Supported by tetfund TERTIARY EDUCATION TRUST FUND

INVESTIGATION OF THREE-PHASE GRID-CONNECTED INVERTER FOR PHOTOVOLTAIC APPLICATION

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Received: January 12, 2018 **Accepted:** August 28, 2018

Abstract: The proposed system ensures the injection of the generated power from the PV array in to the distribution grid with less total harmonic distortion (THD). Photovoltaic (PV) array, Pulse width modulation based (PWM) DC-DC converter, multi-level voltage source inverter, complete system with the control was modelled and simulated in MATLAB Simulink environment. The proposed control strategy has produced a more accurate output current and voltage with Total harmonic distortion (THD) of 1.06 and 1.99%, respectively as compared to a research work conducted in 2014 by Ahuja, R.K. and Kumar, A. S. with current THD of 1.43%.

Keywords: PV Array, DC-DC converter, DC-AC inverter, Total harmonic distortion

Introduction

Photovoltaic (PV) cell is one of the types of renewable energy source which converts sunlight to electrical current without any form of mechanical or thermal interlink, renewable sources of energy such as solar, wind, geo-thermal have gained popularity due to the depletion of conventional energy sources such as coal, gas etc. However, renewable energy sources are becoming very important in electric power generation, presently many distributed generation systems making use of the renewable energy sources are being designed and connected to grid (Zamre *et al*., 2012). PV cells are usually connected together to make PV modules which usually consist of 72 PV cells that generates a DC voltage between 23 Volt to 45 Volt and a typical maximum power of 160 Watt, depending on temperature and solar irradiation. Most of the electrical appliances around the world is based on AC voltage with a voltage of 120 Volt or 230 Volt in the case of single phase and 415 Volt in the case of three phase in the distribution grid. If it is required to power an AC load, PV modules can therefore not be connected directly to the grid, but must be connected through an inverter. Whereas if DC load is required to be powered, PV module can be connected directly. The two main tasks for the inverter are to take the DC voltage from the DC-DC converter as an input and converter it to AC, and to inject a sinusoidal current into the grid (Zamre *et al*., 2012).

The inability of the Nigerian Government to harness the vast solar potentials in the country as a long-term solution to the energy crisis through the adoption of the Renewable Energy Master Plan (REMP) with a target of increasing the 5,000MW generation capacity to 16,000MW by the year 2015 through the exploration of renewable energy resources (Iloje and Ewah, 2002) has to be resuscitated. In actualizing this dream, the exploration of PV energy resources should be one of the key elements of that master plan. PV energy is among the potential alternatives as renewable clean energy. As the 21st century progresses, the electric utility industry seek to take advantage of a novel approaches to meet growing energy demand as such, utilities are under pressure to evolve their classic topologies to accommodate distributed generation, these issues of worry about the future energy production in the world can be solve using the available renewable energy potentials. However, it has been established that the availability of electrical energy is a precondition for the functioning of modern societies (Reddy, 2002). It is used to provide the energy needed for operating information and communication technology, transportation, lighting, food processing and storage as well as a great variety of industrial processes, all of which are characteristic of a modern society. More so, research has indeed shown that there is a significant relation between economic growth and even societal development in general, measured by indicators such as illiteracy and life expectancy and electricity consumption (Reddy, 2002).

In this investigation work, the inverter control system algorithm, strategies and modeling are developed and simulated in MATLAB/SIMULINK environment; the results presented in this paper are based on the simulation window. However, the successfulness of this modelling is very essential in order to convert it to the prototype later on for the result validation. This simulation creates a potential and justification for hardware realization. This research employs Uncoupled Watt-VAR Method of control.

The presented results showed that the inverter control algorithm is successful in converting PV dc power to ac power with acceptable total harmonic distortion (THD) level for supplying power to the load and grid as well. In addition, the system manages to regulate the 50Hz sinusoidal output voltage and response to the grid voltage and frequency disturbances effectively. Overall, this investigation has proved the good performance of the developed inverter control system and protection algorithm

Materials and Methods

The Simulations in this paper were carried out using MATLAB/SIMULINK environment in the following order:

PV array

A single solar cell block was used from the Mat lab Simulink library with other blocks to model a functioning PV cell prototype and thereafter model a prototype PV module and a PV array. The Modelled PV array was made possible to connect with other building blocks that are found in the DC-DC converter.

DC-DC converter

A simple boost converter was modelled in the Simulink which composed of an inductor, current measuring device, Metal oxide semiconductor field effect transistor (Mosfet), output capacitor, and freewheeling diode. The output voltage was controlled using PWM techniques where the output voltage of the converter was taped and compared with a saw tooth signal; the cutting edge determined the firing signal of the switch.

Inverter

The inverter was modelled in current control mode with PWM switching mechanism which ensures the injection of current with less THD into the grid. The output signal from the DC-DC Converter was fed into three phase 3-level bridge inverter where the DC was transformed into high AC, a step-down transformer was fed from the bridge inverter output and the output was filtered using three phase filter.

Utility grid

Transmission line prototype was modelled using a grounding Transformer, three phase generation source, pi (PI) section feeders and step-down transformer. The PI section was chosen because it has a finite state and can allow linear state space analysis.

Control and synchronizations

The control make use of Uncoupled Watt-VAR Method, the goal of this control method is to control the values of the active and reactive current and voltage injected into electrical grid. Direct current voltage (VDC) Regulator, Phase locked loop (PLL), Axes transformation unit (abc/dq0), PI controller and measuring blocks were used in designing the controller. Finally, the overall system was assembled and simulated.

System modelling

PV array

The output voltage of the solar cell is a function of the photocurrent that depends on the solar irradiation level during its operation (Sera *et al.,* 2005).The PV array is simulated using a model of moderated complexity based on (Anca D. Hansen, Poul Sørensen, Lars H. Hansen and Hen-rik Bindner, 2000). In this model, a PV cell is represented by a current source in parallel with a diode, and series resistance as shown in Fig. 1. There is no need for a more complex model with a second diode and/or as hunt resistance. The photo current Iph depends on the ir-radiance G and the cell temperature T. Equation (1) describes the behavior of the output current of the solar cell.

$$I_c = I_{ph} - I_0 = I_{ph} - I_{sat}\left[e^{\frac{q}{nKT_c}(V+IR_s)} - 1\right] \quad (1)$$

Where the saturation current I_0 is temperature dependent, *e* is the charge of an electron, *k* is Boltzmann's gas constant and *n* is the idealizing factor of the diode, R_s is the series resistance.

