Assessment of Total Harmonic Distortion in Buck-Boost DC-AC Converters using Triangular Wave and Saw-Tooth based Unipolar Modulation Schemes

CANDIDUS .U. EYA[1,8], AYODEJI OLALEKAN SALAU[2,7], SEPIRIBO LUCKY BRAIDE[3], S. B. GOYAL[4], VICTOR ADEWALE OWOEYE[5], OLUWAFUNSO OLUWOLE OSALONI[6]

[1]Department of Electrical Engineering, University of Nigeria, Nsukka, NIGERIA
[2,6]Department of Electrical/Electronics and Computer Engineering, Afe Babalola University, Ado-Ekiti, NIGERIA
[3]Department of Electrical and Electronics Engineering, Rivers State University, NIGERIA
[4]Faculty of Information Technology, City University, Petaling Jaya, 46100, MALAYSIA
[5]Department of Physical and Chemical Sciences, Elizade University, Ilara-Mokin, NIGERIA
[7]Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, India
[8]African Centre of Excellence, University of Nigeria, NIGERIA

Abstract: - This paper presents an assessment of the levels of total harmonic distortion (THD) in buck-boost DC-AC converters using triangular wave and saw-tooth unipolar based-modulation schemes. This paper seeks to identify a better technique for mitigating the total harmonic distortion on buck-boost DC-AC converters under unipolar carrier-based modulation schemes. This was achieved by subjecting the buck-boost DC-AC converter under triangular wave-based and saw-tooth based-unipolar modulation schemes. The voltage and current output of the buck- boost DC-AC converter under each scheme was analysed using a power GUI Fast Fourier Transform (FFT) analytical tool resident in the MATLAB Simulink environment unlike with the conventional scheme of computing the percentage of THD. The test system was obtained by a combination of DC-DC buck-boost converter, H-bridge based-insulated unipolar gate transistors, and a logic control unit. It was realized that THD of 0.2865%, peak output voltage of 294.1V and current of 9.805A were obtained by using the saw-tooth based-unipolar modulation scheme, whereas a THD of 0.1479%, peak output voltage of 297.4V and current of 9.53A were obtained by using the triangular wave based-bipolar modulation scheme on the same Buck-boost DC-AC converter circuit. The results imply a high power factor utilization and low power loss in the triangular wave based-unipolar modulation scheme compared to the saw-tooth based-unipolar modulation technique for improving the performance characteristics of the buck-boost converter system. This study showed that power drives and heavy load machines based-power electrical loads are required to use the saw-tooth based-unipolar modulation (STBUM) scheme for high current and low THD%, whereas sensitive power electrical loads such as hospital equipment and communication industries based-power electronic devices are required to use the triangular wave-based unipolar modulation (TWBUM) scheme due to low current and THD%.

Key-words: Assessment, Fast Fourier Transform, total harmonic distortion, triangular wave, Saw-tooth wave, unipolar modulation scheme.

Received: August 24, 2021. Revised: September 5, 2022. Accepted: October 11, 2022. Published: November 8, 2022.

1 Introduction

Apart from other sources of harmonics in power electronics system based-applications, power electronics devices on their own produce harmonics. Excessive harmonics in the power system operations affect the wave shapes of currents and voltages by reducing their qualities, performances and market values. By definition, harmonics are the soaring frequency waveforms, superimposed upon the fundamental frequency that is sufficient to disfigure its waveform. They are high due to the introduction of power electronics drives for AC-DC motors, DC fans, pumps, and other related power electronic devices, [1]. High presence of harmonics results in malfunctioning of some load needs, overheating, excess voltage, error in metering and control, malfunctioning of relay, interference in communication and control signals, [2]. There are various means of mitigating total harmonic distortions (THD) in power electronics systems. A few of them are: wave-shaping regulation by transformer connections, pulse-width modulation techniques, wave-shaping control by multiple commutations in each cycle, waveform regulation by using delta-star transformer output, using filter, high pulsed rectifier cascading , and so on. Under pulse-width modulation, PWM, there are many sub-divisions like carrier-based modulation schemes, third harmonic- injection method, space vector modulation, Random pulse width modulation (RPWM**)** with their both merits and demerits. For instance RPWM technique is mainly dependent on randomizing the frequency of the carrier signal in order to distribute the concentrated energy of the harmonic frequency of the inverter output voltage in a narrow high frequency band. The main advantage of this technique is to reduce the energy of the harmonics, which in turn will reduce the THD of the inverter output voltage, [3]. However, this action will also affect the energy of the fundamental frequency component by minimizing the magnitude of the amplitude which affects the quality of the waveform. Authors in [4] worked on grid-connected photovoltaic system with single stage buck-boost Inverter for a very high gain of PV system using single pulse width modulation. It was observed that total harmonic voltage of their system obtained is 2.78%, at peak voltage of 321.1V. However, naturally, due to the inherent performance characteristic of having one pulse per half cycle, the percentage of odd harmonics are still very high, hence resulting in loss power factor utilization in the system.

Single-stage single-phase transformer-less doubly grounded grid-connected PV interface was carried in [5] using modified pulse width modulation scheme. They realized THD of 4.9% at 0.82A and a utility peak operating voltage of 194V. Meanwhile, the system suffers from the effects of current leakage to ground and EMI to the surrounding. In [6] a novel control scheme for buck-boost DC to AC converter for variable frequency applications was carried out dual slope delta modulation scheme. It is observed that they accomplished total harmonic distortion of 3.95%, at fundamental voltage operating voltage of 317.8V. One demerit of this kind of modulation scheme is increase in component count in logic control circuitries.

Two-stage buck-boost multilevel inverter for photovoltaic power generation. Scheme was presented using high switching frequency modulation (HSFM) based on sinusoidal pulse width modulation technique, [7]. A 64.62% total harmonic distortion was achieved at a fundamental operating voltage of 50V. However, the system has very poor power factor utilization and high power losses as well as it incorporates the conventional method of analysing the parametric percentage of THD. Controlling of boost direct current-alternating converter through energy modelling utilizing non-linear control approach was presented in [8]. The scheme involved high cost and multifaceted implementation. Comparative investigation of pulse-width modulation techniques for five-phase voltage source inverter was presented in [9] using Carrier based sinusoidal PWM Fifth harmonic injection pulse width modulation, offset addition pulse width modulation scheme, traditional space vector pulse width modulation and modified space vector pulse width modulation with the THD of 1.6%, 1.8%, 1.8%. 0.3% and 3.2 respectively. However, the problem the investigation had in the percentage of THD analysis is that they were computed using conventional methods of calculating % of THDs.

Simulation of a buck-boost converter for solar panels using a PID controller was discussed in [10]. The dynamic time response of voltage was very poor. Moreover, a simple boost controlled scheme was proposed in [11]. It utilized two straight lines equivalent or more than the maximum value three phase modulating to regulate the shoot-through duty ratio in a conventional SPWM. This scheme is very simple and easy to implement, however, it has tremendous high switching stress leading to production % of THDs of 0.6%, 1.2%, 1.4%, and 3.5% under four prevailing case conditions between voltage intervals of 170Vand 230V.

