Development of a Wide Input Range Automatic AC Voltage Stabilizer for Low Voltage Residential Areas in Nigeria

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Abstract— **Many commercial domestic AC voltage stabilizers in Nigeria cannot meet the low voltage problem in the distribution network of the country. We present the development of a domestic 500 VA automatic AC voltage stabilizer for use in extremely low voltage residential areas in Nigeria, making use of materials that are locally available such as discrete components and integrated circuits (ICs). It is meant to be of low power, thus the choice of 500 VA. The stabilizer was designed to operate within 30 V to 240 V of input mains voltage. The developed stabilizer is divided into four units namely: the control unit, the switching network, the 12 V battery/charging unit and the autotransformer. The switching system employed is input switching in which the autotransformer taps are switched at the input. The control unit senses the input mains voltage level and activate appropriate relay(s) corresponding to the input mains voltage level to connect the appropriate input autotransformer tap to the input mains supply. The control unit is powered by an in-built power supply and a 12 V rechargeable battery. The 12 V rechargeable battery powers the control unit at 'switch-on' and when the input mains voltage is very low. Delay is included to delay the mains voltage from getting to the autotransformer for 24 seconds at 'switch-on' and also to prevent it from damage under abnormal high input voltages. The performance and results achieved during testing of the developed stabilizer were satisfactory and comparatively better than existing commercial stabilizers in the Nigeria market. Our developed stabilizer is therefore recommended for home use.**

Keywords—**voltage stabilizer; *autotransformer*; *relay*; *charging*; *under voltage*; *over voltage.***

I. INTRODUCTION

In Nigeria, increase in demand of electricity, and inefficient maintenance of the electrical power system have resulted in incapability of most distribution substations to handle the load demand of electricity consumers. There is continuous increase in load which is not balanced with continuous adequate upgrading of existing facilities or installation of new ones. This has brought about the supply of very low voltage to some areas due to expansion of the electrical network and distribution lines.

In Nigeria, household appliances are constantly under threat of fluctuation in voltage level [1]. According to the Nigeria Electricity Regulatory Commission (2007), the supply voltage from the supply authority is allowed to fluctuate between ± 6% of the declared nominal voltage if under system stress or following system faults [2]. Any voltage below or above this is under-voltage and over-voltage respectively. Under-voltage conditions are more prevalent than over-voltage conditions in Nigeria, therefore the major power quality problem experienced in most parts of Nigeria is that of brown out and voltage sags. Even though voltage surge and spikes also occur, they are occasional and occur for a very short period of time as compared to brown out and voltage sags [1]. A survey study by [3] in a city in south western Nigeria revealed that voltage drop of more than 40% is common. Also, a survey study by [4] in some selected areas in south western Nigeria revealed that about 30% of consumers receive voltage less than 80 V while up to 50% receive less than 120 V. A study by [5] on impact of power outages in developing countries especially in Niger Delta area of Nigeria showed that rampant power outages have severe negative impact on the social and economic lives of the people.

In confronting this low voltage problem at the consumers' end in Nigeria, various voltage stabilizers are being employed. As reported by [1], there are many automatic AC voltage stabilizers in the Nigeria market, but within the Nigeria context, most are not durable due to their inability to regulate at low voltage. The trend of commercial automatic AC voltage stabilizers produced by most manufacturers and imported into Nigeria are unable to cope with the demand of users of these stabilizers. Many commercial stabilizers regulate input voltage that is within 160 V and 260 V, which is a range that is denying them their adequate utilization [1]. Output performance evaluation tests carried out by [1] on 12 selected different brands of 1 kVA domestic AC voltage stabilizers available in the Nigeria market confirmed that many of the stabilizers are unable to adequately meet the current low voltage situation experienced by consumers of electricity in Nigeria.

There are automatic voltage stabilizers (AVS) with solid state relays, or with conventional relays, and/or with servomechanism control motor. The AVS with solid-state relays uses either power transistor or thyristors in the switching network, and are limited to low power design. AVS with conventional relays are the most common type for commercial purposes due to its price and circuitry simplicity. The conventional relays used are simply electromagnetic switches. AVS with servo-mechanism are expensive types of AVS. They are used where high stability is required. They have the most complex configuration, and their response can be slow with respect to the rate of fluctuation of the input AC voltage [6].

A microcontroller based AC voltage stabilizer is presented by [7] using Sinusoidal Pulse Width Modulation (SPWM) technique. Complexity and high cost are the main challenges of this stabilizer. SPWM technique was also adopted by [8] in their design of voltage regulation for variable speed wind turbine. There is also the challenge of high level of complexity and cost.

A 3-phase AC voltage stabilizer using solid state relays (thyristors) is presented by [9]. A major challenge is the resultant harmonics in the output load current. A microcontroller based system to provide programmable control with multi taps transformer using output switching control system was developed by [10], and with greater precision by [11]. A tolerable input range of 150 – 273 volt with output range of 215 - 237 volt regulation was achieved. Overvoltage and under voltage cut-off are at 274 V and 145 V respectively.

Attia (2015) developed a three step AC voltage regulator based on one step-down transformer [12], and in 2016, developed a binary weighted 7-steps automatic voltage regulator [13]. Also, in 2017, he designed by simulation a 9-step automatic voltage regulator based on two step-down transformers [14]. Output voltage stability between 210 V and 230 V was achieved by using the two step-down transformers in series with the mains winding either in additive phase polarity or subtractive phase polarity. While good stability was achieved up to theoretical input voltage range of 280 V, the lowest input voltage range is somewhat limited to 180 V.

[15] developed a 500 W AVR-based three phase voltage selector system that gives an output voltage of 200 V to 240 V from an input voltage range of 160 V to 270 V, and [16] developed an automatic AC voltage regulator that ensures a steady output voltage magnitude of 230 V within a possible input voltage variation range of 90 V to 230 V.

In order to increase the input voltage range, [17] developed an automatic AC voltage regulator in which the autotransformer used has eleven taps with gap of 15 V between the taps, and resulting in the use of ten relays. The AVR produces output voltage range of 194 V-230 V, with input voltage range of 75 V-245 V.

The demand for improvement in the lowest input voltage range achievable is the motivation behind this work – the development of an automatic AC voltage stabilizer for low voltage (down to 30 volts) residential areas in Nigeria with features surpassing existing commercial stabilizers. Our developed stabilizer employed the use of discrete circuits, integrated circuits, rechargeable batteries and other materials that are locally available. It is not microcontroller based. The stabilizer used an autotransformer with controlled electromagnetic relays, and employed input switching system of the autotransformer in order to regulate down to 30 V. Due to the input switching method of the autotransformer, at very low input voltage, the input current into the autotransformer would be very high, hence the choice of limiting the developed stabilizer to 500 VA. The control unit of the stabilizer is powered by an in-built power supply and a 12 V rechargeable battery when the input voltage is very low. In this paper, we present the circuit design and analysis of each stage, as well as their implementation, and construction of the AVS as a finished product. Its performance evaluation in terms of voltage regulation test was carried out in comparison with other commercially available 1 kVA stabilizers in Nigeria market.

