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Transformer-less Voltage Stabilizer Controlled By Proportional-Plus-Integral (PI) Controller

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Abstract
Transformer-based voltage stabilizers are characterized by large size, heavy weight, noise pollution, expensive production, unreliable operation and have limited ability to stabilize output voltage. To overcome this problem, a pulse-width modulated transformerless voltage stabilizer is considered in this paper. The output voltage variation is stabilized by Plus Integral (PI) controller. The main properties of this proposed system are: (i) It is light in weight and occupies small space; (ii) It has low total harmonic distortions; (iii) the output possesses pure sine wave signals; (iv) It is very cheap for mass production. In this paper, we applied the modulation index of 0.86 in the proposed system (PS). The total harmonic distortion, THD of 3.968% was realized and we ensured constant voltage output of proposed system within the input voltage band of (120-230) VAC. The proposed topic can be applied at homes, offices and also in industries.

***Keywords:** Bridge rectifier, boost converter, inverter, PI controller, transformer-less*

INTRODUCTION

Power instability supply to electrical and electronics appliances at homes and in industries had been an enormous disturbing problems to the effective utilization of electricity. It causes a lot of damages to our equipment, and increases cost of living. This power supply irregularities are caused mostly by voltage fluctuations. In literature, many protective devices had been proposed and implemented to ensure adequate protection of equipment and appliances [1−5].

In case of abnormalities in power supply occur, the relay senses them and immediately causes the breaker to open and the facility element is isolated as according to author in [1]. But since relay operates mechanically, the parts wear out as the switch contacts become dirty. Besides, it cannot be switched ON and OFF at high speeds to control the rapid transiency of voltage oscillations [1].

Moreover, fuse is another protective device that makes use of breaking principle on safe- guarding the life span of electrical appliances [1]. But its maintenance time factor when it cuts, reduces the efficiency of whatever system it is protecting. Hence, to improve beyond the breaking principles seen in fuse and relay, the regulators are used [2−4]. A regulator as seen in [2, 4, 18] is a device which is applied to control an output quantity which may be electrical quantity or not, such regulators includes speed regulator, fuel flow regulators, voltage regulator etc. Voltage regulator [2, 18] is an electrical regulator designed to automatically maintain or provide the constant output voltage signal using either electromagnetic mechanism or passive or active electronic components. Since a steady voltage is needed in certain equipment, a voltage stabilizer is then applied in this case [2]. Voltage stabilizer is a voltage regulator that is utilized in home to output a constant voltage even if the backend power supply fluctuates [2]. It conditions the oscillation of AC power supply. It could be static voltage stabilizer or servo controlled voltage stabilizer [2]. Static voltage and servo stabilizers [3, 5] are mostly transformer-based stabilizer with different tapping and a sensor control current that senses the input supply and accordingly, the output is taken from one of the tapping of the transformer. The transformer – based stabilizers, even though have the advantages of operational ruggedness and capability in riding out momentary breaks in mains, yet they have the following demerits: large in size , unbearable audible humming sound , very bulky and difficult to carry about, more expensive in production and low level operating frequency.

For higher power quality, and to solve the most of the problems created by the transformer-based stabilizer [2, 5−7], the transformer-less converters, despite some little harmonic distorting seen in them, they have better characteristics performance over the transformer based converters. The harmonic distortions in transformer-less converters are highly mitigated by filtering and Pulse width modulation, PWM, measures in the power electronic switches such as MOSFETS, thyristors, insulated gate bipolar transistor (IGBT), etc. [10−15].

In this paper, a transformer-less voltage stabilizer controlled by PI controller is proposed. The stabilizer's operational principle is based on the output voltage adjustment by the process of pulse–width modulation scheme. At its input and output of this device, there are analog filters meant for active smoothening of the impulsive noises in the circuit. The core merits of this proposed stabilizer are: it is portable, noiseless in operation, takes the operational range of 120−230VAC at 50Hz, less expensive in mass production, and occupies little space and small power loss.