In this paper, the level of total harmonic distortion in buck-boost DC-AC converter is examined using power graphical user interface FFT analytical tool with the aid of triangular wave-based unipolar modulation (TWBUM) and saw-tooth based-unipolar modulation (STBUM) schemes which has not been undertaken before now. It is resident in the MATLAB/Simulink environment. The research will be of great importance in finding out which scheme is better for buck-boost DC-AC converter operation to avoid working at low power factor. Moreover, the assessment tool we employed in this research is a very fast, less time-consuming, and more accurate method of analysing total harmonic distortion of any waveform unlike computational conventional methods. This research work closes the gap of using traditional methods of computing % of THD in terms of complexity, inaccuracies and longer time consumption as well as better identification of carrier-based modulation schemes. This research work is structured based on introduction, methodology, simulation results and discussion as well as the concluding part. The introduction aspect has been carried out. Mathematical modelling of the system, modelling of Fourier series, total harmonic distortion analysis and buck-boost dc-ac converter system are dealt with in methodology. The performance characteristics and their descriptions of the test systems are shown in simulation results and discussion.

2 Methodology

The materials that are utilized are insulated gate bipolar transistors, inductors, capacitors, battery, voltmeters, ammeters, sensor and resistors. The methods applied are triangular and saw-tooth based unipolar modulation techniques available in the Simulink environment. The tool used for the examination of voltage and current level of THD is power graphical user interface FFT analytical tool in MATLAB Simulink Environment, 2014.

2.1 Mathematical Modelling of the System

2.1.1 Triangular wave- based and Saw-tooth based Unipolar modulation Schemes

The triangular wave-based unipolar modulation (TWBUM), saw-tooth based unipolar modulation (STBUM), and 50Hz sine reference, V_{ref} signals are modelled using MATLAB/ Simulink environment with the expressions in Equations (1), (2), (3), and (4) [12].

$$TWBUM = \begin{bmatrix} 0 & \frac{1}{4f_c} & \frac{1}{f_c} & \frac{1}{4f_c} & \frac{1}{f_c} \\ 0 & A_t & 0 & A_t & 0 \end{bmatrix} \quad (1)$$

$$\text{STBUM} = \begin{bmatrix} 0 & \frac{1}{f_c} \\ -x_t & x_t \end{bmatrix} \quad (2)$$

$$v_{ref1} = v_a sin\theta_i \quad (3)$$

$$v_{ref2} = v_a sin(\theta_i - 180) \quad (4)$$

where f_c , A_t , V_a x_t and θ_i are the carrier frequency of both $TWBUM$ and STBUM, amplitude of $TWBUM$, amplitude of STBUM, amplitude of v_{ref} and the angle of the reference sine wave. The Equations (1), (2), (3) and (4) represent triangular wave carrier, saw-tooth carrier, reference sine wave and inverted sine wave expressions. In order to fire the power switches, S1, S2, S3 and S4 of DC-AC buck-boost converter in Fig. 1 under TWBUM, Equations (1) and (3); Equations (1) and (4) are compared using two comparators for each set to produce Equations (5), (6), (7) and (5). The Equations (1), (2), (3), and (4) are used to generate the triangular carrier wave, saw-tooth carrier wave, modulating signal at 0o, while the modulating signal operating at 180^0 is used in generating waves forms in Figs. 4 and 10 respectively.

$$\text{S}_{\text{G1}} = \begin{cases} 1 & if\ v_{ref1} > TWBUM \\ 0 & ,else \end{cases} \quad (5)$$

$$\text{S}_{\text{G2}} = \overline{\text{S}_{\text{G1}}} \quad (6)$$

$$\text{S}_{\text{G3}} = \begin{cases} 1 & \text{if TWBUM} > v_{ref2} \\ 0 & ,else \end{cases} \quad (7)$$

$$\text{S}_{\text{G4}} = \overline{\text{S}_{\text{G3}}} \quad (8)$$

S_{G1} ,S_{G2} , S_{G3} and S_{G4} are the switching signals for triggering S1, S2, S3 and S4 power switches. The Equations (5), (6), (7), and (8) are used in generating the triggering signals in Fig. 5.

Under the STBUM scheme, Equations (2) and (3); Equations (2) and (4) are compared using the same two comparators for each set to generate Equations (9), (10), (11), and (12).

$$\text{S}_{\text{Gs1}} = \begin{cases} 1 & if\ v_{ref1} > STBUM \\ 0 & ,else \end{cases} \quad (9)$$

$$\text{S}_{\text{Gs2}} = \overline{\text{S}_{\text{Gs1}}} \quad (10)$$

$$\text{S}_{\text{Gs3}} = \begin{cases} 1 & \text{if STBUM} > v_{ref2} \\ 0 & ,else \end{cases} \quad (11)$$

$$\text{S}_{\text{Gs4}} = \overline{\text{S}_{\text{Gs3}}} \quad (12)$$

S_{Gs1}, S_{Gs2}, S_{Gs3} and S_{Gs4} are the switching signals for triggering S1, S2, S3, and S4 power switches under STBUM technique. The Equations (9), (10), (11), and (12) are used in generating the triggering signals in Fig. 11.

2.1.2 Modelling of Fourier series

Fourier series of triangular wave and Saw-tooth can be modelled using Equations (13) [12] and (14) [13].

$$f(x) = \frac{2A}{\pi}\sum_{n=1}^{\infty}\left((-1)^{k}\frac{\sin(2\pi kft)}{k}\right) \tag{13}$$

$$f(x) = \sum_{n=1}^{\infty}\left(\frac{4}{(2k-1)^2\pi^2}\cos\left((2k-1)\pi x\right)\right) \tag{14}$$

where f- Frequency, k and n are integers.

2.1.3 Total Harmonic Distortion Analysis

(i) **Formula for Computing THD**

The current and voltage of total harmonic distortions are computed traditionally using the expressions in Equations (15) and (16) [2], [14].

$$THD\ (for\ Current) = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \tag{15}$$

$$THD\ (for\ Voltage) = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \tag{16}$$

where I_n and V_n are amplitude harmonic components of current, I_1 and voltage, V_1.

The computation of THD of current and voltage waveforms using Equations (15) and (16) is an approximate method [6]. It is also a very cumbersome, difficult and time-consuming process [15] and because of that reason, we employed power graphical user interface Fast Fourier Transform (PGUIFFT). It does not require much expertise to use. It is also faster and better than using Equations (15) and (16).

(ii) **Steps in using power graphical user interface Fast Fourier Transform**

Step 1: Build the proposed system in the Simulink environment.

Step 2: Pick the PGUIFFT from the Simulink Library browser.

Step 3: Double click on workspace block, single click on the “parameters” inside the workspace. Then click on “History” and change its “Format” with “Structure with time” and then click “OK”.

Step 4: Run or simulate the proposed system.

Step 5: Double click on the PGUIFFT block, it will display “simulation and configuration Option”.

Step 6: Single click on “FFT analysis”, it will display four sub-sections: signal section, FFT analysis section, available signal section, and FFT setting section.

Step 7: Finally, click on the display button, the FFT analysis section will show the total harmonic distortion level of the output wave in percentage value and in bar chart form.