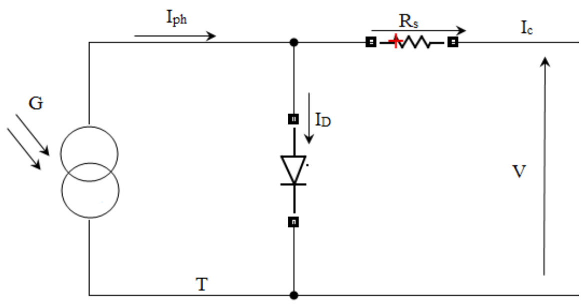

Fig. 1: Equivalent circuit of a PV cell[2]

The generation of required PV voltage and current for the DC-DC input stage is achieved by forming the module in series-parallel structure.

The power output of the PV array is the product of output current and output voltage of PV represented in equation (2) (Perez *et al.*, 2008).

$$P_{PV} = I_{PV} \times V_{PV} \quad (2)$$

Boost Converter

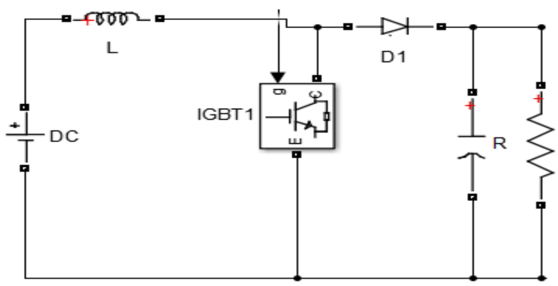

Fig. 2: Circuit diagram of a DC-DC converter

The output voltage of the DC-DC converter, the inductor value, output capacitor value which are the determinant in the design are governed by equation (3), (4) and (5);

$$V_{out} = (V_{DC} - V_{Don}) + V_L \quad (3)$$

$$L = {}^{1}/_{2}\, KR_o T_{on} \times \left(\frac{V_{Dc}}{V_{out}}\right)^2 \quad (4)$$

$$C > \frac{I_{oav} T_{ON}}{V_{ripple}} \quad (5)$$

Where I_{oav} is the average output current, T_{ON} is the ON period of the switch, K is a constant having value from zero to one, $R_o$is the output load resistance, V_{ripple} is the ripple voltage.

Inverter

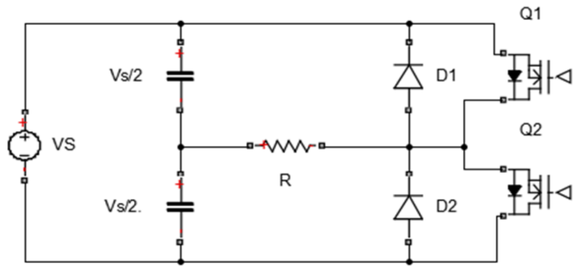

Fig. 3: Circuit diagram of a DC-DC converter

Vrms Output voltage is expressed as follows:

$$V_{o\,rms} = [{}^{2}/_{T} \int_0^{\frac{T}{2}} \frac{Vs^2}{4}\, dt]^{\frac{1}{2}} = {}^{Vs}/_{2} \quad (6)$$

Instantaneous output voltage can be expressed by Fourier series as follows

$$V_o = \sum_{n=1,3,5,\dots}^{\infty} \frac{2vs}{n\pi} \sin nwt \quad (7)$$

$= 0$ for $n = 2,4,6, \dots \Longrightarrow$Even harmonics component

Fundamental component, $n = 1$

For $n = 1$, the Fundamental voltage equation (7) gives the rms value of:

$$V_{o1} = \frac{2V_s}{\sqrt{2}\pi} = 0.45V_s \quad (8)$$

Where $V_p = \frac{Vs}{\sqrt{2}}$ And $n = 1$

The Instantaneous load current, i_o can be obtained by dividing the instantaneous output voltage by the load impedance,

$$Z = R + jnxl = R + jnwl \quad (9)$$

i.e.

$$i_o = \sum_{n=1,3,5}^{\infty} \frac{2V_s}{n\pi\sqrt{R^2+(nwl)^2}} \sin(nwt - \theta_1) \quad (10)$$

Where $Q_n = \tan^{-1}(\frac{nwl}{R})$ (11)

This is the phase angle between voltage and current that is the angle which the current lags the voltage

Given thati_o, is the rms fundamental load current, then the fundamental power $(n = 1)$ Is expressed as:

$$P_{01} = V_{01} I_{01} \cos Q_1 = {I_{01}}^2 R \quad (12)$$

But $I_{o1} = \frac{V_{o1}}{Z} = \frac{2V_s}{\sqrt{2}\pi\sqrt{R^2+(wl)^2}}$ (13)

i.e. $P_{01} = \left[\frac{2V_s}{\sqrt{2}\pi\sqrt{R^2+(wl)^2}}\right]^2 R$ (14)

Simulation model

The simulation was conducted in MATLAB Simulink environment utilizing components from Simpower system, Simelectronics and Simscape libraries. The value used durring the simulation for the PV cell is 0.6V, for the PV modules are 43.2 V for the Open circuit output voltage and 7.34A for the short circuit output current. In order to produce a total output DC current of 105A and voltage of 425Vwith a power capacity of 45kW, 720 units of PV cells were connected in series to form the module and 66 of such module were connected in parallel structure to form the PV array. The system as shown in Fig. 4 was simulated for 2 second.

The designed DC-DC boost converter that steps up the voltage to 1500V was also simulated as shown in Fig. 5. The converter uses a feedback control to achieve the set voltage. The output of the converter is taped and send to the controller where the output is compared with a saw tooth, the cutting edge determine the firing signal for the switch.

The complete circuit for the simulation is as shown in Fig. 6 in which the PV-array, DC-DC converter, inverter, and the grid were connected together. The controller is designed in current control mode with PWM switching technique in order to make the current to be in phase with the grid current and obtain a low THD injected current. This research employs Uncoupled Watt-VAR Method of control.