THE POWER CIRCUIT OF TRANSFORMER-LESS VOLTAGE STABILIZER

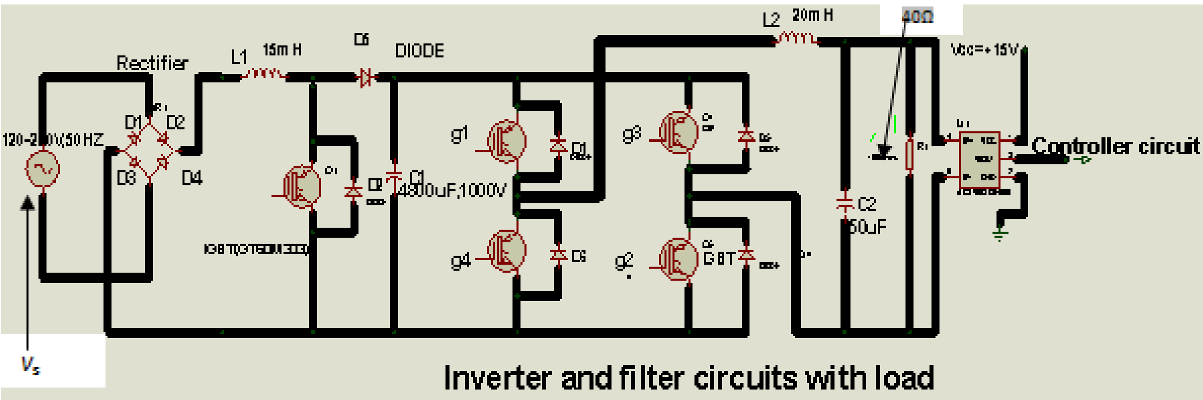

Figure 1: *The topology of power circuit of transformer-less voltage stabilizer.*

The AC power supply (120−230) V meant for rectification is applied to the diagonally opposite ends of the bridge rectifier (D1, D2, D3 and D4) without any transformer. In full rectification, the current undergoes positive and negative cycles. The rectified output voltage of rectifier, V_{rec}, is expressed as:

$$V_{rec} = \frac{2v_s\sqrt{2}}{\pi} \quad (1)$$

v_s- Supply voltage (120-230) V

After the rectification, the boost converter steps up and filter the rectified output voltage of the rectifier and supplies it to the inverter. During the ON-STATE, the boost switch is closed, which makes the rectified voltage, V_{rec}, appears across the inductor at the interval of $0 \leq t \leq D$, D5 is reversed biased by the rectified voltage and sets off. The change in inductor current of the boost converter Δi_{LON} is expressed as in (2):

$$\Delta i_{LON} = \frac{V_{rec} * DT}{L} \quad (2)$$

L - Inductance of the inductor in H; T– switching period, V_{rec} -rectified voltage, D- Duty cycle which represents the fraction of operating period. When the IGBT boosting switch is opened or OFF, the inductor current flows from source to load. Considering zero voltage drops across the diode and the capacitors large enough for its voltage to remain constant, at interval of $DT \leq t < T$, then the change in inductor current during OFF-period is written as:

$$\Delta i_{LOFF} = \left(\frac{(V_{rec} - V_{ob})(1-D)}{L} \frac{T}{\ } \right) \quad (3)$$

Under steady-state conditions, the inductor current remains the same. This means that the overall change in current (the sum of the changes) is zero. Therefore, summing equation 2 and 3; and equating them zero, then, that the output voltage of the boost converter; V_{ob} (boosted voltage) is written as:

$$V_{ob} = \frac{V_{rec}}{1-D} \quad (4)$$

ANALYSIS OF PROPORTIONAL-PLUS-INTEGRAL CONTROLLER

It is a controller that calculates an error voltage or current between a measured processed variable and a desired reference value (set point) [16−18]. The PI Controller algorithm is made of proportional and integral terms. The integral term accelerates the system action based on the rate of sum of the voltage error compensation by shifting the band-width of the signals whereas the action that will be taken based on the signals got by either sending the signal to turn ON or OFF the boost Power switch is carried out by proportional term. The transfer function of PI controller is given from PI section of Fig. 3:

$$T(s) = -\left[\frac{R_4}{R_{in}} + \frac{1}{sC_3R_{in}} \right] = \left| \frac{R_4}{R_{in}} + \frac{1}{sC_3R_{in}} \right| \quad (5)$$

or as[16-18]

$$T(s) = K_p + \frac{K_i}{s} \quad (6)$$

T(s)- gain of PI, R_{in}-input resistance to PI, C3 and R4 are feedback components of PI.

$$\left| R_{in} = \frac{(R_1 + R_2) * R_3}{(R_1 + R_2) + R_3} \right| \quad (7)$$

Comparing equations 5 and 6, there exists:

$$K_p = \frac{R_4}{R_{in}} \text{ and } K_i = \frac{1}{sC_3R_{in}} \quad (8)$$

In order to compute, K_p and K_i, the following $R_1 = 10k\Omega$, $R_2 = 20k\Omega$, C_3 and $R_3 = 10k\Omega$, were the parameters used. Then, substituting them in equations 7 and 8, give K_p and K_i equal 10.00 and 0.097.