2.1.4 Buck-Boost DC-AC Converter System

The circuit diagram of the Buck-boost DC-AC converter used in this research is shown in Fig. 1 [16].

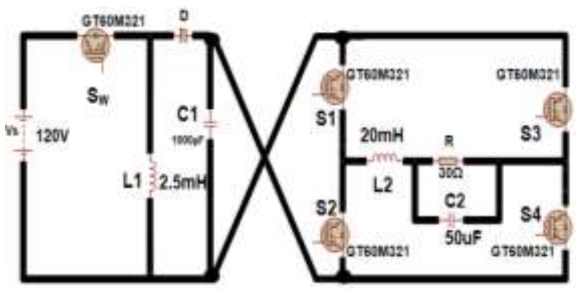

Fig. 1: Circuit diagram of boost DC-AC converter.

Fig. 1 displays the circuit diagram of the boost DC-AC converter. The converter is made of a battery source, DC-DC boost converter (power diode, D, input inductor, L and capacitance C), inverter, and low pass filter, single phase inverter, L-C filter, and load. When the duty cycle of the DC-DC converter is less than 50%, it blocks the output voltage but when it is greater than 50%, it boosts the output voltage. During the positive half cycle, Sw = ON and D = OFF, the L1 momentary builds up the magnetic energy, while the electrical energy stored in C1 feeds the inverter. During the negative half cycle, Sw = OFF and D = ON, the energy built in L1 discharges to charge that capacitor and to feed the inverter. As the inverter is fed, it converts the DC power to AC power at the desired frequency [17].

The parameters of minimum inductance of inductor, L_{min} and minimum capacitance of Capacitor, C_{min} of the DC-to-DC converter, are obtained using Equations (17) and (18).

$$L_{min} = \frac{(1-D)^2 R}{2f_c} \tag{17}$$

$$C_{min} = \frac{D}{R\left(\frac{\Delta V_o}{V}\right)f_c} \tag{18}$$

L_{min}, C_{min}, V_o, f_c, and R are the minimum capacitance, minimum inductance, output voltage, carrier frequency, and output load resistance of the DC-DC converter.

The MATLAB/Simulink models of the proposed system are shown in Fig. 2 and Fig. 3.

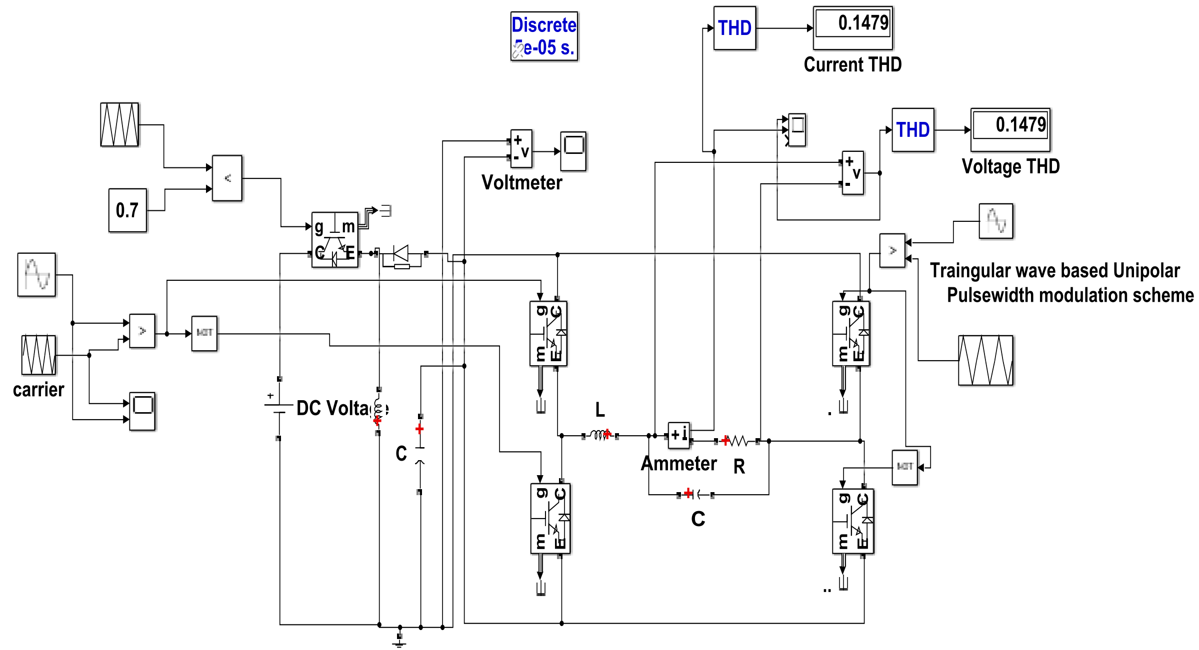

Fig. 2: Simulink model of DC-AC converter under TWBUM.

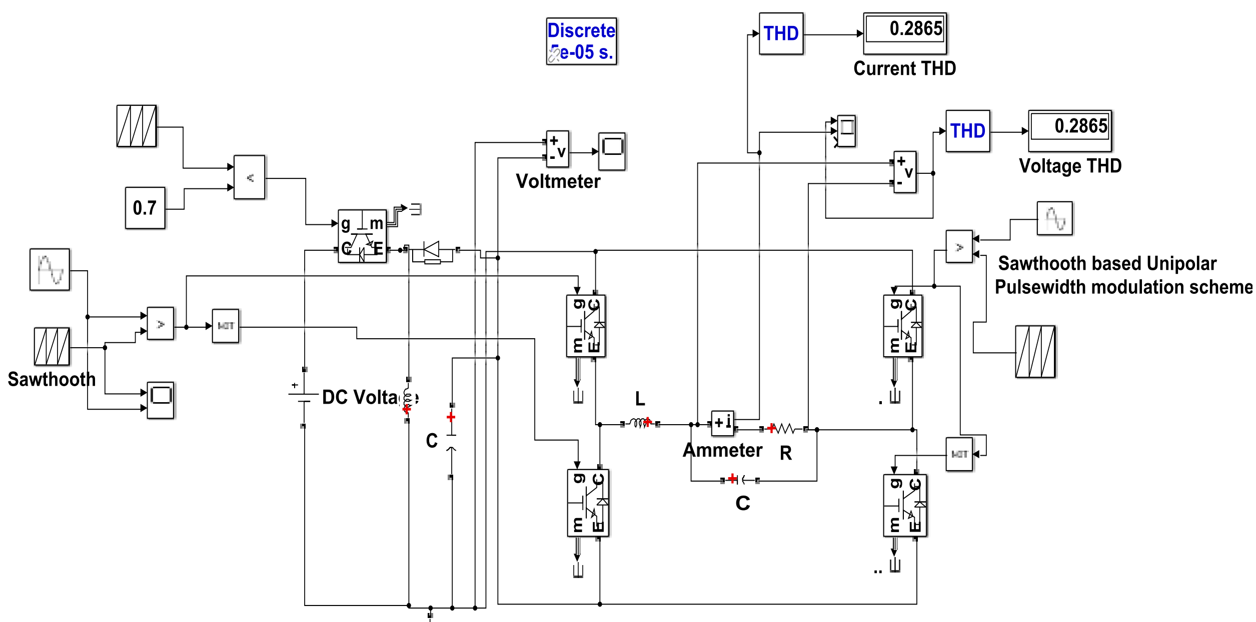

Fig. 3: Simulink model of DC-AC Converter using STBUM.