As shown in Fig. 7, the controller uses two control loop, an external control loop which regulates the DC link voltage to ± 1500V and an internal control loop which regulates Id and Iq grid currents (Active and reactive current components). Id current reference is the output of the DC voltage external controller, Iq current reference is set to zero in order to maintain unity power factor. Vd and Vq voltage outputs of the current controller are converted to three modulating signals used by the PWM generator. Figure 8 shows a model of a national grid. The model consist of a pi (PI) section feeder, step down transformer, grounding transformer, three phase source and some loads. PI section feeder was used because it allows steady state analysis.

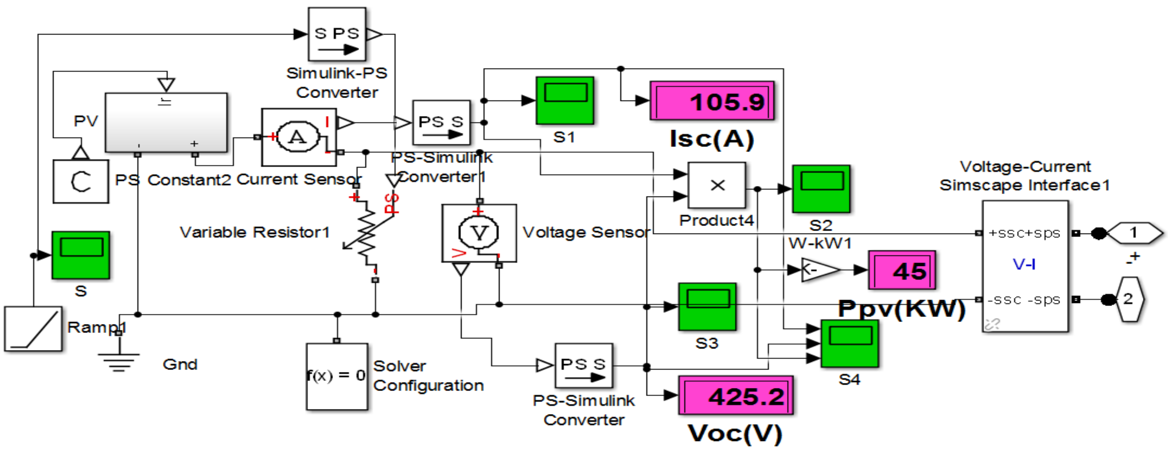

Fig. 4: Simulation circuit diagram for the photo-voltaic array

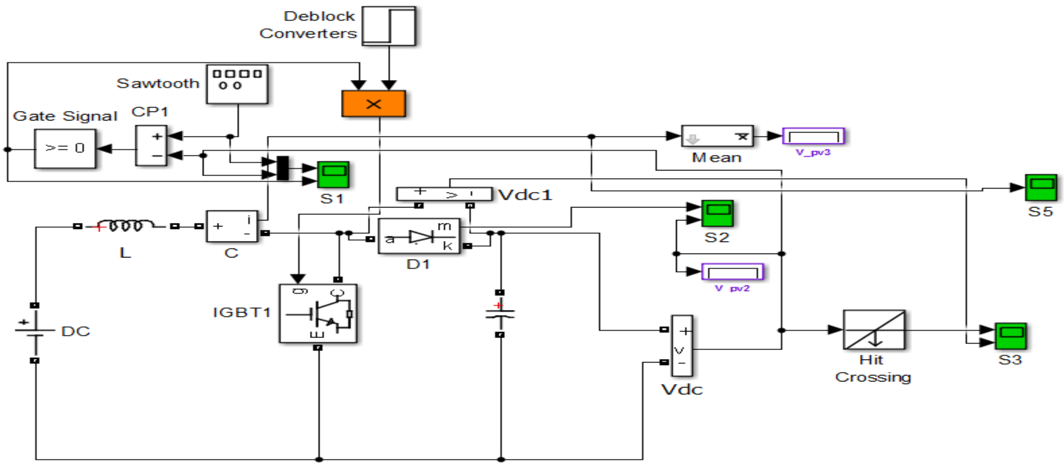

Fig.: 5: Simulation circuit for the DC-DC converter

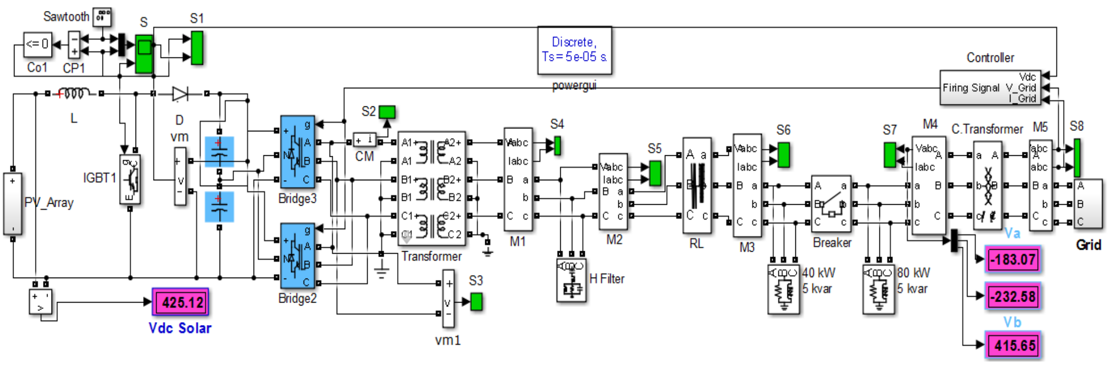

Fig. 6: Simulation circuit for the complete system

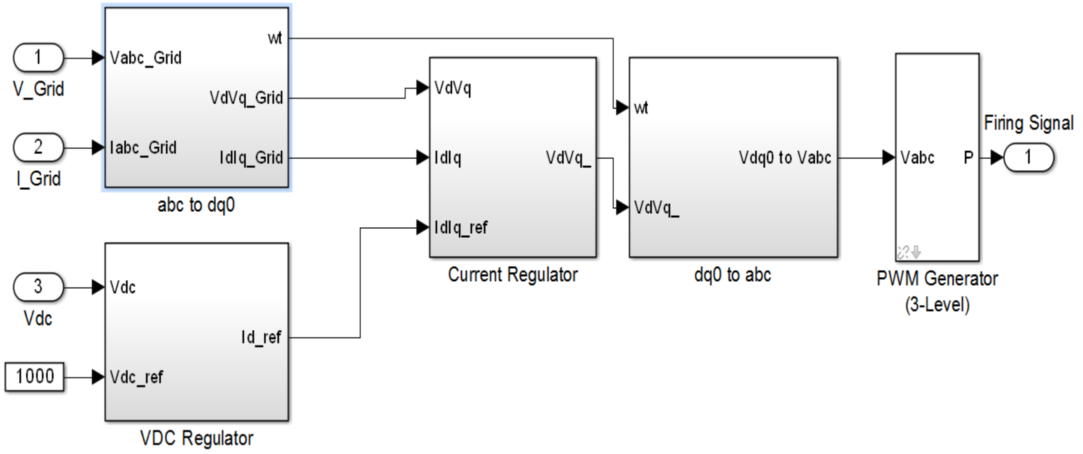

Fig. 7: Block diagram of the controller

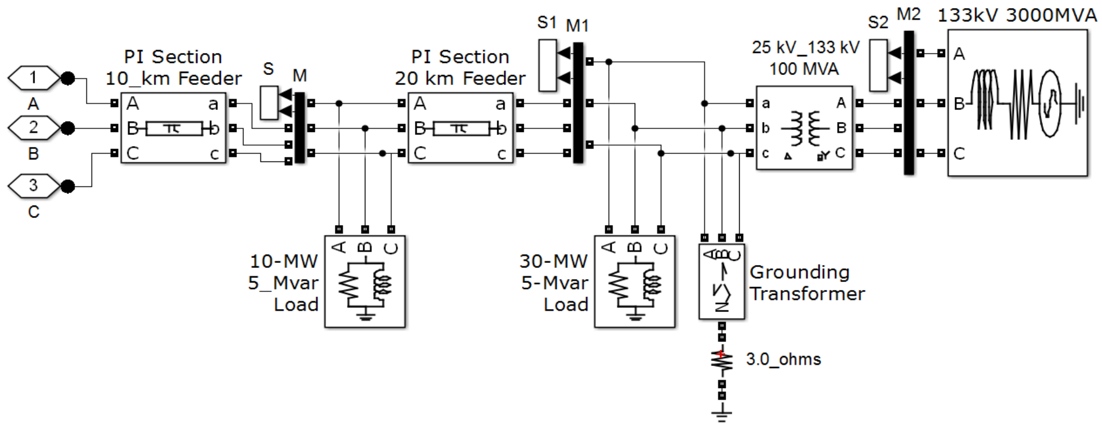

Fig. 8: Model of a national grid

Results and Discussions

The Simulated results are presented here to validate the effectiveness of the proposed system.

PV array results

Figure 9 shows the Current and Voltage curve for the Photovoltaic Array that is capable of generating an average output voltage and current of 425V, 105A, respectively and average power of 45KW. The voltage start rising lineally and end