GENERATION OF FIRING SIGNALS FOR THE INVERTER SWITCHES

The firing signals are generated by comparing the two identical modulating sine waves of 50Hz but out of phase by 180^o to each other at frequency of 1.07kHz to produce pulse- width modulated signals. The 1.07kHz was used in order to mitigate the third harmonics in the inverter system. The topology is shown in Fig. 2. In the same figure, pulse- width modulated signals generated are negated using logical Not-gates to obtain their corresponding complementary pulses.Their output signal are shown Fig. 7

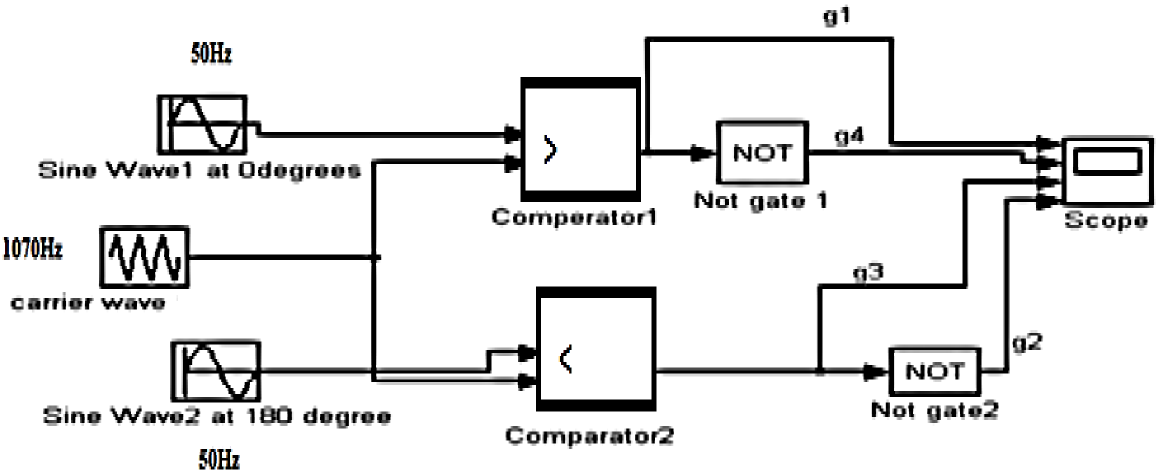

***Figure 2:** The topology for the generating of firing signals.*

Modulation Index

The modulation index of a modulation method portrays by how much the modulated variable of a carrier varies in the region of its unmodulated level [15]. The modulation index of the sinusoidal pulse-width modulation (SPWM) can be stated as:

$$m_a = \frac{V_m}{V_{cr}} \quad (4)$$

Where, m_a- modulation index, V_m- amplitude level voltage of sine wave signal, V_{cr}- amplitude level voltage of carrier wave signal. From the Fig. 6, the V_m of sine wave signal is 7.4V and the V_r of carrier wave signal is 8.6V. Then substituting them appropriately in equation.4, the modulation index of the proposed system of Fig. 1 becomes 0.86. Practically, from the Fig. 12, the V_m = 7.4V and V_r = 8.6V which also yields m_a of 0.86.

STABILIZATION STAGE USING PROPORTIONAL-INTEGRAL CONTROLLER

The control circuit unit consists of voltage sensor, operational amplifiers and IGBT driver. When voltage fluctuation occurs in the PS system, the change in the output voltage of the inverter is sensed instantaneously by the voltage sensor and is rectified by diode D3 in the control unit. This signal is passed through RC circuit. The signal is filtered for better signal quality but is now 180° out of phase. An op amp within the RC circuit then inverts the signals and sends it to where it is compared with the negative reference DC signal volatage(-Vref) as shown in Fig. 3. The error voltage is then sent to the proportional-integral compensator which appropriately modifies and integrates the voltage signals; and then takes them to the comparator labeled 2 where, they are compared with the carriers' signals of high switching frequency of 1.07kHz. The output of the comparator is then moved to the IGBTdriver circuit and boost switch.This produces pulse signals. During voltage oscillations,the proportional term, determines the value of the error voltage, V_e and then signals the driving circuit to turn ON the boost switch for voltage stabilization. When the boost switch starts operating, the P term determines the error voltage to be compensated in geometrical progression. If the speed at which the compensation of the lost voltage is not enough, the integral part (term) will adjust the band width of the pulses to quicken up the rate of stabilizing the voltage. The continuous process in case of either voltage decrease or increase will regulate and stabilize the output at rms of 220V.The control circuit is shown as follow in Fig. 3.