The results in Fig. 3 are similar to those in Fig. 2. The only difference is that Fig. 3 possesses a saw-tooth wave carrier, while Fig. 2 has a triangular wave carrier.

3 Simulation Results and Discussion

This research work was modelled using 2014 MATLAB/ Simulink Environment. Fig. 4 shows the triangular based-unipolar modulation scheme. It consists of two reference sine waves at amplitudes of 0.8V, 50Hz, and at 180^o out of phase and triangular wave carrier with peak value of 1.0V and frequency of 1k Hz.

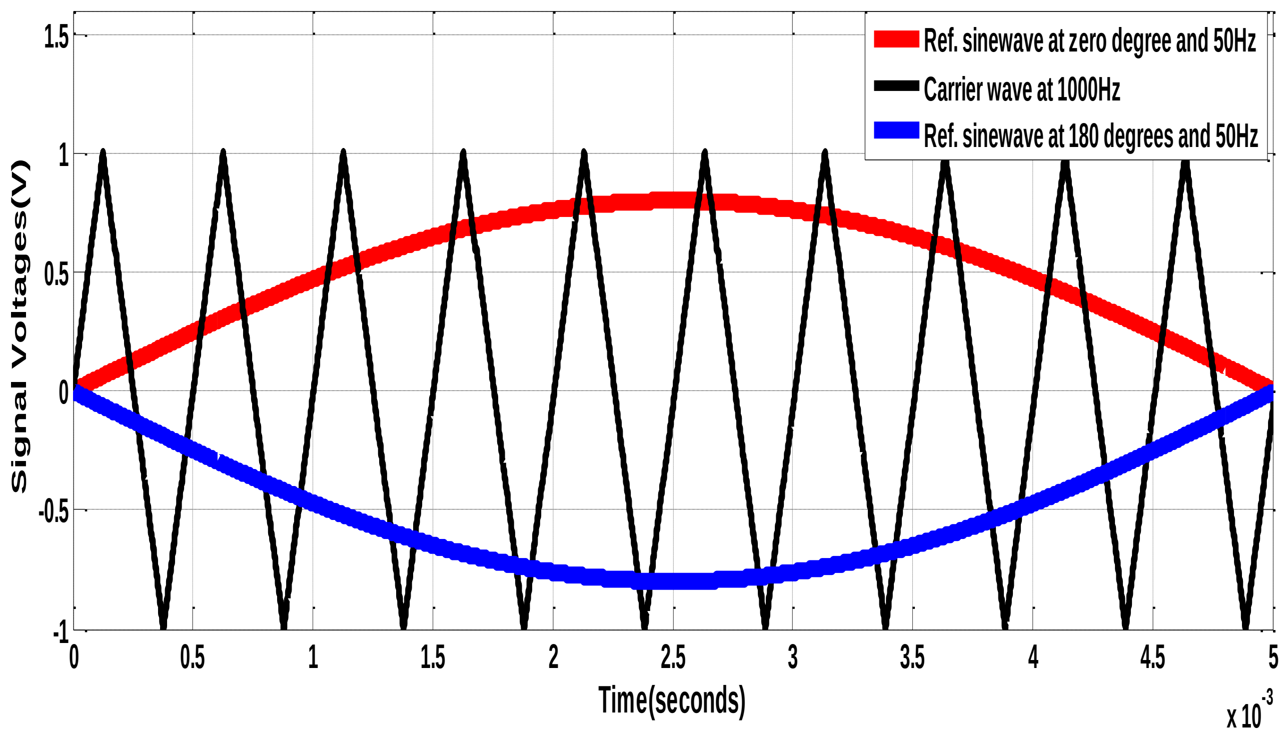

Fig. 4: Triangular wave based unipolar modulation scheme.

The two reference sine waves are generated using Equations (3) and (4) are derived from Equation (1). It implies that their modulation index is 0.8. When the two reference sine waves are compared with the carrier wave according to Equations (5) and (7) and inverted based on Equations (6) and (8), they produce the firing signals shown in Fig. 5.

Fig. 5 contains 1V switching signals that are responsible for setting the model shown in Fig. 3 into an operational mode for producing waveforms in Fig. 6(b) and Fig. 7. It is made of S1, S2, S3 and S4-firing signals which are the same thing with S_{G1} ,S_{G2} , S_{G3} and S_{G4} under TWBUM of Equations (5)-(8).

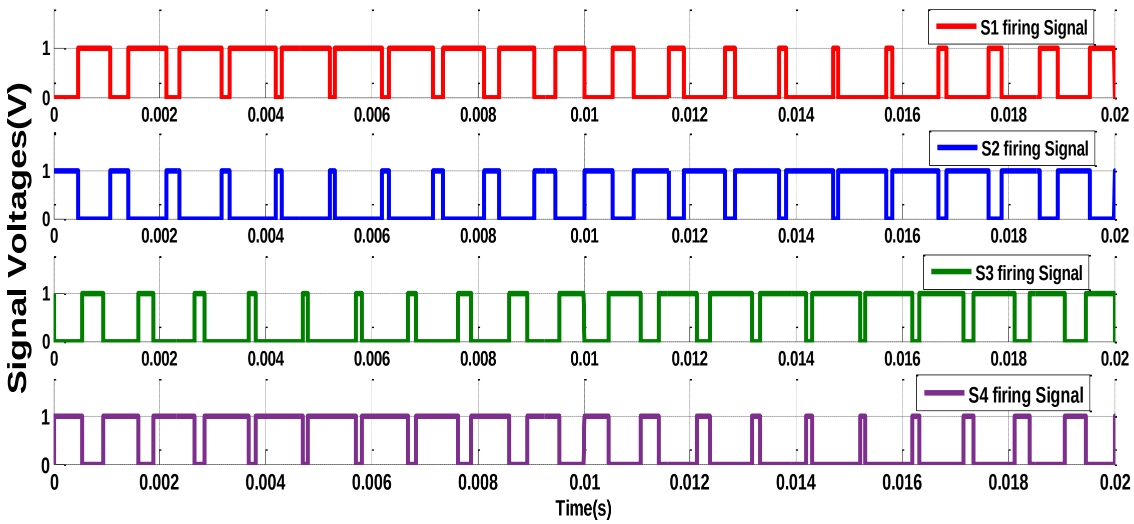

Fig. 5: Switching pulses of DC-AC converter using TWBUM.

