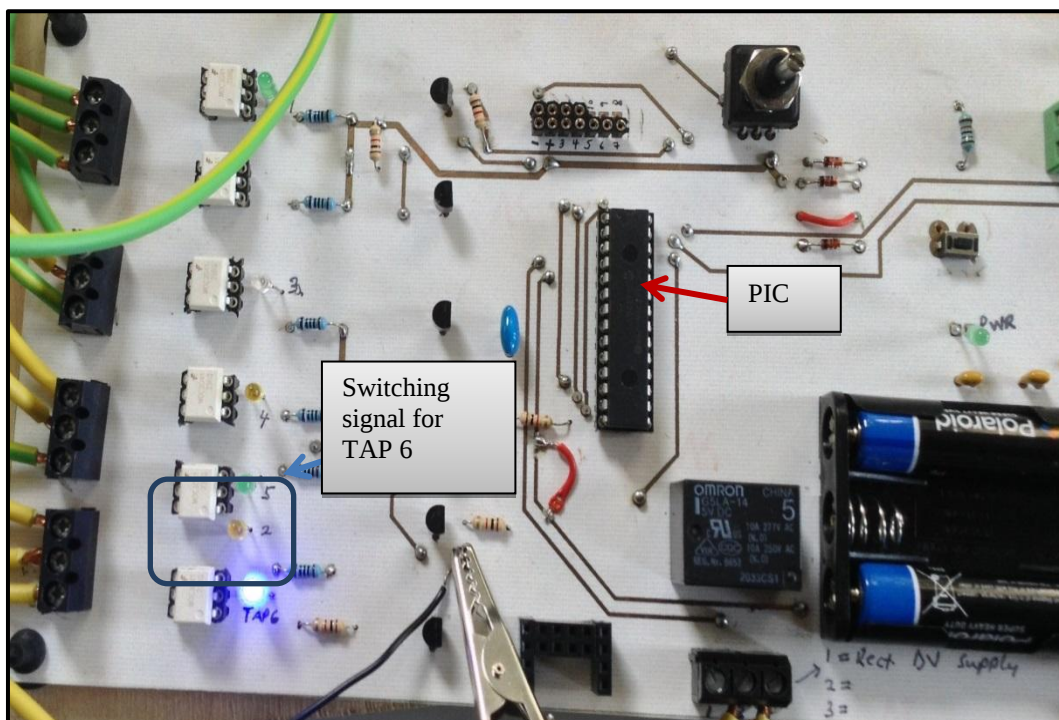


Figure 11. Tap 6 switching



**Figure 12. LCD displaying the measured input and output voltages**

Cost benefits of the voltage optimization device are now discussed. Assuming a load of  $50\Omega$  running for 10 hours a day and 300 days in a year, the savings on bills was calculated. Calculations were done for single phase supply at unity power factor.

$$P = \frac{V^2}{Z}$$

For operation of load at +25% of nominal value (that is  $40 + 10 = 50W$ );

$$P = \frac{50^2}{50} = 50 W$$

Energy per day =  $50 \times 10 \text{ hours} = 500 Wh$

Energy per year =  $500 Wh \times 300 \text{ days} = 150kWh$

The energy price of 13.870p [15] would give a bill of;

$$150 \times 13.870p = £20.8$$

For the same load on a nominal supply of 40V;

$$P = \frac{40^2}{50} = 32 W$$

Energy per day =  $32 \times 10 \text{ hours} = 320 Wh$

Energy per year =  $320 Wh \times 300 \text{ days} = 96kWh$

Cost of energy;

$$96 \times 13.870p = £13.31$$

Savings made =  $£7.49 \approx 36\%$

The calculated savings made excludes that derived from maintenance reduction and prolonged lifespan of the equipment.

## **VII. CONCLUSION**

Possible solutions to the problem of obtaining an optimized voltage from a varying supply voltage have been presented. The solution included the use of a variac as a controlled voltage source varying the supply voltage from 25 to 50 volts with emphasis on safety as the reason for the choice of voltage magnitude. The optimal system voltage was set at 40VAC and the use of PIC16F876A microcontroller was used for the monitoring, logic operation and process control of the system. Tap selection method employed was by power electronic switching device, triac, with relevant key selection factors highlighted. The benefits of the device was calculated and found to be of sound economic and environmental significance.

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