II. DESIGN METHODOLOGY

A. Block Diagram of the Automatic A.C Voltage Stabilizer for Extremely Low Voltage

The automatic voltage stabilizer represented in block diagram is shown in Fig. 1. The stabilizer is divided into five sections. They are: the control circuit, the switching network, the auto-transformer, the battery charger, and the external source.

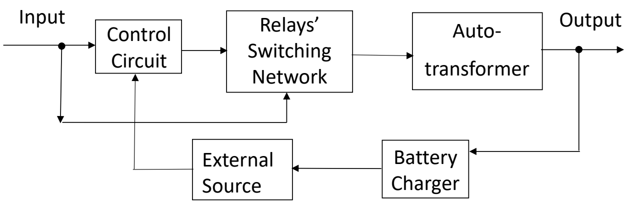

Figure 1: Block diagram of the developed Automatic Voltage Stabilizer.

1) *Control Circuit:* This consists of electronic components that function majorly as comparators. The circuitry senses the incoming input voltage and compares it to a reference voltage source to perform its operation. Its output is linked to the switching network in which each relay carry out switching action connecting the corresponding autotransformer taps that matches the incoming voltage range.

2) *Switching Network:* This comprises of electromagnetic relays and protective devices. They are responsible for the connection of autotransformer taps to the supply mains voltage.

3) *Auto-Transformer:* This is a special transformer from which a variable a.c. voltage can be obtained. It uses a single coil with one or more taps. In contrast to the two-winding transformer, the primary and secondary are physically connected. However, the basic principle of operation is the same as that of

the two-winding transformer. In this design, the primary winding is of varying taps producing a single output voltage tap.

4) *External Source and Battery Charger:* The external source is a 12 V rechargeable battery that activates the control circuit at the instance when input voltage is supplied to the stabilizer, and also during the switching time lag between one relay and the other. Also, the battery takes over the job of powering the control circuit when the input supply is at an extremely low voltage for the battery charging circuit to charge the battery. The battery is necessitated because in the stabilizer, the transformer input winding is varied depending on the input supply voltage. In addition, it initially activates the control circuit to supply A.C. power to the stabilizer at switch-on. The battery charger restores energy back into the battery during normal operation of the stabilizer.

B. Design of the Auto-Transformer

The auto-transformer is made up of six taps at the input and a single tap at the output with isolated auxiliary winding to supply voltage to the battery charging circuit. The transformer is designed to regulate input voltage in the range of 240 volts to 30 volts. The determination of voltage in each tap at every input voltage supplied is achieved based on the switching operation adopted in getting desired output voltage.

The schematic diagram of the autotransformer is shown in Fig. 2, and the input voltage range, the corresponding autotransformer taps and the respective output voltage range is shown in Table 1. A, B, C, D, E and F represent the taps of the transformer. The taps are switched within the input range to give corresponding output voltage range as specified in Table 1.

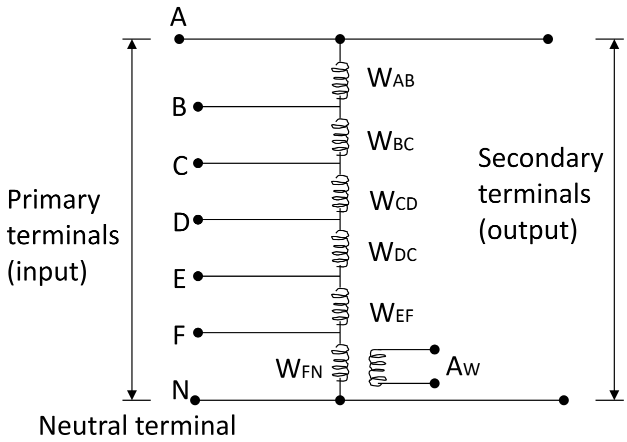

Figure 2: The designed auto-transformer schematic.

The voltage ratios of the taps are calculated thus: Using terminal N as reference, voltage ratio, V_{BN}/V_{AN} = 190/240 = 0.79 = N_{BN}. Following similar procedure, the voltage ratio between the other terminals C, D, E, F and N were obtained. For the auxiliary winding, V_{AW}/V_{AN} = 15/240 = 0.0625 = N_{AW}

Table 1: Input voltage range, autotransformer taps and the output voltage range of the autotransformer

Input Voltage Range (Volts)	Autotransformer Taps	Output Voltage Range (Volts)
240 – 190	A	240 – 190
190 – 150	B	240 – 190
150 – 118	C	240 – 190
118 – 94	D	240 – 190
94 – 74	E	240 – 190
74 – 30	F	240 – 120
240	W (Auxiliary Winding)	15

1) *Determination of Turns of Coils:* From the assumption and derivation of transformer equation in [18],

Primary e.m.f., $E_p = 4.44\, fBAN_p$ (1)

where *f* is the frequency in hertz, *B* is the maximum flux density in tesla, *A* is the area of the core in square metres, and N_p is the number of turns of primary coil. From equation (1)

$$N_p = \frac{E_p}{4.44\, fBA} \quad (2)$$

The coil former that was used is of dimension 4.4 cm by 3.9 cm, *f* = 50 Hz (power line frequency in Nigeria). Substituting values and assuming a flux density of 1.1 tesla, N_p is approximately 600 turns, which is the number of turns of coil between terminal A and the neutral terminal.

For tap B, this is calculated as follows: $T_{BN} = N_p \times N_{BN}$ = 600 x 0.79 = 474 turns; which then makes the number of turns for the winding between terminals A and B, W_{AB} to be 600 - 474 = 126 turns. The number of turns for the other windings was obtained following the procedure as for W_{AB}. Table 2 shows the number of turns of each of the windings that make up the autotransformer.

Table 2: Number of Turns of the Auto-transformer's Coils

Windings	W_{AB}	W_{BC}	W_{CD}	W_{DE}	W_{EF}	W_{FN}	A_W
Number of turns	126	99	78	63	48	186	37

C. Design of the Control Circuit

The control circuit is divided into four sections. They are:

1) Mains Voltage Sensing Circuit
2) Under Voltage and Over Voltage Circuit.
3) Delay Circuit
4) Switching Comparator Circuit.

The above sub-divisions of control circuit are powered with 12 volts from rechargeable battery/battery charger. The control circuit in block diagram is shown in Fig. 3.