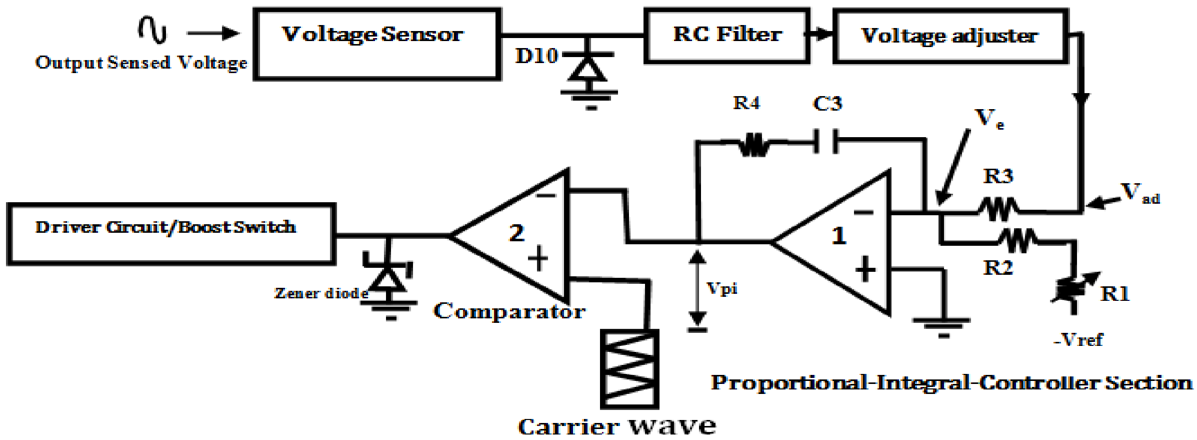

Figure 3: *Outline ofoutput control circuit unit.*

SIMULATION AND RESULTS

The proposed system in Figures 1, 2 and 3 are simulated in matlab/simulnk 2013 environment and various results of many stages are shown in Fig. 4 to 11.

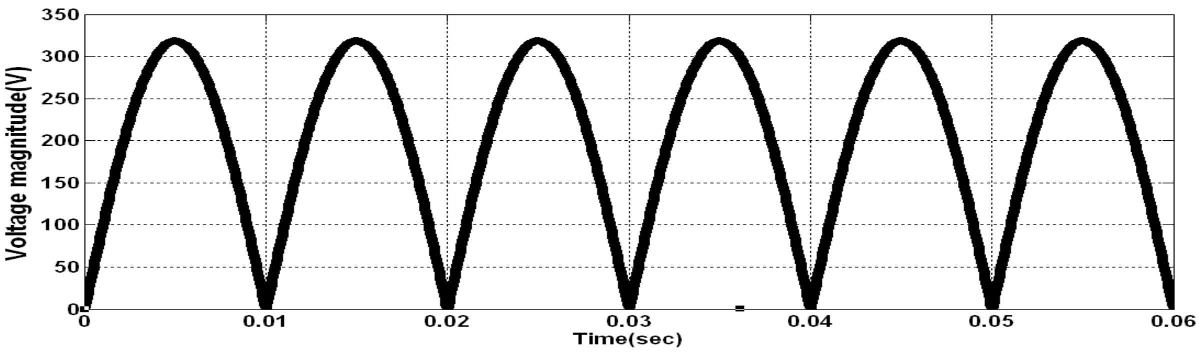

Figure 4: *The rectified output of the full bridge rectifier.*

The Fig. 4 displayed the output waveform of the rectified voltage emanating from the full bridge rectifier. The operating frequency of the rectified wave signal of 100Hz has a ripple factor of 0.4843 [2]. This implies that the DC components in full bridge rectifier are greater than AC components.

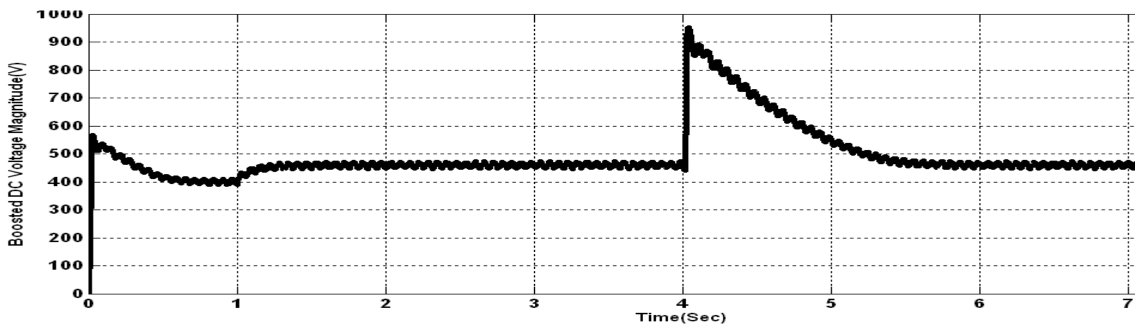

Figure 5: *The graphical representation of the output voltage of boost inverter.*