up in it open circuit value of 425V within one second. Similarly, the current maintained a constant value at the initial time and start depreciating exponentially after 0.3 second and end up in it short circuit value of 105A within two second.

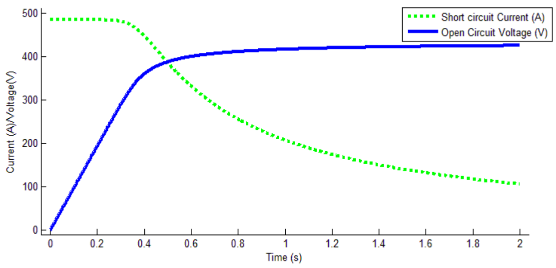

Fig. 9: Power curve of the PV array

As shown in Fig. 10 the power from the PV array start rising linearly and reach it maximum point within 0.4 second which produces a maximum power of 160KW and it start decaying and finally end up at a power of 45KW.

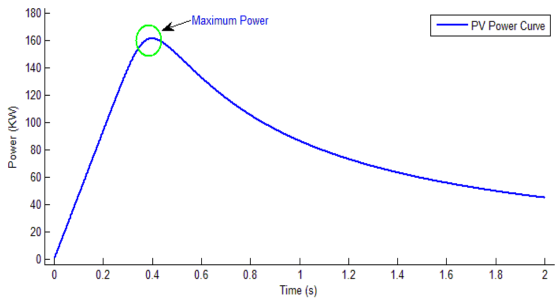

Fig. 10: Power curve of the PV array

DC-DC converter results

Figure 11 shows the interaction of a saw tooth signal with the DC output voltage of the DC-DC converter were the firing signal for the switch of the DC-DC converter is been generated based on the cutting edge. A feedback control technique was employed where the output voltage of the converter was taped and send to a comparator which compared the output signal with the saw tooth, the output of the comparator is fed to a compare to zero block which detects the cutting edge and produced pulses depending on the level of the output voltage. At the early time when the output voltage of the converter is small, the turn ON period were seen to be more thereby allowing the system to produce more power, but as the output voltage of the converter is getting higher, the system reduces the turn ON period.

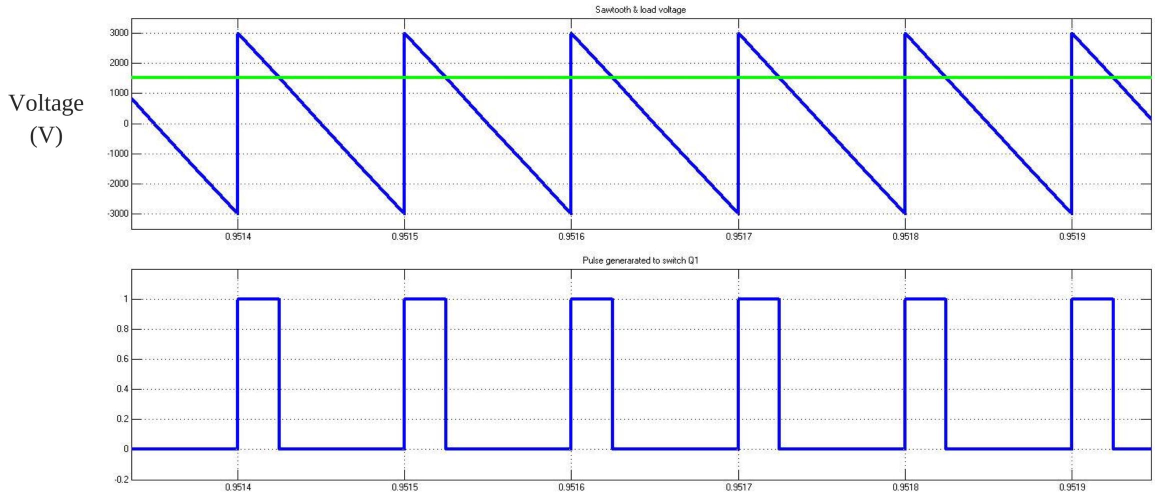

Fig. 11: Sawtooth compared with output voltage of the boost converter and the firing signal