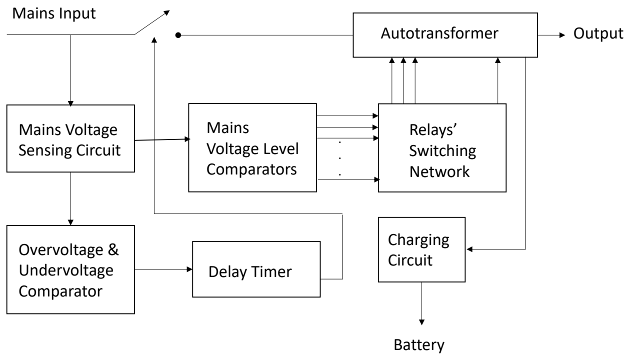

Figure 3: Block Diagram of the Control Circuit

1) *Mains Voltage Sensing Circuit Design and Analysis:* The mains voltage sensing circuit is incorporated into the control circuit to facilitate the comparison of voltage variation in the supply voltage with a reference source. The circuit is shown in Fig. 4. The circuit made use of a two windings 240V/12V step down transformer T_1 to provide isolation. In case of increase in supply voltage above 250V, the transformer high voltage primary winding was designed in such a way that it can withstand input mains voltage up to 500 V. Alternatively, an opto-isolator can be used. The diode D_1 in the circuit provides half wave rectification and the capacitor C_1 smoothens out the ripples present in the rectified output.

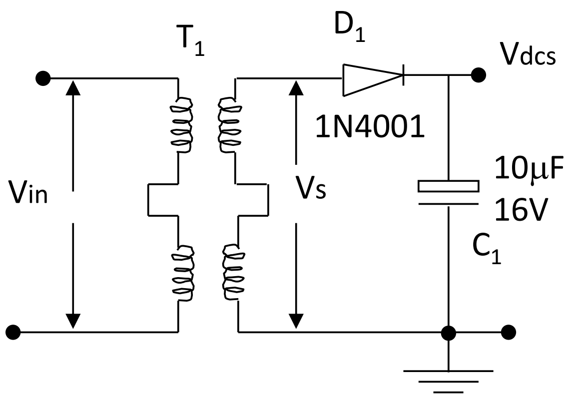

Figure 4: Mains voltage-sensing circuit.

If the input mains voltage (rms) is V_m, the transformer secondary voltage (rms) is V_s, and the secondary to primary windings turns ratio is N_v, then

$$V_s = N_v V_m \quad (3)$$

Secondary winding peak voltage, $V_{sp} = \sqrt{2} V_s$ (4)

From [19], rectified and filtered dc voltage, V_{dcs}, (voltage sensed by the comparators)

$$V_{dcs} = V_{sp} - V_D - \frac{V_{dcs}}{2fCR_L} \text{ (half-wave rectification)} \quad (5)$$

where V_D is the diode voltage drop, *f* is the mains frequency, C is the capacitance of the filtering capacitor, and R_L is the load seeing by the sensing circuit.

Substituting for V_s and V_{sp} from equations (3) and (4), and re-arrange

$$V_{dcs}\left(\frac{1+2fCR_L}{2fCR_L}\right) = \sqrt{2} N_v V_m - V_D \quad (6)$$

In this case N_v = 1/20 (i.e. 12V/240V), *f* = 50 Hz, and *C* = 10 µF. R_L is the combined resistance of parallel set of preset resistors used to set the various switching levels, and is around 10 kΩ.

$$\frac{1+2fCR_L}{2fCR_L} = \frac{11}{10} \approx 1$$

Therefore, $$V_{dcs} \approx \frac{\sqrt{2}V_m}{20} - V_D \quad (7)$$

Equation (7) shows a direct relationship between the input mains voltage (V_m) and the representative voltage (V_{dcs}) actually sensed by the comparators. At mains voltage of 250 V (rms), V_{dcs} = 16.97 V. At mains voltage of 30 V (rms), V_{dcs} = 1.42 V.

There will be virtually no V_{dcs} that can be sensed when V_m is at or below a certain value. This happens at $V_{m\min}$ when $\frac{\sqrt{2}V_{m\min}}{20} = V_D$.

$$\Rightarrow V_{m\min} \approx 10\,\text{V (rms)}.$$

2) *Over Voltage and Under Voltage Circuit Design:* The overvoltage and under-voltage circuitry is built around LM 339 IC quad - comparator. The over and under voltage circuit design is shown in Fig. 5. The circuit uses two comparators configured as window comparators, and their outputs are hardwired together and fed to the trigger of the delay circuit.

V_{dcs} is the filtered output of the mains sensing circuit, and V_{rs} is the voltage sensed by the two comparators. Since the comparators have fixed supply voltage of +5 V, therefore, the voltage to be sensed must fall within 5 V throughout the operational range of the input voltage for the stabilizer.

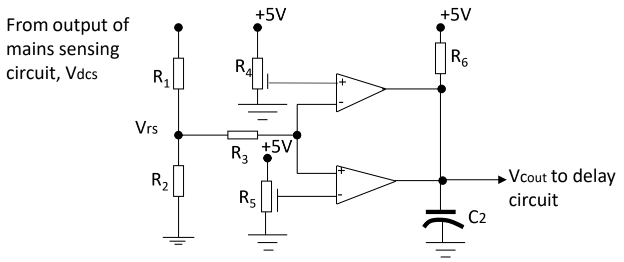

Figure 5: The over and under voltage circuit.

Since V_{dcs} could be higher than 5 V, V_{rs} has to be a divided - down value of V_{dcs}. R_4, R_5 and R_6 are connected to a fixed +5 V supply from an IC regulator. The values of resistor R_1 and R_2 were chosen so that the value of V_{rs} at very high and low mains voltage will make the designed circuit to produce a low output voltage.

$$V_{rs} = \frac{R_2}{R_1 + R_2} V_{dcs} \quad (8)$$

Taking V_{rs} as 0.25 V_{dcs}, at input mains voltage of 250V (rms), V_{rs} = 4.63 V < +5 V. If R_1 = 100 kΩ, then, R_2 can be 33 kΩ.

R_4 and R_5 are preset resistors of value 50 kΩ while R_6 is the pull-up resistor of the comparators. A value of 10 kΩ for R_6 is satisfactory with little current drain from the +5 V supply when in low output state. Capacitor C_2 is included to set Vc_{out} to delay circuit at "switch – on" to 0 V, and rapidly charges to +5 V. This will always trigger the delay circuit at 'switch - on'. A value of 10 μF proved satisfactory.