The waveform pattern of the boosted voltage values of the boost DC/DC converter is displayed in Fig. 5 and it is observed that the transient voltage signals appeared at $0 \leq t \leq 1.20$ seconds after which, it is stabilized at average voltage value of 450VDC. This stabilized situation continued within the time intervals of 1.20 ≤ t ≤ 4seconds .After t=4seconds, there exists sudden voltage rise of 954VDC.This rise in voltage is restored back to the average voltage with the aid of the PI controller at time interval of 4 ≤ t ≤ 5.85seconds or after 1.85seconds

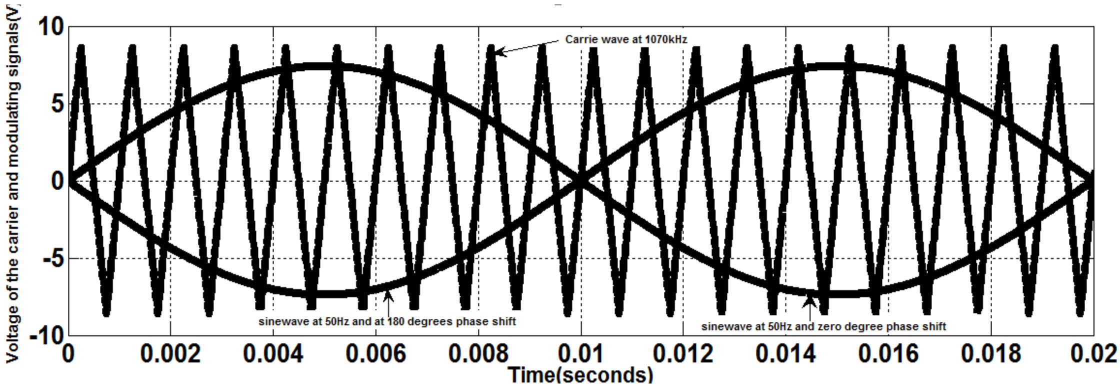

Figure 6: *Comparison triangular wave.*

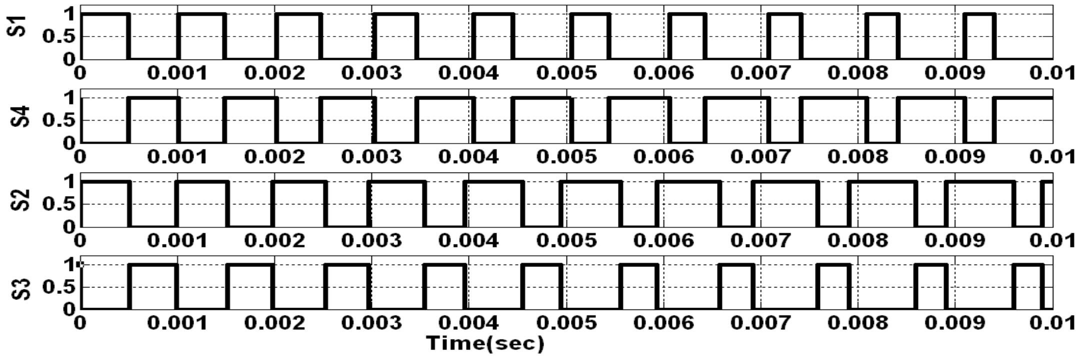

Figure7: *Triggering gate signals of the inverter and two reference sine waves.*

The carreir signal of peak voltage of 8.6V and the modulating wave signal of amplitude value of 7.4V are shown in Fig. 6 while their resultant pulse waveforms S1 to S4 are displayed in Fig. 7. The S1 to S4 are applied in firing the power IGBTs shown in Fig. 1.

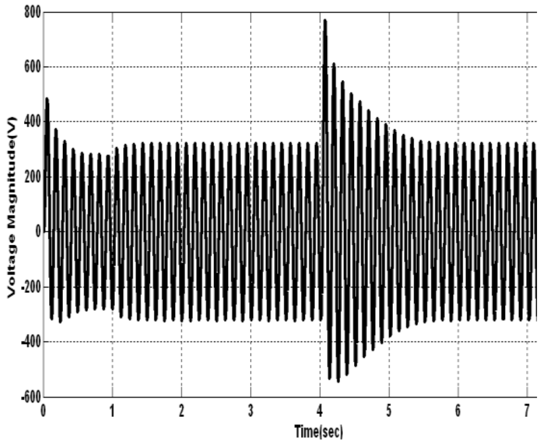

Figure 8: *The stabilization pattern of the filtered. filtered voltage output of inverter/load.*