Inverter results

Figure 12 shows the inverter current, the current takes a sine-shape with a little ripple.

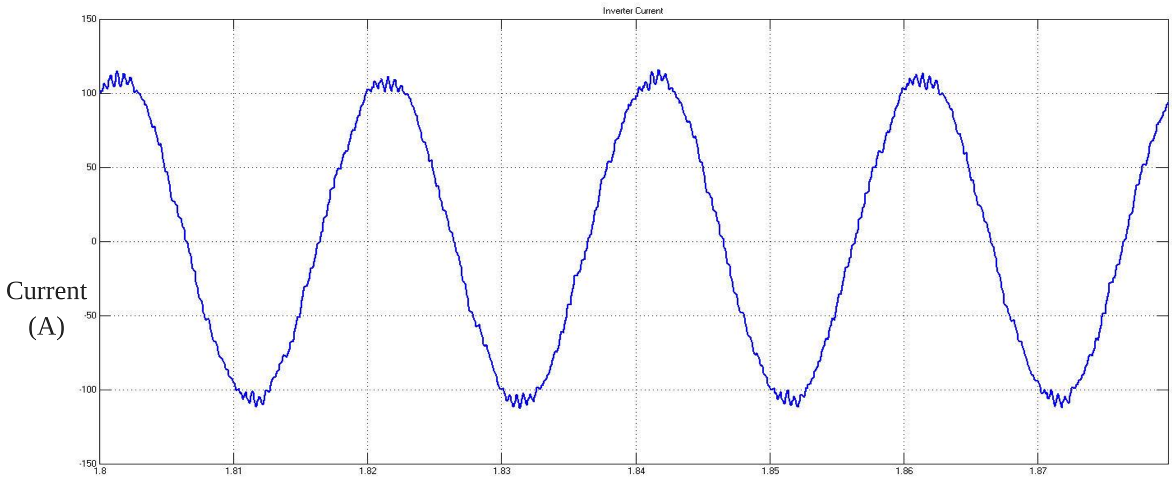

Fig. 12: Inverter current

Figure 13 shows an inverter Voltage, the voltage takes a stair-modified Sine-wave.

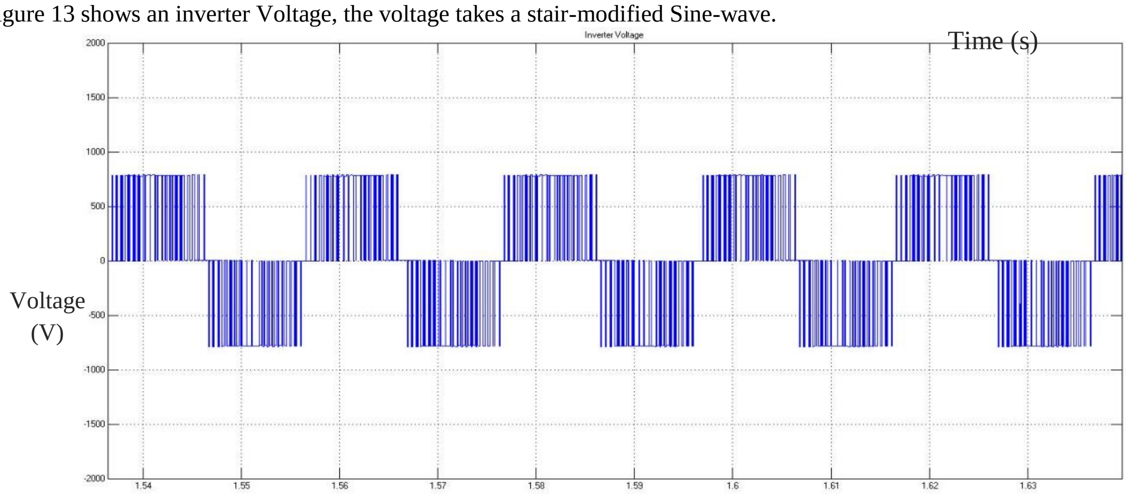

Fig. 13: Inverter voltage

Time (s)

Figure 14a&b shows the three phase voltage and current after filtering, a double-tuned parallel filter was used to reduce the harmonics generated by the power electronics devices.