3) *Delay Circuit Design:* This is a circuit wired around a 555 timer IC. The delay circuit is shown in Fig. 6 and is a monostable multivibrator (MV) circuit that produces a HIGH output (at pin 3 of the IC) for a predefined time whenever pin 2 is triggered by a negative going pulse. The triggering pulse is received from the output of the overvoltage and under voltage sensing circuit (i.e. Vc_{out}).

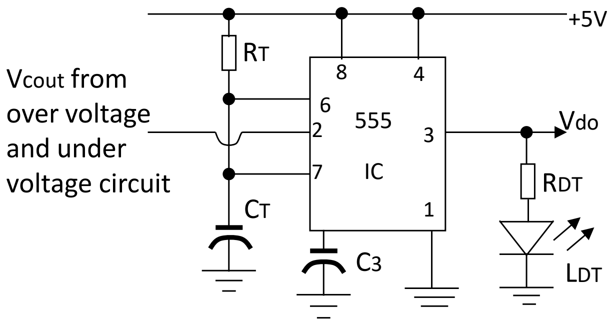

Figure 6: The delay circuit.

The time delay 't_d' is taken as 24 seconds.
From [20], time delay for the 555 monostable MV,

$$t_d = 1.1 R_T C_T \tag{9}$$

If R_T = 100 kΩ (preferred value), then C_T = 218 x 10^{-6}F (220 μF preferred value).
A LED L_{DT} in series with resistor R_{DT} across the time output serves as a delay/undervoltage/overvoltage indicator. R_{DT} of 1 kΩ limited the LED current to 3 mA. C_3 is 10 nF preferred value.

4) *Delay Relay Circuit Design:* This is the circuit that switches on/off the mains input supply to the auto-transformer during normal/abnormal conditions respectively. At switch-on, delay circuit output is HIGH for 24s. During this period, the delay relay is de-energized. After the delayed period, the delay relay is activated thereby connecting the input mains supply to the autotransformer. The delay relay circuit is shown in Fig. 7. R_6 and R_7 are current limiting resistors (base resistors) to the two transistors Q_1 and Q_2 respectively when they are conducting. R_7 also serves as Q_1 collector resistor when it is ON. R_6 = 100 kΩ, and R_7 = 10 kΩ. Q_1 and Q_2 are BC337.

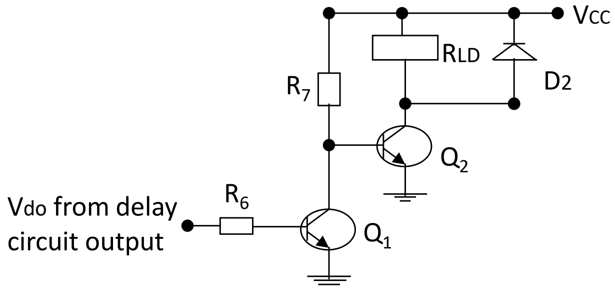

Figure 7: Delay relay circuit.

At switch-on, delay circuit output is high for 24 seconds and Q_1 is 'ON' making Q_2 to be OFF. After the delayed period, Q_1 is OFF and Q_2 is ON thereby activating delay relay R_{LD} making it to connect the input mains supply to the auto-transformer.

During abnormal conditions (over and under voltage) delay circuit output is high causing delay relay R_{LD} to automatically switch off until normal input voltage range is sensed. The essence of the inclusion of the delay relay is to prevent the auto-transformer from getting damage under abnormal input high voltage. Most commercial AVS in Nigeria only disconnect the output load from the stabilizer but not the stabilizer auto-transformer from the mains supply under this condition resulting in overheating and eventual damage of the transformer (though fuses are usually connected between the mains supply and the transformer). During the delay period of 24 seconds after 'switch-on', the autotransformer taps switching relays would have switched sequentially to the appropriate one corresponding to the input mains voltage level.

5) *Switching Comparator Circuit Design:* The comparator used is LM339 and each comparator in the set up follows hysteresis in its switching action within the set point. Five comparators are used in all since there are six voltage taps on the autotransformer. The diagram of a single comparator circuit is shown in Fig. 8 with the transfer characteristics.

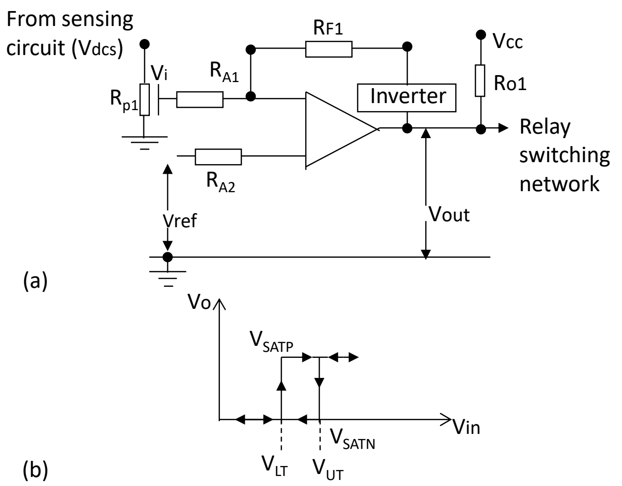

Figure 8: (a) The designed single comparator circuit with hysteresis. (b) Transfer characteristics.

V_{LT}: Lower threshold voltage (V_{iH}),
V_{UT}: Upper threshold voltage (V_{iL}),
V_{SATP}: Positive saturation voltage (comparator output voltage, in this case V_{CC}),
V_{SATN}: Negative saturation voltage (comparator output voltage, in this case 0V),
V_{iH}: Comparator input voltage for V_{out} LOW to HIGH transition, and
V_{iL}: Comparator input voltage for V_{out} HIGH to LOW transition.

R_{P1} is the preset resistor used to set the switching level. R_{A2} (of 1 kΩ) is connected to the non-inverting input of each of the comparators so as to provide some isolation of the inputs from each other since five comparators are used and all their non-inverting inputs are connected to a reference voltage source fed with their input currents. R_{F1} forms the feedback resistor which together with R_{A1} provides hysteresis. It is actually connected to the comparator output through an inverter to provide positive feedback as indicated in the diagram. This inversion was actualized by connecting R_{F1} to the collector of the relay-switching transistor. V_{ref} is the reference voltage and V_i is the input voltage to the inverting pin of the comparators. R_{o1} is the pull up resistor at the output since the comparator is of open collector output type; a value of 10 kΩ is satisfactory. V_{out} HIGH (which is V_{cc} in this case) switches 'on' the relay and V_{out} LOW (0 V in this case) switches it off.