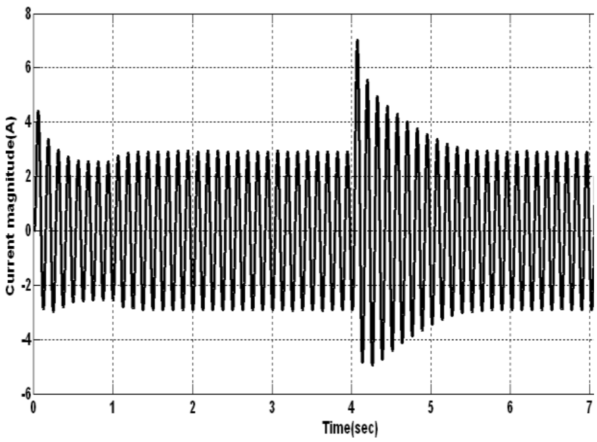

Figure 9: *The stabilization pattern of the current output of inverter/load.*

The Fig. 8 illustrates the behavourial charateristics of the the proposed system(PS). When the PS is energized, it experiences transient state at $0 \leq t \leq 1.20$ seconds. After this duration, the PI controller stabilizes it at peak to peak voltage of 320VAC from the inverter output. At t = 4 seconds, it is noticed that there is abrupt rise in voltage due to the variation of input AC voltage. It could be caused by temporary fault conditions or load variations.This results in changes in the output voltage signals of the inverter. This instability lasted for only 1.85 seconds ($4 \leq t \leq 5.85$seconds) after which, the PI controller restored it back to 320VAC.

The Fig. 9 shows the nature of how the inverter output current of the PS operates. It is noticed that it mimics the corresponding voltage waveform in Figure 8 based on transient, instability and steady states but different in amplitudes. At transient state, the peak current is 4.30A. In the steady state, the maximum output current is 2.45A and at sudden rise in voltage, the corresponding rise in peak current is 6.51A.

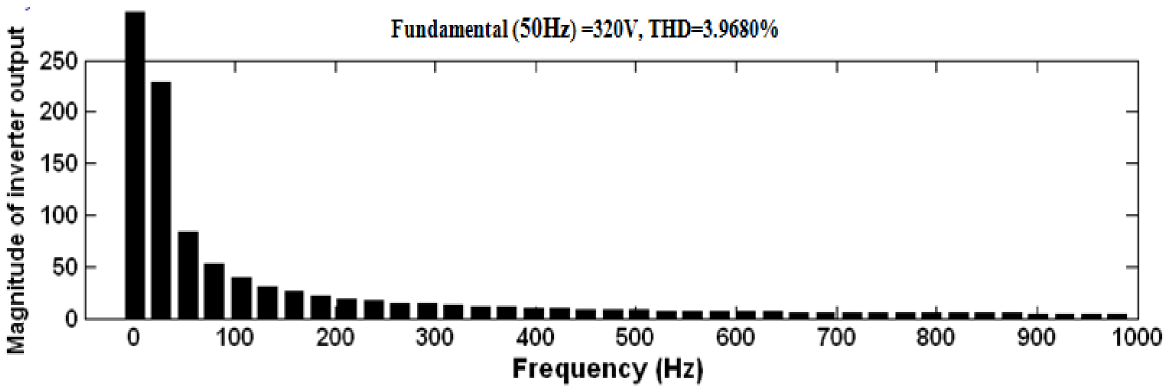

***Figure 10:** The output voltage frequency spectral characteristics of PS under resistive load of 40 ohms.*

The output voltage-frequency spectral characteristics of PS is illustrated in Fig. 10 and it can be noticed that, at fundamental frequency of 50Hz and the voltage amplitude of 320V, the total harmoinic distortion, THD is 3.9680 %. This implies the extent of reduction rate of power loss in the proposed system.

EXPERIMENTAL RESULTS

The experimental tests were carried with system configuration in Figure 17 to produce the results in Figures 11−17.

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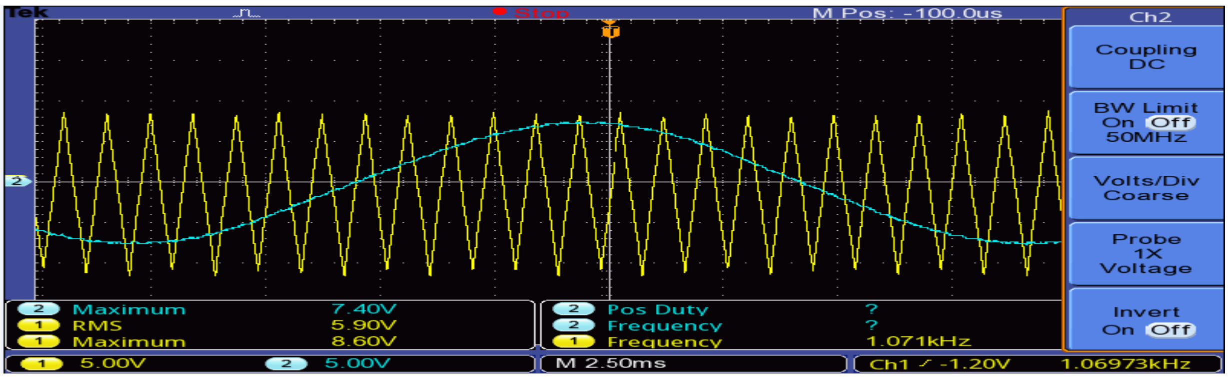