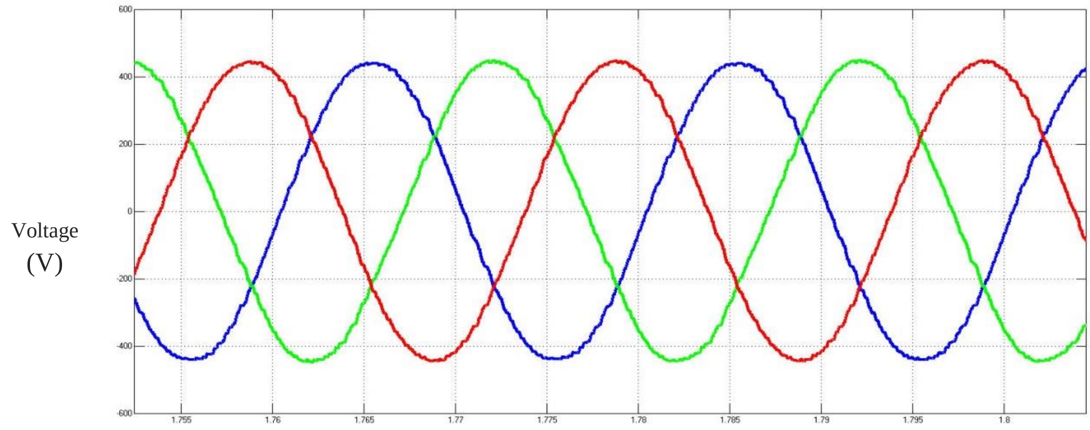

Fig. 14a: Three phase filtered inverter voltage

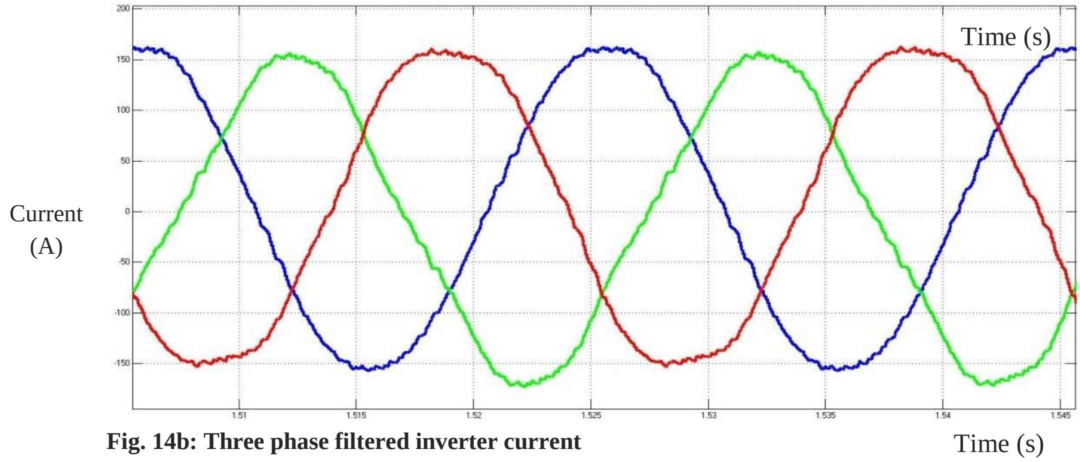

Fig. 14b: Three phase filtered inverter current

Controller results

Figure 15 shows a current which serves as the direct axis (Id_ref) reference signal for the current controller. The controller has a rise time of 0.65s, an overshoot of 0.007% and had attained a steady state at 0.7s with an error of 0.016. The voltage controller has a proportional gain (Kp) and integral gain (Ki) of 6, 700, respectively.

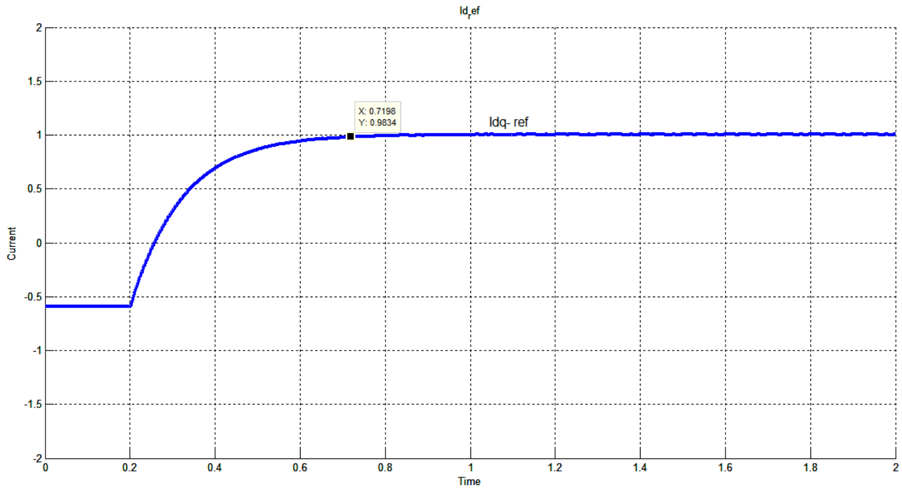

Fig. 15: Id reference signal

Figure 16 shows the transformed signal from abc to dqo. The transformation is necessary in order to control three phase signal. When three phase signal is passed through the abc to dqo block, the signal is transformed to direct, quadratic and zero axis.

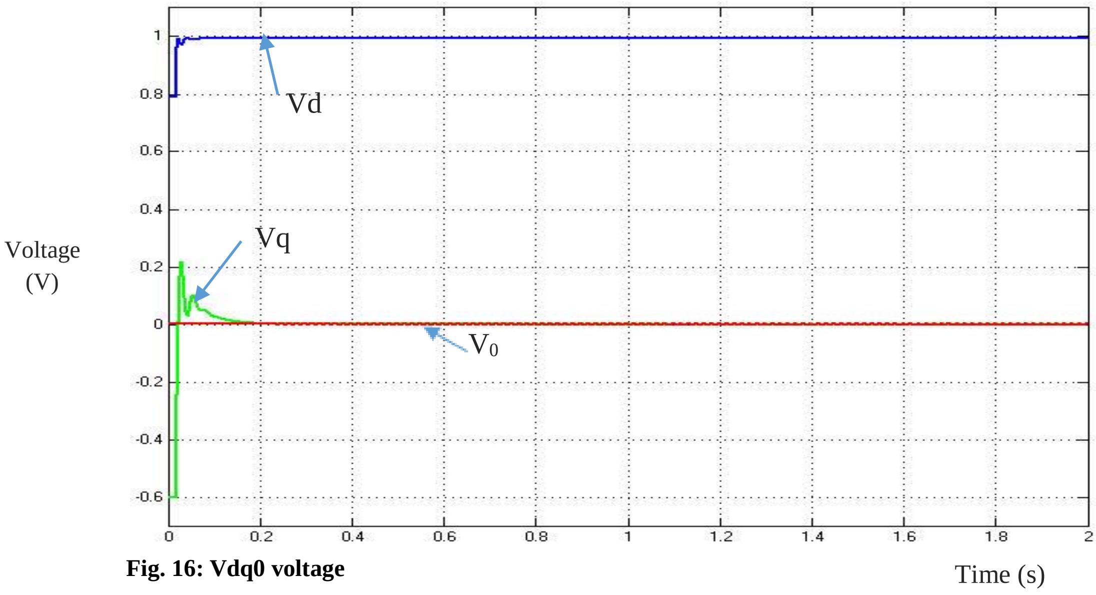

Fig. 16: Vdq0 voltage

Figure 17 shows a transformed Iabc to Idq0.