For V_{out} LOW to HIGH transition,

$$\frac{R_{A1}}{R_{A1}+R_{F1}}\left(V_{cc}-V_{iH}\right)+V_{iH}=V_{ref} \quad (10)$$

Upon simplification,

$$V_{iH}=\left(\frac{R_{A1}+R_{F1}}{R_{F1}}\right)V_{ref}-\frac{R_{A1}}{R_{F1}}V_{CC} \quad (11)$$

For V_{out} HIGH to LOW transition,

$$V_{iL}=\left(\frac{R_{A1}+R_{F1}}{R_{F1}}\right)V_{ref} \quad (12)$$

Hysteresis, (upper threshold minus the lower threshold), from equations (11) and (12),

$$V_{iL}-V_{iH}=H_T=\frac{R_{A1}}{R_{F1}}V_{CC} \quad (13)$$

R_{A1} = 1 kΩ, and if R_{F1} = 100 kΩ, V_{cc} = 12 V; then, hysteresis, H_T = 0.12 V.

If K is the division ratio of the preset resistor (K < 1), then V_{dcs} hysteresis (from sensing circuit)

$$H_{TK}=\frac{H_T}{K} \quad (14)$$

From equation (7), $V_{dcs}\approx\frac{\sqrt{2}V_m}{20}-V_D$

Assuming $V_D<<\frac{\sqrt{2}V_m}{20}$,

Then, mains hysteresis, $H_m=\frac{20H_{TK}}{\sqrt{2}}=\frac{20H_T}{K\sqrt{2}}$ (15)

If K = 1, and H_T = 0.12 V,

Then H_m = 1.7 V (rms).

For all the preset resistors, K varies below 1, and the values of K for each preset resistor are different since each is set to different values of the input mains voltage. This implies that the mains voltage hysteresis is not the same at all the switching points. Hysteresis increases as K reduces. Minimum K exists for the first switching relay preset resistor as the mains voltage falls past 190 V (rms). Therefore, the mains voltage hysteresis is maximum for the first switching relay, and is minimum for the fifth switching relay as the mains voltage falls past 74 V (rms).

6) *Autotransformer Taps Switching Network Circuit Design:* The autotransformer taps-relay switching network was designed to receive all the comparison carried out by the control circuit before switching power to the output via the autotransformer in the stabilizer. The components of the switching circuit are relays, transistors, LEDS and protective devices. The relays used are 12 volts five-terminal type with 10 A contact rating. The switching of each relay is controlled via transistors from the output of the switching comparators. The designed circuit is shown in Fig. 9. The transistors employed in the design (Q_{A1} and Q_{A2}) are NPN BC337.

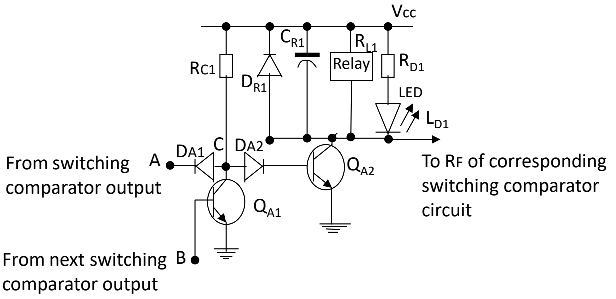

Figure 9: The Autotransformer Taps-Relay Switching Network Circuit.

Q_{A2} is the transistor that energizes the relay R_{L1}. When the output of a particular comparator is high (say node A), Q_{A2} is driven to saturation through R_{C1} and D_{A2}, and R_{L1} is energized. When the input voltage drops to the set point capable of making the next comparator output high (node B), transistor Q_{A1} brings the V_{BE} of Q_{A2} near 0 V which switches off Q_{A2} and R_{L1}. This is done in order to ensure that at all times, only the effective relay that connects the input mains to the appropriate and corresponding autotransformer tap remains energized. This reduces current drain from the control circuit power supply.

R_{L1} is the relay that actually connects input mains to the autotransformer primary winding taps. C_{R1} is the capacitor that prevents clattering of the relay contacts due to continuous slight variations in input mains voltage. Preferred value of 220 µF proved satisfactory. D_{R1} is a diode that is reverse-connected across the relay coil as shown to protect the transistor Q_{A2} from breaking down due to high inductive voltage kickback generated by the relay coil during switching. The LED L_{D1} indicates the relay that is energized. R_{D1} limits the

LED current to a safe value that still gives satisfactory brightness.

Switching action is as follows:

When the comparator output (node A) is LOW (at 0 V), node C is at 0.7 V which is not enough to bias the base of Q_{A2} and diode D_{A2}. Diode D_{A1} drops a voltage of 0.7 V. When the comparator output (node A) is HIGH, diode D_{A1} is reverse-biased and node C is raised to two-diode voltage drop by R_{C1}, and Q_{A2} is biased into conduction. R_{L1} is energized and the LED L_{D1} indicator is lit.

Relay current I_L = Collector current I_C. Let this current be a saturating current, Ic_{SAT}. The relay used has a coil dc resistance of 180 Ω, therefore for V_{CC} of 12 V,
$I_L = Ic_{SAT.}$ = 66.6 mA.

The base current, I_B producing this current must be a saturating base current, I_{BSAT}.

Normal base current, I_B (with h_{FE} of 200) is 333 μA.
I_{BSAT} must be greater than I_B of 333 μA.

If R_{C1} = 10 kΩ, then $I_{BSAT} = \frac{V_{CC} - 2V_{BE}}{R_C}$ (16)

= 1060 μA, which is > 333 μA.

As mains voltage reduces, the next comparator output switches HIGH, node B is raised to 0.7 V biasing Q_{A1} into conduction. Q_{A1} saturates and grounds node C thus switching off Q_{A2}. Diode D_{A1} is included and connected as shown to prevent the grounding of node C from affecting the 'HIGH' state of the previous comparator output. This diode is performing a dual role. It helps Q_{A2} to conduct when only the previous comparator output is HIGH. Also, it prevents grounding of node C from affecting HIGH state of the previous comparator output when both the comparator (previous and next) outputs are both HIGH. D_{A1} and D_{A2} used are small signal IN4148 diodes. R_{D1} of 3.3 kΩ provides a safe limiting current through the LED.

7) *Reference Voltage Circuit Design:* This circuit supplies the reference voltage to the non-inverting terminals of the switching comparators in the control circuit. It is made up of two transistors, potential divider and a capacitor as shown in Fig. 10. The reference voltage is derived from a fixed voltage 7805 IC regulator through a resistive voltage divider circuit.

Q_3 takes input from the output of over and under voltage circuit. For the design input voltage range, the output of the over and under voltage circuit is HIGH thereby saturating Q_3 (V_{CE3} = 0), and turning off Q_4. Q_4 output (V_{CE4}) is V_{ref} (this happens during normal condition).