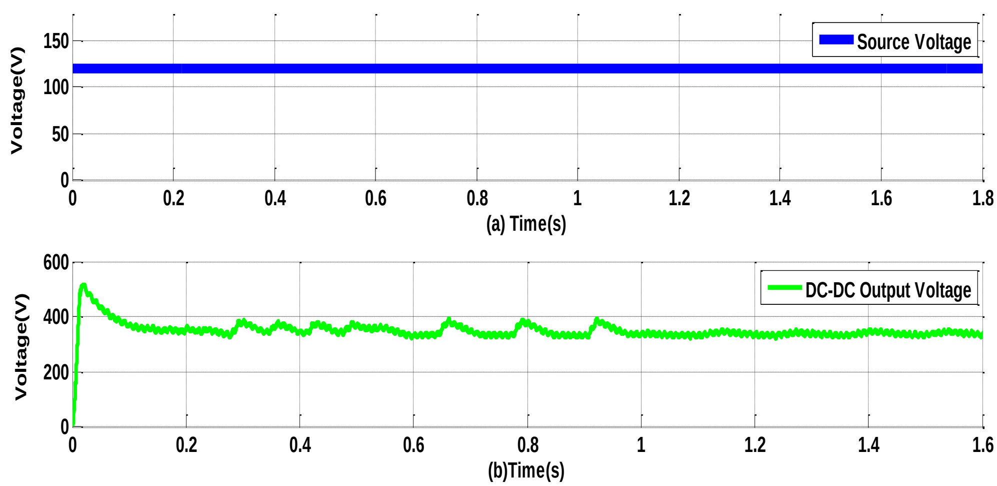

Fig. 6: (a) DC voltage source, and (b) DC-DC Converter output voltage.

Fig. 6(a) shows that the source voltage of the modelled power system is 120V DC. The DC-DC converter output voltage is shown in Fig. 6(b). It transiently fluctuates at a time interval of $0 \leq t \leq 0.96$ seconds and at $0.96 \leq t \leq 1.6$ seconds, it stabilizes.

Fig. 7(a) shows the filter output voltage of the buck-boost DC-AC converter. The transient stage of the voltage occurred at a time interval of $0 \leq t \leq 0.96$ seconds. During the period, the output fluctuates between 450V and 295V. Beyond t = 0.96 seconds, the output voltage of the DC-AC occurred 285.9V±0.5%. The filtered output shown in Fig. 7(b), mimicked the output voltage pattern but different in amplitudes.

The analysis of the inverter output voltage under TWBUM is demonstrated in Fig. 8. In Fig. 8(a), a filter output voltage is equally shown but this moment it is from the pguifft system. The pguifft displayed the magnitude of the voltage against the frequency in Fig. 8(b). It is observed that the magnitude of the inverter output and the percentage of total harmonic distortions at frequency of 50 Hz are 297.4V and 0.1471%. In addition, the percentage of total harmonic distortion seen in Fig. 8b is similar to the one seen in Fig. 2 of the modelled Simulink block.

Candidus U. Eya, Ayodeji Olalekan Salau,
Sepiribo Lucky Braide, S. B. Goyal,
Victor Adewale Owoeye, Oluwafunso Oluwole Osaloni

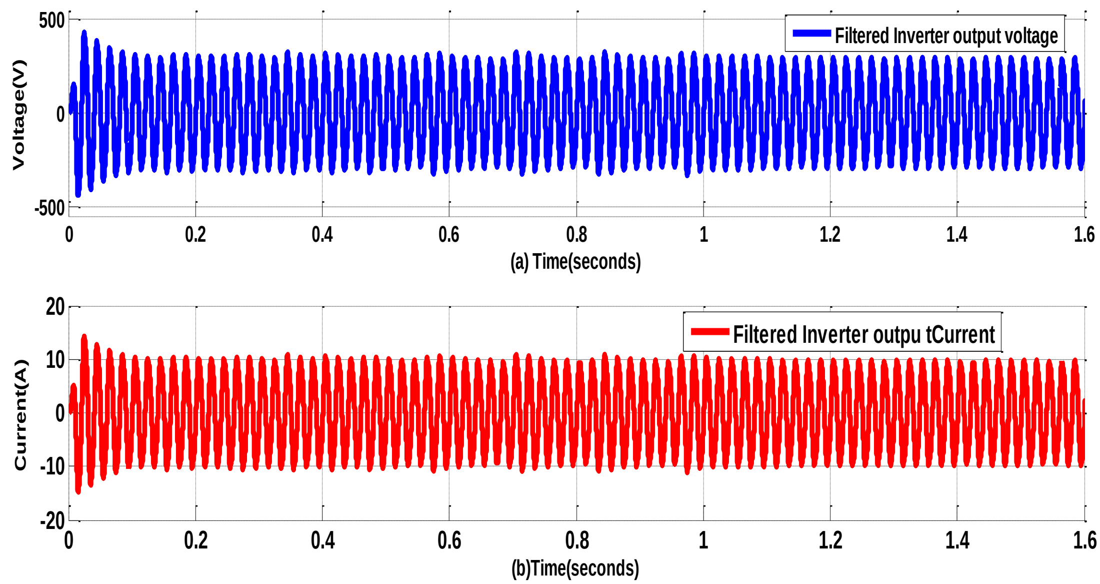

Fig. 7: Filter Output Voltage and Current under TWBUM.

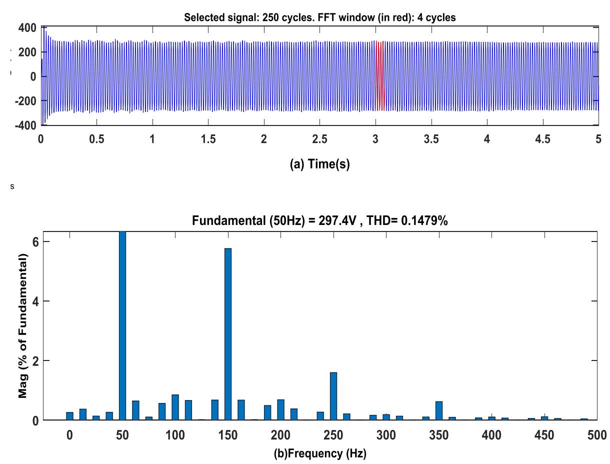

Fig. 8: Spectral analysis of Output Voltage of DC-AC converter under TWBUM.

Candidus U. Eya, Ayodeji Olalekan Salau,
Sepiribo Lucky Braide, S. B. Goyal,
Victor Adewale Owoeye, Oluwafunso Oluwole Osaloni

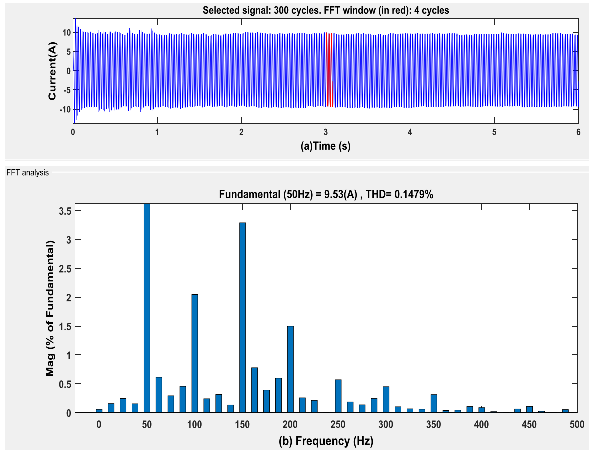

Fig. 9: Spectral analysis of Output current of buck-boost DC-AC converter under TWBUM.

The spectral analysis of current output of the inverter system is shown in Fig. 9. It is noticed that the THD of current and its amplitude are 9.53A and 0.1479%.