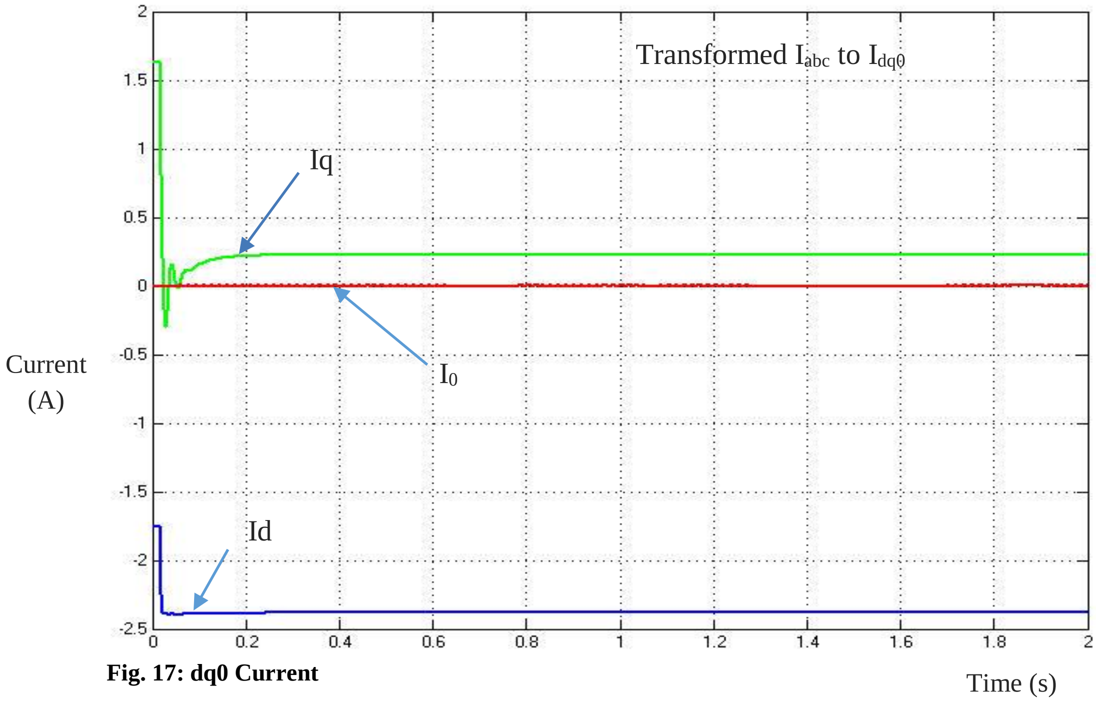

Fig. 17: dq0 Current

Figure 18 shows the Output of the Current Controller, the controller was able to achieve steady state value within 0.03 and 0.1 second for the Id and Iq, respectively. The current controller has a proportional gain (Kp) and integral gain (Ki) of 0.2, 19, respectively.

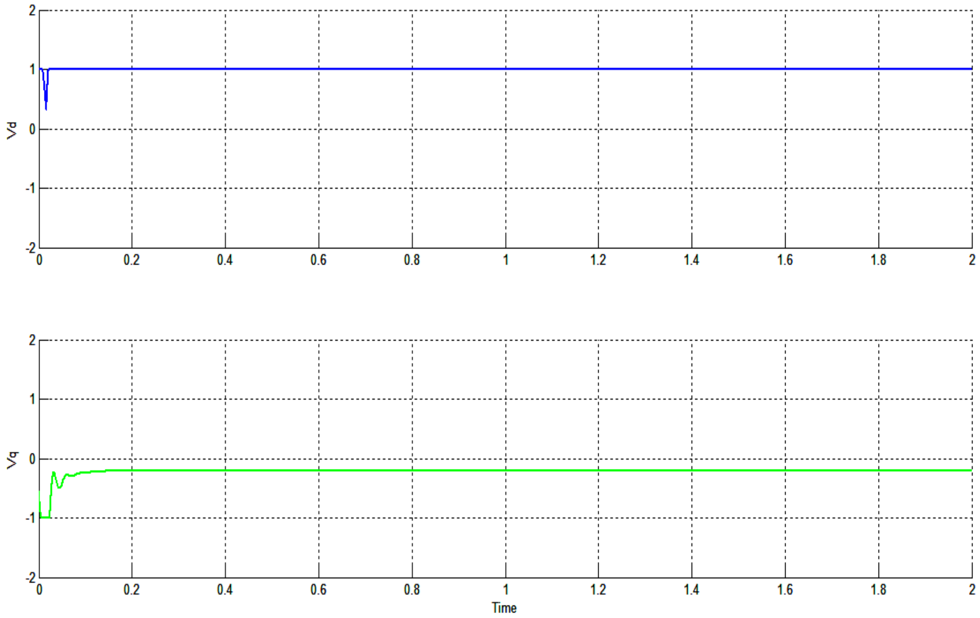

Fig. 18: Output of the current controller

Figure 19 shows the transformed V_{dq0} to V_{abc}, the Voltages from the current regulator are converted to three modulating signal which will be use by the PWM generator to generates firing signals.