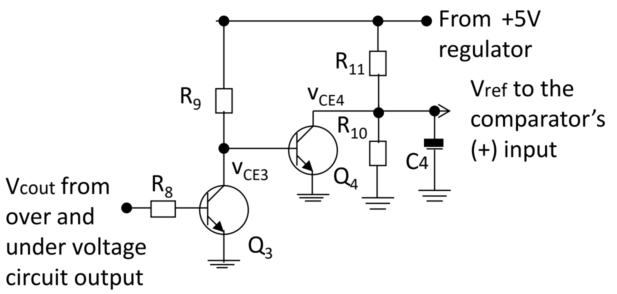

Figure 10: The reference voltage circuit.

Let V_{ref} = 2.5 V and R_9 = 1 kΩ, therefore, R_4 = 1 kΩ. Transistors Q_3 and Q_4 used are BC337.

The capacitor C_4 charges up at the instance when the power is switched on to the stabilizer. This makes the five autotransformer taps' relays (R_{L1} – R_{L5}) to switch 'on' sequentially in the order of input voltage (i.e. from R_{L1} to the appropriate R_{L5}). During over and under voltage condition, over and under voltage comparator output is LOW, Q_3 is off turning 'on' Q_4 and thereby making V_{ref} to become 0V. Capacitor C_4 discharges rapidly through Q_4. Thus the five relays switch off in descending order of input voltage sensing (i.e. from R_{L5} to the appropriate R_{L1}). The purpose of this network circuit for the reference voltage is to ensure that:

i. At 'switch-on' during the delay, the relays are energized sequentially (though rapidly but not erratically) to the appropriate one depending on the input mains voltage level. The relays also switch-off sequentially in the reverse order of input voltage sensing. Most commercial stabilizers in Nigeria market switch erratically at 'switch-on'.
ii. Under over and under voltage conditions, all the relays are de-energised.

8) *Battery Charging Circuit Design:* The battery charger comprises of a rectifier for changing a.c. from the auxiliary winding of the output transformer in the regulator to d.c. suitable for the battery charging with a current limiting resistor. The designed circuit is shown in Fig. 11.

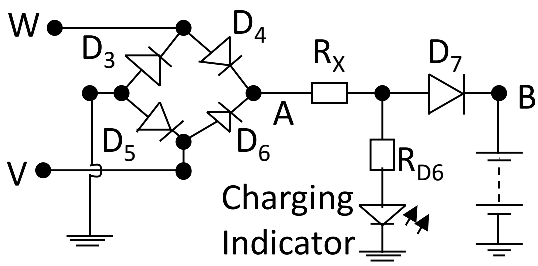

Figure 11: The battery charging circuit.

D_3, D_4, D_5, D_6 are connected in bridge configuration. Diode D_7 prevents the battery from discharging into the LED circuit in the absence of a.c. mains supply or when the stabilizer is switched off. The rectifier used is IN5401. The IN5401 has peak inverse voltage (PIV) of 100 V, and maximum rated forward current of 3 A.

At node A,

$$V_{dc(peak)} = \sqrt{2}N_{AW}V_m - 2V_D \qquad (17)$$

where N_{AW} is the transformation ratio of the auxiliary winding of the autotransformer, V_m is the input mains (rms) voltage, and V_D is the voltage drop across a diode.

At input mains voltage of 240 Vrms, peak dc voltage at node A,

$V_{dc\ (peak)}$ = 2 x 0.0625 x 240 – 1.4,
= 19.81 V.

From [18],

$$V_{dc(average)} = \frac{2V_{dc(peak)}}{\pi} \text{ (full-wave rectification)} \quad (18)$$

$= 12.6$ V

Voltage at node B is taken as 12 V since the circuit is required to charge 12 V battery. If R_x (current limiting resistor) = 2.7 Ω (preferred value), then peak charging current, Ipeak

$$I_{peak} = \frac{V_{dc(peak)} - (V_B + V_D)}{R_X} \quad (19)$$

$= 2.67$ A.

This current flows in pulses with conduction angle less than 180^o. It only flows whenever the voltage at node A rises above the battery voltage. Conduction angle decreases as the battery voltage rises, therefore the average charging current will be less than the maximum average charging current of the battery used. The average charging current also reduces as the battery voltage increases. R_x used is 2.7 Ω, 10 W.

III. IMPLEMENTATION, TESTING AND PERFORMANCE

A. Construction and Assembly

The autotransformer core used is a shell type. Standard wire gauge 22 was used for the windings. This gauge is a compromise between being able (the common winding of the autotransformer between input and output) to withstand the return current at rated load when low input mains voltage is connected to the stabilizer; and bulkiness of the transformer. Thicker coil gauge is better, but increases the bulkiness. The winding is continuous and started from turn number 1 to 600 with the appropriate taps in between. The auxiliary (battery charging) winding is isolated from the main autotransformer winding so as to electrically isolate the control circuit and battery terminals from the lethal mains voltage.

On completion of the winding, the former and the windings were wrapped with paper tape for safety purpose and protection against damage by laminated sheets. The laminated sheets-EI types forming the core were arranged altogether. The transformer core was clamped tightly and varnish was applied to aid proper insulation between laminated sheets and prevention of humming and flux leakages due to air space within the laminated sheets. The auto-transformer was tested to ascertain the voltage at the taps. The circuits making up the block diagram of the AVS were combined and constructed. The autotransformer and the battery were mounted separately and joined to other circuit through wires. All other circuits were combined and soldered on Vero board. The casing of the project was fabricated from iron sheet of 1.5 mm thickness. The front and back covers were cut at appropriate places to hold socket outlet, switch, fuse, voltmeter and indicating LEDS. Ventilations slots were cut on both sides of the casing for air ventilation. The overall dimension of the stabilizer is 24.5 cm by 21.5 cm by 12 cm.

Inside the casing, the auto-transformer, battery and sensing transformer were screwed down. All the electronic components already soldered on Veroboard were also mounted in the casing. Then the output of the transformer was connected to the socket outlet which is in parallel with the voltmeter used to indicate the output voltage. The physical outlook of the developed stabilizer is drawn in Fig. 12. The stabilizer weighs (excluding the battery) 5.0 kg.