Saw-tooth wave based unipolar modulation scheme is represented in Fig. 10. It is detected that the saw-tooth wave ramped up from zero volt to 1V and sharply dropped down to -1.0V. The three waveforms are formed from Equations (2)-(3). The comparison of the two reference signals with the 1.0V saw-tooth carrier wave using logic comparators generates the triggering signals in Fig. 11.

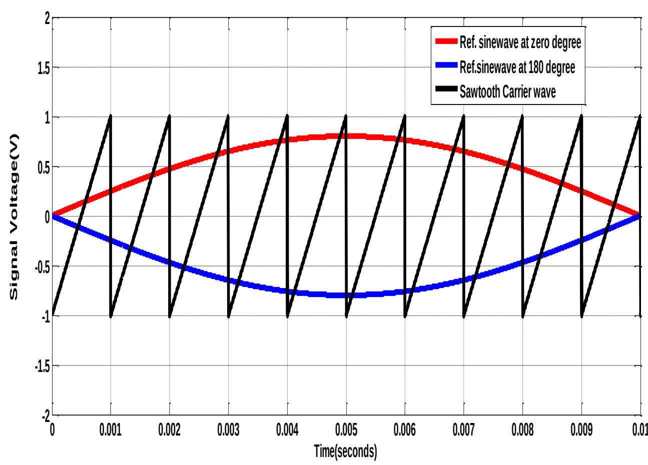

Fig. 10: Saw-tooth wave based unipolar modulation scheme.

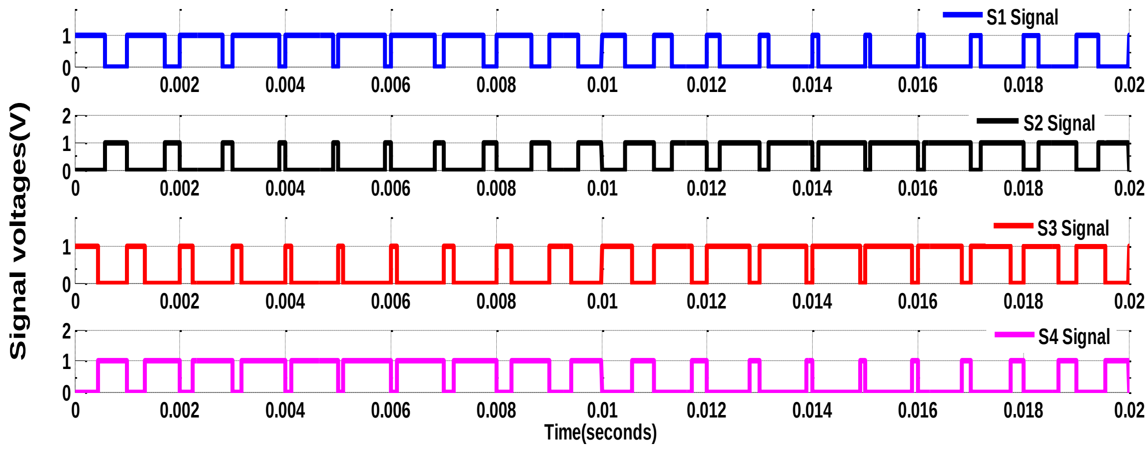

Fig. 11: Switching Pulses of DC-AC Converter under STBUM.

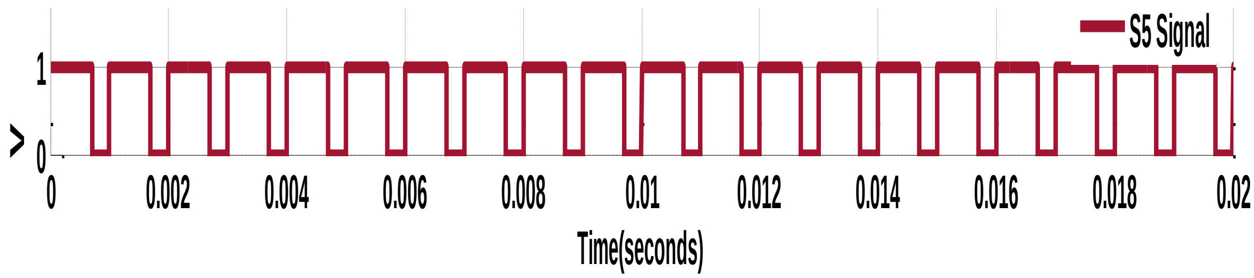

Fig. 12: Firing Signal of DC-DC Converter.

Fig. 11 is used for switching the H-bridge of buck-boost DC-AC converter under STBUM. Fig. 12 represents the signal for triggering the DC-DC converter. It has maximum voltage of 1.0V

Fig. 13(a) displayed that the source voltage of the modelled DC-AC converter system has 120V DC. The DC-DC converter output voltage is shown in Fig. 11(b). It transiently varies at a time interval of $0 \leq t \leq 1.0$ second and at $1.0 \leq t \leq 1.6$ seconds, it stabilizes.

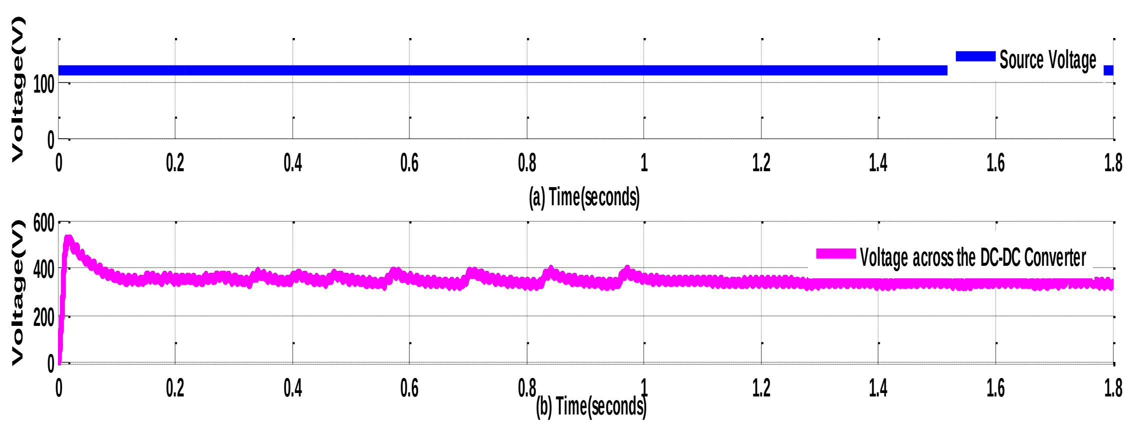

Fig. 13: (a) DC Voltage, and (b) DC-DC Converter Output Voltage.