***Figure 11:** The comparison of triangular wave and reference signals.*

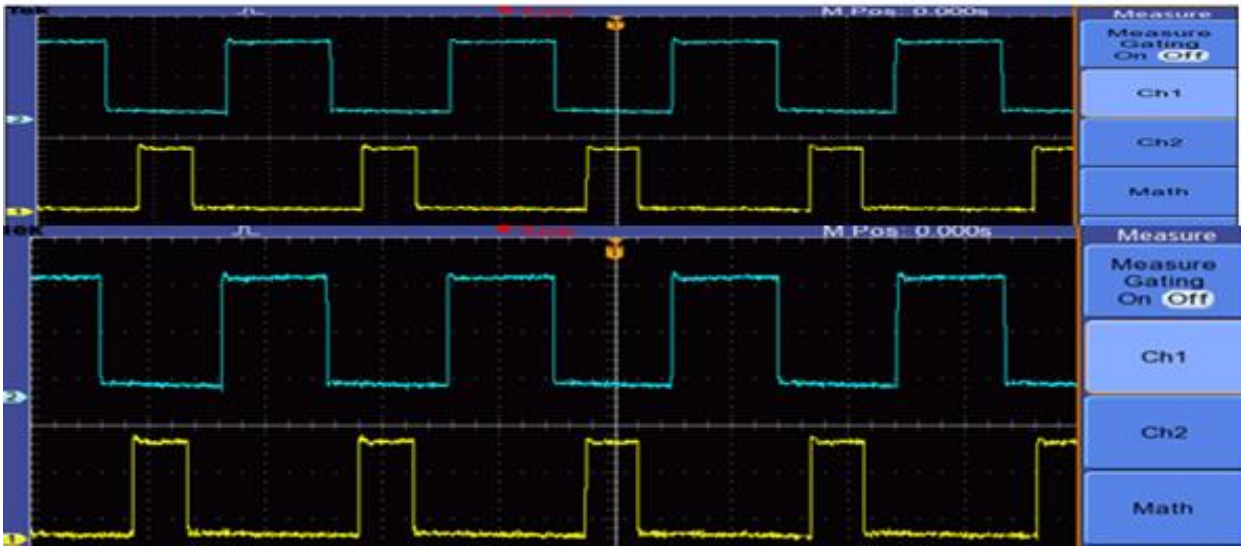

Figure12: *The comparative outcomes of triangular wave and reference signals.*

The Figures 11 and 12 presented the experimental outcomes of oscilator circuit of Figure 2 that are using for firing the power switches.

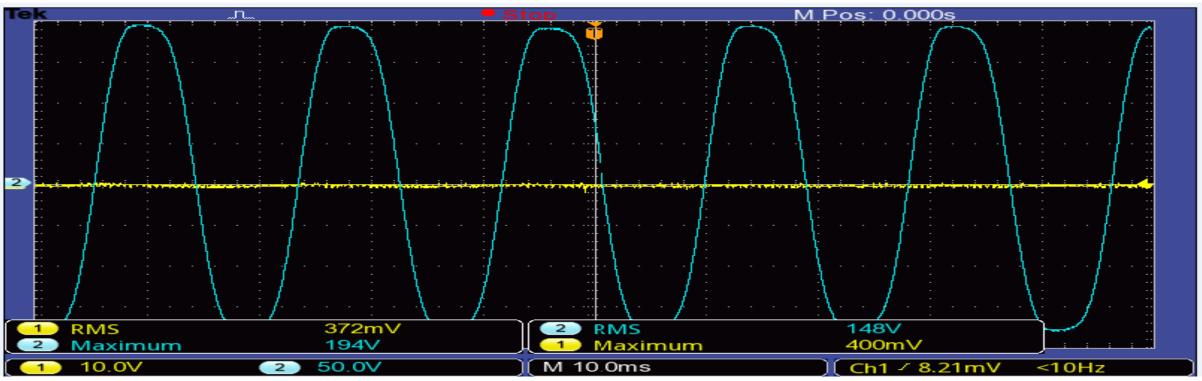

Figure 13: *The steady state of filtered voltage output of the proposed system.*
Figure 13 illustrates the output voltage waveform of the stabilizer.