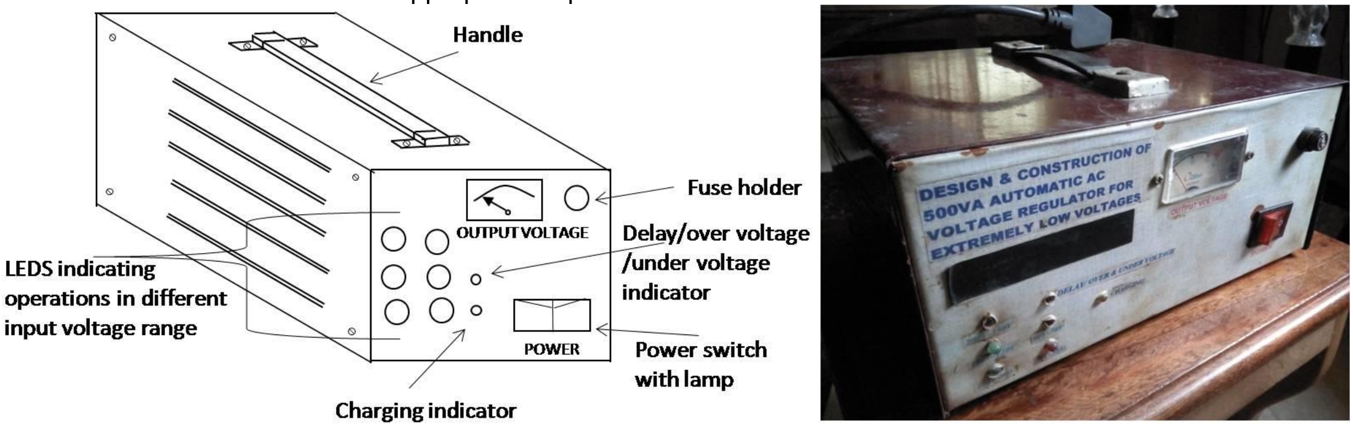

Figure 12: The physical outlook of the developed stabilizer.

B. Principle of Operation

The developed automatic voltage stabilizer for extremely low voltage is an input switching type (switching relays are connected to the primary side of the main autotransformer) compared to the output switching type of the available stabilizers in the Nigeria market. The switching relays and autotransformer circuit of the AVS is shown in Fig. 13, while the internal arrangement and connections of the developed AVS is shown in Fig. 14.

When the AVS is connected to the mains supply and switched ON by the main power switch of the stabilizer, the under and over voltage circuit will sense and compare the input voltage to the reference voltage of the comparators in the control circuit through the sensing circuit.

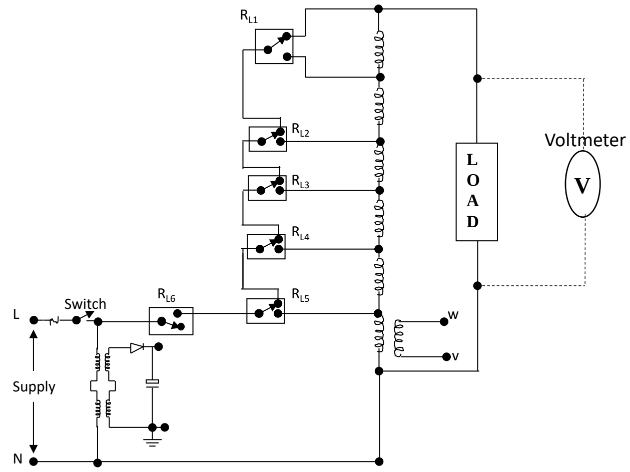

Figure 13: Switching relay and auto-transformer diagram.

For the AVS, over voltage is above 240 volts while under-voltage is below 30 volts. If the input voltage is within the specified range, then the output of the window comparators will be 'HIGH' causing the time delay circuit to operate for 24 seconds (i.e. pin 3 of 555 timer is HIGH, Q_1 is saturated and Q_2 is at cut off) before relay R_{L6} is activated. At the same time switching comparator circuit compares the input voltage with a reference source. It then switches the appropriate relay (among R_{L1} to R_{L5}) in the switching network to connect the autotransformer input tap to the a.c. input supply to get regulated output voltage. All these are achieved before the elapse of 24 seconds. On completion of the time delay, Q_1 is cut off thereby driving Q_2 into saturation and switching ON relay R_{L6} to supply input voltage to the appropriate autotransformer tap. LED indicators indicate the input voltage range, and an analogue voltmeter indicates the output voltage value.

Whenever there is sudden increase in voltage above 240 volts or fall below 30 volts, the AVS will automatically shut down and time delay LED will light up i.e. over and under voltage output is LOW. This will trigger 555 timer circuit causing R_{L6} to open and at the same time grounding the reference voltage to the switching comparators. It makes the switching network relays R_{L1} to R_{L5} to return contact to their 'normally closed' terminals. This condition remains until the input voltage falls within the designed specified range. Then the time delay circuit will start to activate its set time and the operational procedure for the normal input range is repeated. When load is being supplied, the main transformer will at the same time supply voltage to the charging circuit that will restore the energy expended in the battery. The internal arrangement and connections of the developed AVS is shown in Fig. 14.

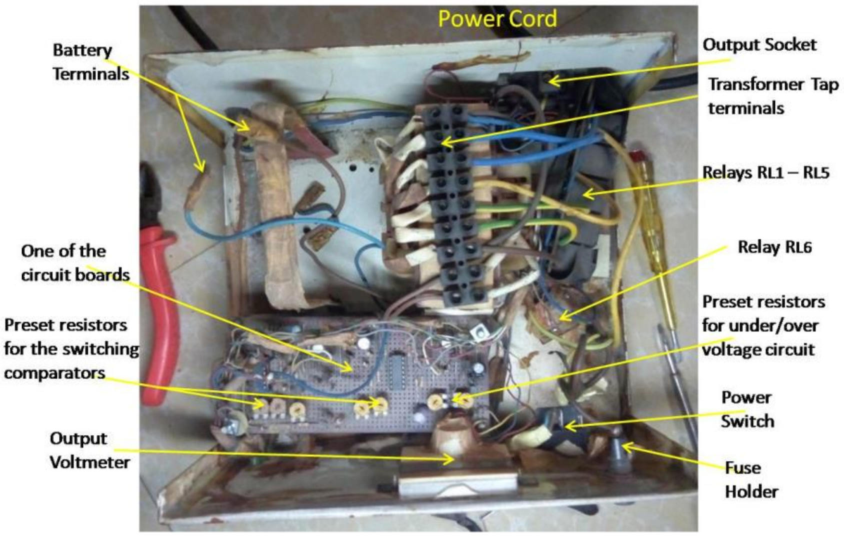

Figure 14: Internal arrangement of the developed stabilizer. The battery is excluded.

C. Test and Performance

1) Line Regulation Test: The major test carried out on the developed AVS is line regulation test (voltage test). This was done by varying the input voltage to the stabilizer. The result of the test is shown in Fig. 15. The materials utilized in the course of the tests are AC voltmeters, AC ammeters, 3 kVA variac, wires for connection, testers and screwdrivers. Below 30 V and above 240 V, the stabilizer shuts down as designed.