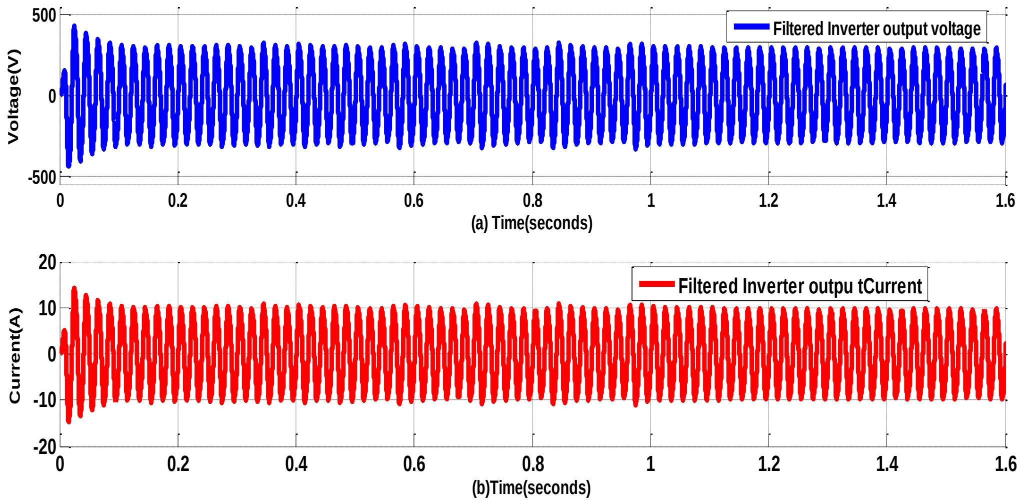

Fig. 14: Filter Output Voltage and Current under STBUM.

Fig. 14(a) and Fig. 14(b) show the filtered output voltage and current of the DC-AC converter under STBUM.

The Spectral analysis of the output voltage and current of buck-boost DC-AC Converter using STBUM are displayed in Fig. 15 and Fig. 16. It is observed that Fig. 15(b) has peak voltage of 294.1V under stabilized state and total harmonic distortion of 0.2865% at fundamental frequency of 50Hz. It is also observed that in Fig. 16(b), the total harmonic distortion and current amplitude are 0.2865% and 9.805A.

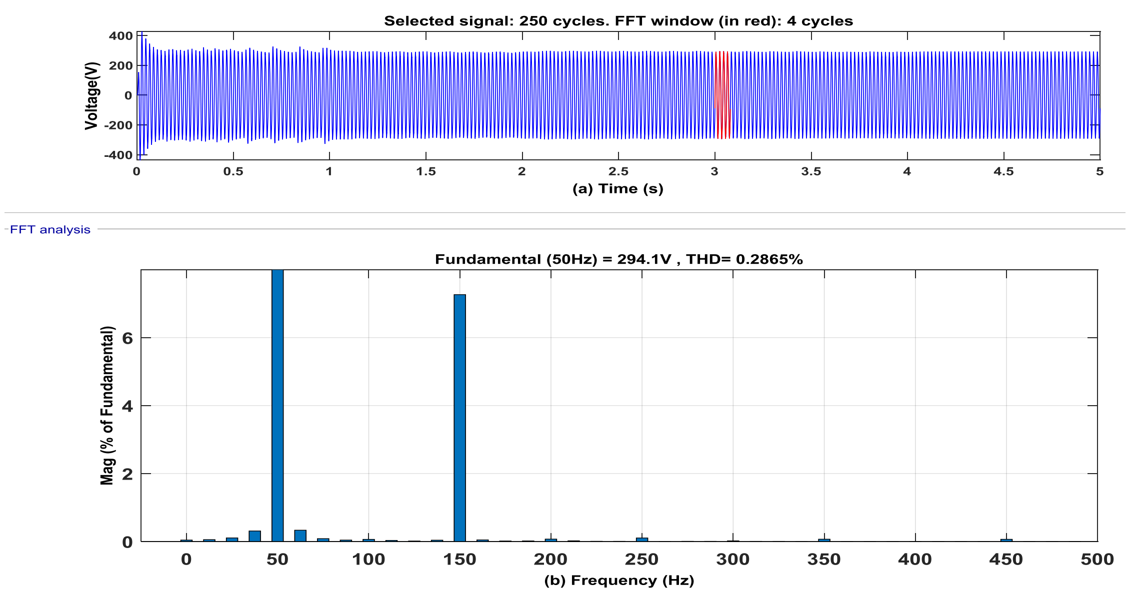

Fig. 15: Spectral analysis of Output Voltage of DC-AC converter under STBUM.

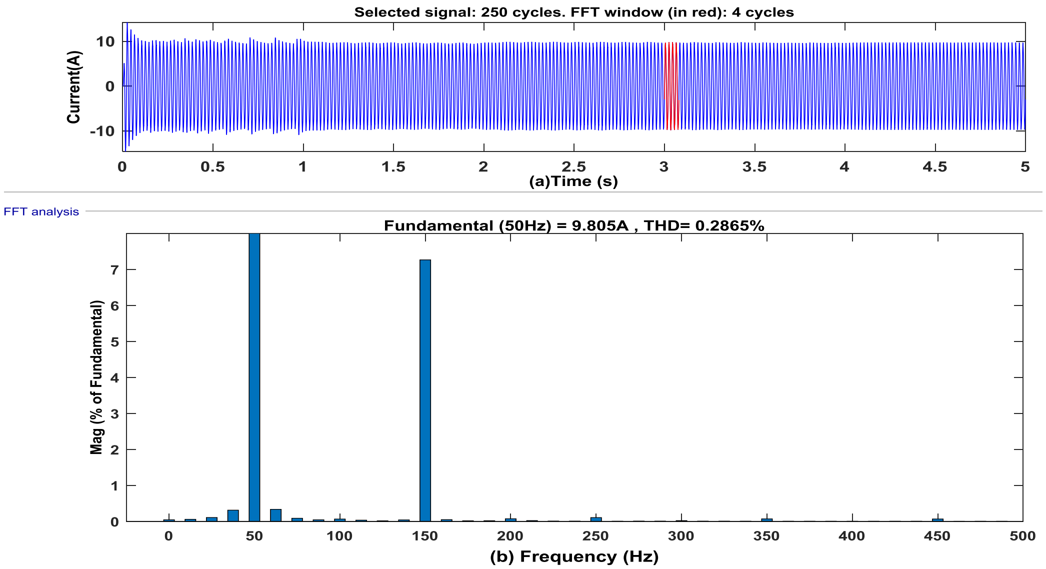

Fig. 16: Spectral analysis of output current of DC-AC converter under STBUM.

Table 1 shows the similarities and differences of using STBUM and TWBUM to switch the buck-boost inverter. It is observed that the saw-tooth based-unipolar modulation scheme using the buck-boost DC-AC converter has higher percentage THD as well as lower output voltage but higher current values than the triangular wave based-unipolar modulation scheme. This implies a low power factor utilization and higher power losses are experienced in the STBUM than in the TWBUM. Then, from the study, it was observed that in sensitive power electrical loads such as hospital equipment and communication industries loads, STBUM scheme is preferred, while in power drives and heavy load machines, the TWBUM is needed due to high current control.

Table 1. Comparison of using STBUM and TWBUM buck-boost DC-AC converter.