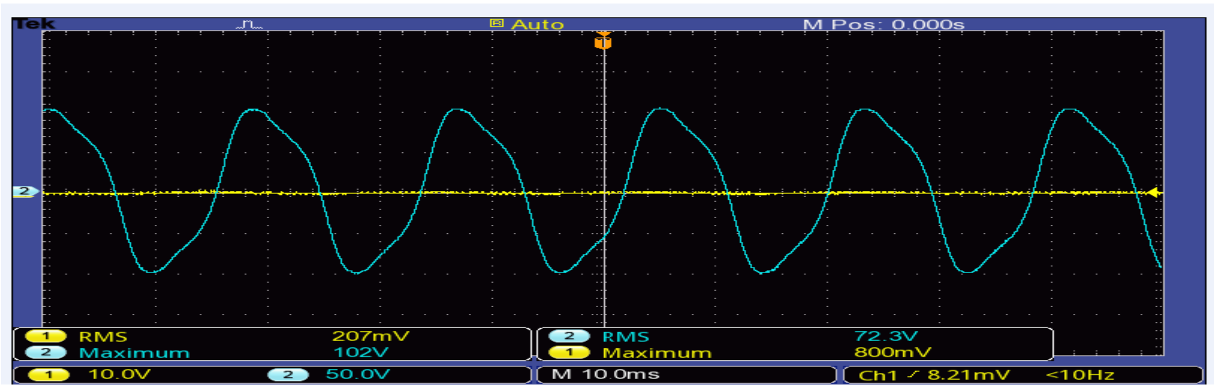

Figure14: *The unstable state of filtered voltage output of stablizer due to power instability.*

The Figure 14 indicates the appearance of the AC voltage output waveform during the period of voltage input fluctuations and load variation. Under that condition, the load/appliance connected to system without PI controller, draws more current which may lead to the distruction of it life span. But for our proposed system, the

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voltage fluctuation are solved and keep constant by operation of proportonal-integral controller. The diagram of the stabilized voltage after flactuation is shown in Figure 15 while the experimental power circuit is shown in Figure 16.

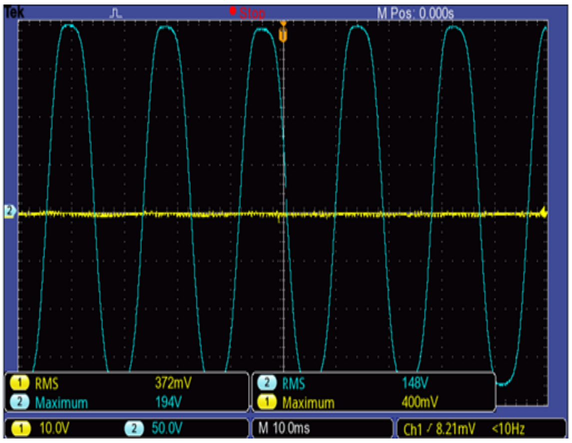

Figure 15: *The stabilized state of filtered voltage output of in at rms of 220v by PI controller.*

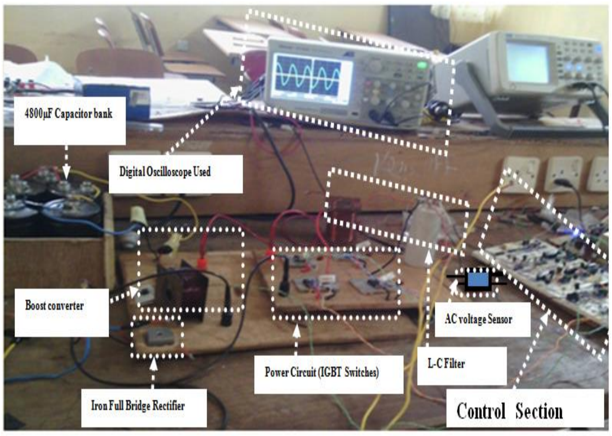

Figure 16: *The experimental prototype of transformer-less voltage stabilizer.*

CONCLUSION

The transformer-less voltage stabilizer controlled by proportional-plus-integral controller has been pragmatically presented in this paper.The control unit was exhaustively described. The paper equally presented with waveforms the graphically representation of rectification, boosting pattern, inversion/filtering, voltage fluctuation and stabilization processes. In the prototype the modulation index of 0.86, THD of 3.969 % and a pure sine wave were achieved. Also, the output of the protype was stabilized to the proposed system peak to peak voltage of 320VAC. This proposed system offers the values of simplicity and declined intricacy of the circuit. Moreover, it is also light in credence, noiseless in operations and can be significantly mass-produced due its lesser components price tag and simple control method. Therefore, this type of stabilizer has great applications at homes, offices and meduim firms.

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