2) Comparison of Output Voltage Variation with Some Other Commercial AC Stabilizers: Line regulation tests of some other selected commercial domestic AC 1 kVA stabilizers in the Nigeria market were performed by [1], and Fig. 16 shows the result of the test in comparison with the developed stabilizer.

Average output voltage and standard deviation for input between 100 V – 240 V for the selected stabilizers from [1] in comparison with the developed stabilizer are shown in Fig. 17. For the developed stabilizer, the average of the output voltage for input range of 100 V to 240 V is 217.3 V with a standard deviation of 14.67 V.

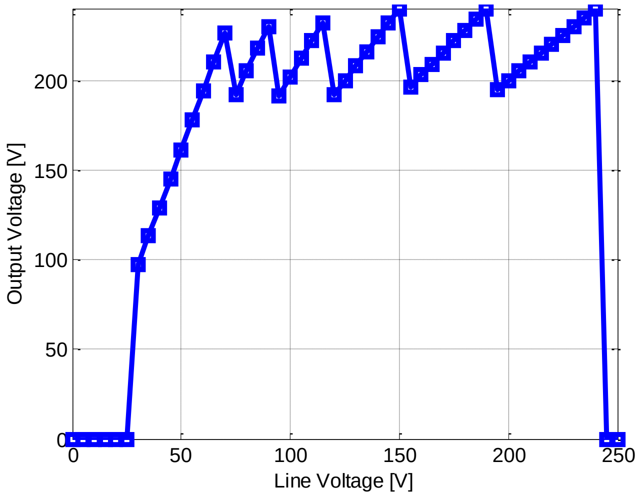

Figure 15: Output voltage with input voltage of the developed stabilizer.

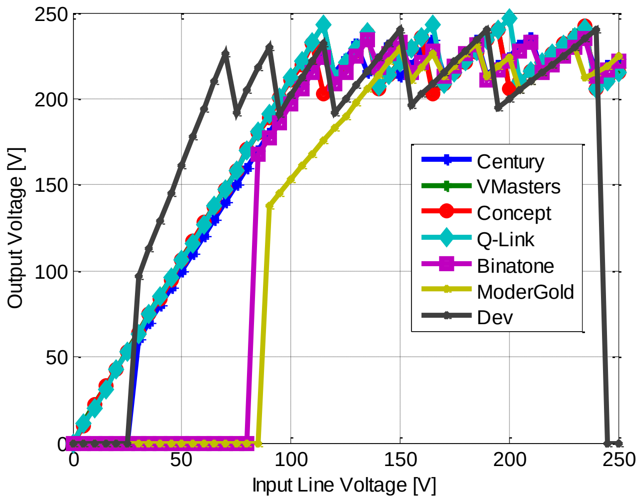

Figure 16 (a): Output Voltage against Input Voltage for Century, V Masters, Concept, Q-Link, Binatone and Moder Gold stabilizers, and the developed stabilizer.

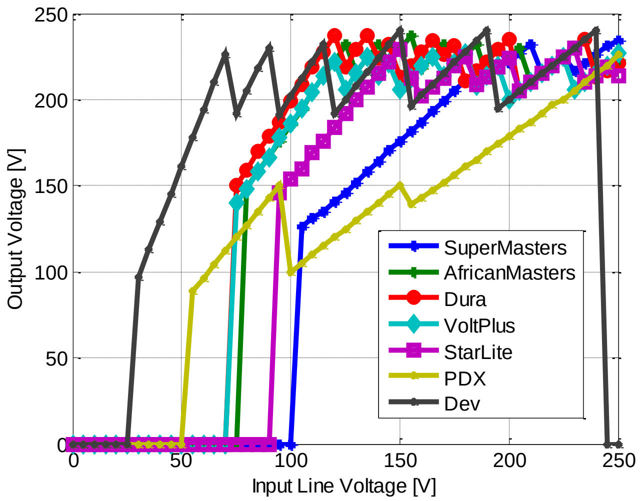

Figure 16 (b): Output Voltage against Input Voltage for Super Masters, African Masters, Dura, Volt Plus, Star Lite and PDX stabilizers, and the developed stabilizer.

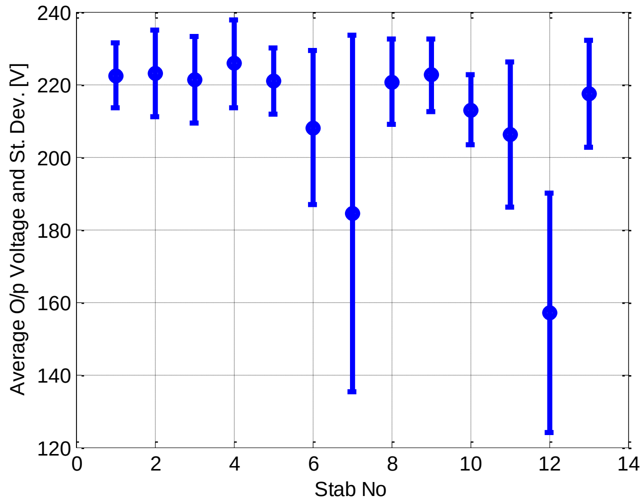

Figure 17: Average output voltage and standard deviation for input between 100V – 240V for all the stabilizers. 1. Century, 2. VMasters, 3. Concept, 4. Q-Link, 5. Binatone, 6. Moder Gold, 7. Super Masters, 8. African Masters, 9. Dura, 10. Volt Plus, 11. StarLite, 12. PDX, 13. The developed stabilizer.

IV. CONCLUSION

Necessity is the mother of invention. Since most commercial domestic AC voltage stabilizers in the Nigeria market cannot meet the low supply voltage problem in some areas in Nigeria, and is denying their buyers from adequately utilizing electrical/electronic appliances in such areas, therefore, this brought about the design and development of this 500 VA automatic AC voltage stabilizer for extremely low voltage areas in the country. The developed AVS was a success in view of the test results obtained. The developed stabilizer is of low power, hence it is meant for electronic equipment like television, computer, video player etc. The stabilizer shuts down at input mains voltage of 30 V and 240 V. Nevertheless, further improvement can be made in terms of power rating by using high current capacity relays and autotransformer. The control operations can also be microcontroller based.

This work has brought to light that input control switching system of an AVS is more advantageous than the output control switching system. It helps in protecting the output transformer from dangerous over voltage. It reduces cost in terms of transformer construction because the number of turns of coil needed in achieving regulation is minimized. Also, in the output switching AVS, transformer taps for stepping up very low voltage will produce very high voltage when normal or high input voltage is supplied. This always causes insulation deterioration and consequent breakdown. Furthermore, output switching type is only limited for good regulation down to input mains voltage of about 150 volts which characterized many of the available domestic stabilizers in Nigeria. Lower input voltage range can be achieved with input switching type.

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