Modulation scheme used	Saw-tooth based-unipolar modulation (STBUM)	Triangular wave based- bipolar modulation (TWBUM)
Type of inverter	Buck-boost DC-AC converter	Buck-boost DC-AC converter
DC-DC converter modulation index	0.70	0.70
DC-AC converter modulation index	0.8	0.8
Source voltage	120V	120V
DC-DC output	318V	300V

voltage		
Inverter output voltage	294.1V	297.4V
Inverter output current	9.805A	9.530A
Percentage of Total Harmonic Distortion (THD)	0.2865%	0.1471%

In Table 2, the comparison of the present research work with already published works is tabulated. It is evident that the TWBUM technique outperformed existing works in terms of percentage of total harmonic distortion.

Table 2. Comparison of the proposed STBUM and TWBUM schemes with other existing modulation techniques.

Modulation schemes	single pulse width modulation scheme [4]	pulse width modulation scheme [5]	dual slope delta modulation scheme [6]	High switching frequency modulation (HSFM) based on sinusoidal pulse width modulation technique [7]	Carrier based sinusoidal PWM Fifth harmonic injection pulse width modulation [10]	simple boost controlled scheme [11]	Saw-tooth based-unipolar modulation (STBUM)	Triangular wave based-bipolar modulation (TWBUM)
Inverter output voltage	321.1 V	194V	317.8 V	50V	(311-345)V	(170-230)V	294.1V	297.4V
Total Harmonic Distortion (THD)	2.78%	4.9%	3.95%	64.62%	1.6%-3.2%	0.6% - 3.5%	0.2865%	0.1471%.

4 Conclusion

This paper presented the assessment of total harmonic distortion (THD) in buck-boost DC-AC converter using triangular wave and saw-tooth based-unipolar modulation schemes and PGUIFFT tool resident in MATLAB software. In addition, proposed methods were modelled and simulated in MATLAB 2018 environment. The assessment results show that the saw-tooth based- unipolar modulation (STBUM) realized a THD of 0.2865%, peak output voltage of 294.1V and current of 9.805A respectively, while the triangular wave based-bipolar modulation (TWBUM) produced a THD of 0.1479%, peak output voltage of 297.4V and current of 9.530A. Therefore, the TWBUM outperformed the STBUM.

This implies that overheating, high power losses, and low power factor existence are prevalent in the STBUM based system and vice versa. Then for this reason, the STBUM scheme should be used in power electronics buck-boost converter based drive systems where high current and THD are considered less importance; whereas the TWBUM scheme should be used in sensitive power electronics buck-boost converter based hospital and communication industries where very low total harmonics distortion is required.

Acknowledgement:
The authors acknowledge the support received from the Africa Centre of Excellence for Sustainable Power and Energy Development (ACE-SPED), University of Nigeria, Nsukka that enabled the timely completion of this research work. In addition, the authors acknowledge the Laboratory of Industrial Electronics, Power Devices and New Energy Systems, University of Nigeria, Nsukka and the laboratory Afe Babalola University that assisted us in using their Computer systems to carry out the MATLAB/Simulink simulation work.

References:
[1] Paice, D. A. (1996). Power Electronic Converter Harmonics: Multi-pulse Methods for Clean Power. IEEE *Press, Piscataway, NJ*.
[2] Eya, C.U., Salau, A.O., Oti, S.E. (2021). High Performance DC-to-AC Converter Using Snubberless H-Bridge Power Switches and an Improved DC-to-DC Converter. International Journal of Circuits, Systems and Signal Processing, Vol. 15, pp. 315-333. DOI: 10.46300/9106.2021.15.36
[3] Eya, C.U., Salau, A.O., Oti, S.E. (2022). Constant and wireless controlled DC-to-AC based boost differential converter with a sensor-less changeover system. Int J Syst Assur Eng Manag, DOI: 10.1007/s13198-021-01451-x
[4] Reddy, C.S., Purushotham, G.R., Reddy, P.P. (2018). Grid Connected Photovoltaic System with Single stage Buck-Boost Inverter. IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE), pp. 90-99.
[5] Patel, H. and Agarwal, V. (2009). A Single-Stage Single-Phase Transformer-Less Doubly Grounded Grid-Connected PV Interface. IEEE Transactions on Energy Conversion, Vol. 24, No. 1, pp. 93-101.
[6] Sarowara, G., Choudhuryb, M.A., and Hoque, M.A. (2015). A Novel Control Scheme for Buck-Boost DC to AC Converter for Variable Frequency Application, Elsevier. Science Direct, pp. 2511 – 2519.
[7] EL-Hosainy, A., Azazi, H.Z., Hamed, H.A., and El- Kholy, E. E. (2017). A Two-Stage Buck-Boost Multilevel Inverter for Photovoltaic Power Generation. Faculty of Energy Engineering - Aswan University - Aswan – Egypt.
[8] Albea, C. and Gordillo, F. (2007). Control of the boost Direct current –Alternating converter with Resistance-inductance Load through energy shaping scheme. Computer Science, Decision at Conference on 46th IEEE Control. DOI: 10.1109/CDC.2007.4434621
[9] Gupta, S. K., Khan, M. A., Iqbal, A., and Husain, Z. (2012). Comparative analysis of pulse width modulation schemes for five phase voltage source inverter. *Students Conference on Engineering and Systems*, pp. 1-6. DOI: 10.1109/SCES.2012.6199036.
[10] Dinniyah, F.S., Wahab, W., and Alif, M. (2017). Simulation of buck-boost converter for solar panels using PID controller. International Conference – Alternative and Renewable Energy Quest, AREQ 2017, pp. 104-113.
[11] Peng, F.Z. (2003). Z-source inverter. IEEE Transactions on Industrial Applications, on Industrial Electronics, Vol. 39, No. 2, pp. 504-510.
[12] Eya, C. U., Salau, A. O., and Oti, S. E. (2021). Uninterruptible DC-powered boost differential inverter with a Sensorless Changeover System. WSEAS Transactions on Circuits and Systems, Vol. 20, pp. 10-26. DOI: 10.37394/23201.2021.20.2
[13] Montgomery, H.L., and Vaughan, R. C. (2007). Multiplicative number theory I. Classical theory, Cambridge tracts in advanced mathematics, Vol. 97. pp. 536–537.
[14] Salau, A. O., Eya, C. U., Onyebuchi, O.C. (2020). Nonzero Staircase Modulation Scheme for Switching DC-DC Boost Converter. Journal of Control Science and Engineering, Vol. 2020, 8347462, pp. 1-15. DOI: 10.1155/2020/8347462.

[15] Farokhnia, N., Vadizadeh, H., Fathi, S. H., and Anvariasl, F. (2011). Calculating the Formula of Line-Voltage THD in Multilevel Inverter with Unequal DC Sources. IEEE Transactions on Ind. Electronics, Vol. 58, No. 8, pp. 3359-3372.

[16] Kumar, D., Gupta, R. A., and Tiwari, H. (2019). Mitigation of Commutation Current Ripple in the BLDC Motor Drive Based on DC-DC Converter Using PR Compensator. International Journal of Emerging Electric Power Systems, Vol. 20, No. 6. DOI: 10.1515/ijeeps-2019-0069.

[17] Aeggegn, D. B., Salau, A. O., Gebru, Y.W., Agajie, T.F. (2022). Mitigation of Reactive Power and Harmonics in a Case of Industrial Customer. International Journal of Engineering Research in Africa, Vol. 60, pp. 107-124.