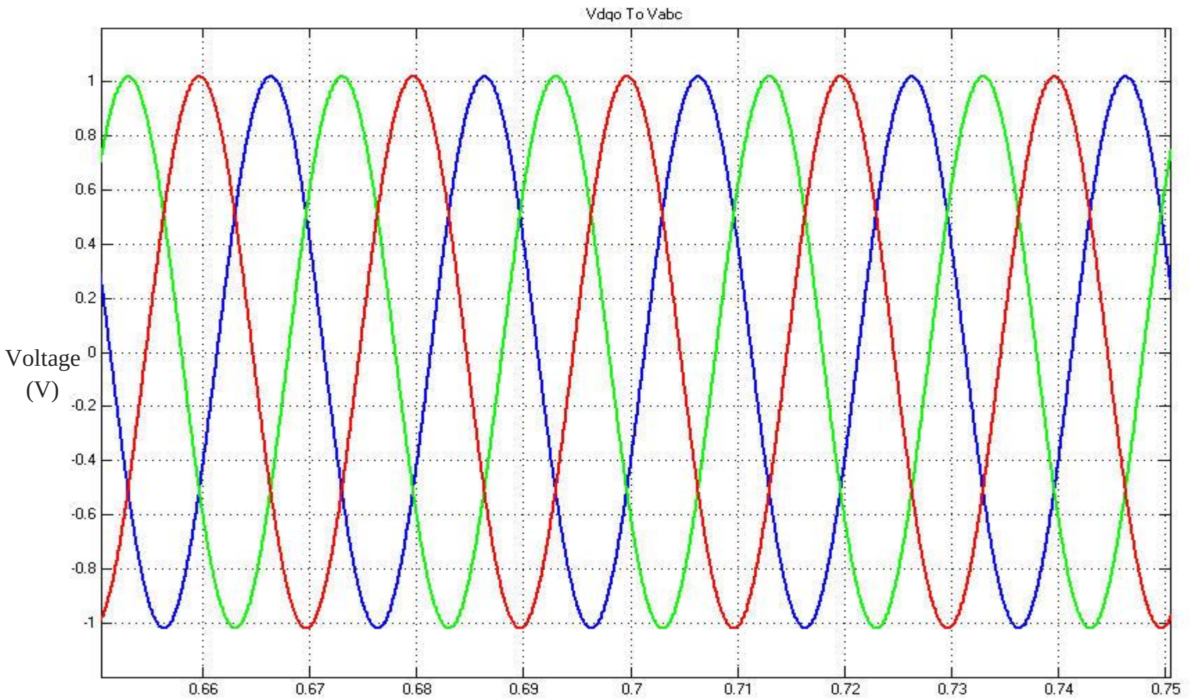

Fig. 19: Vabc from Vdq0

Figure 20 shows the firing signals to the IGBTs for the inverter.

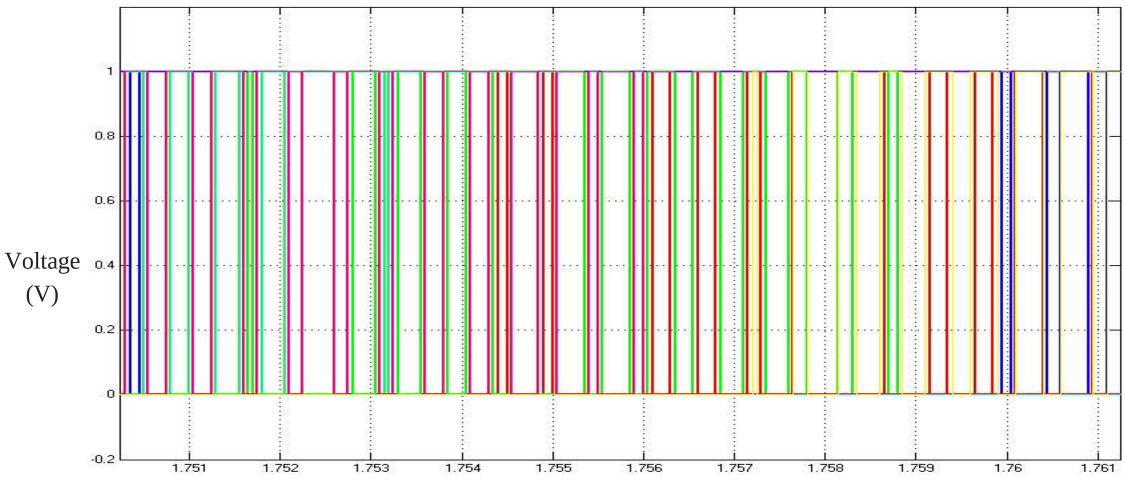

Fig. 20: Firing signal

Performance parameters results

Figures 21 and 22 show the Bar representation of THD of the Phase current and voltage waveforms Relative to the fundamental which was 1.06 and 1.99% for current and voltage, respectively. That is in compliance with below 5% in voltage and 3% in current by IEEE519-1992 standard. The result exhibits the improvement from the adapted multi-level power processing topology and control strategy proposed in this paper.

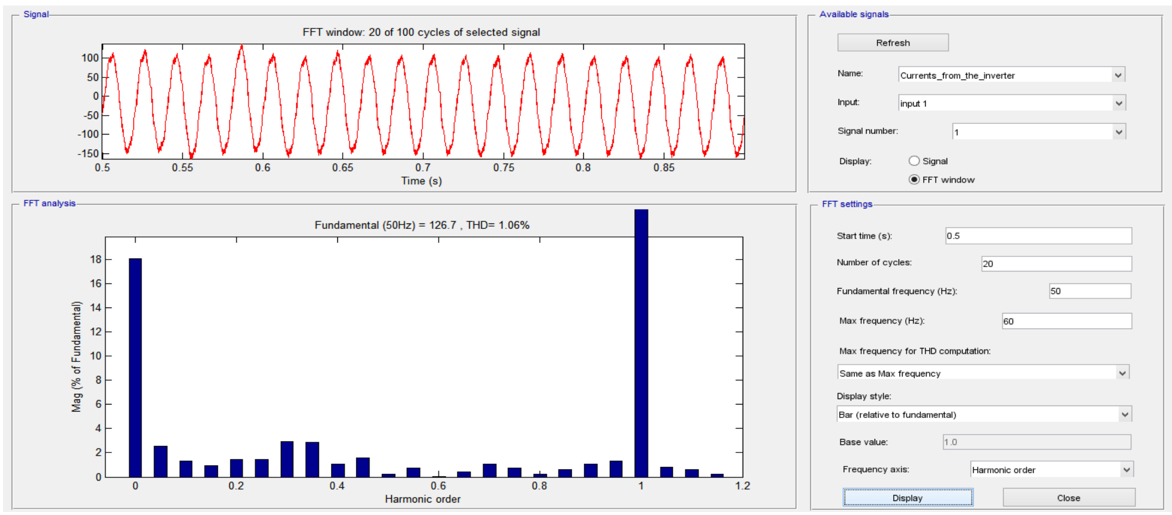

Fig. 21: Bar representation of CTHD relative to the fundamental

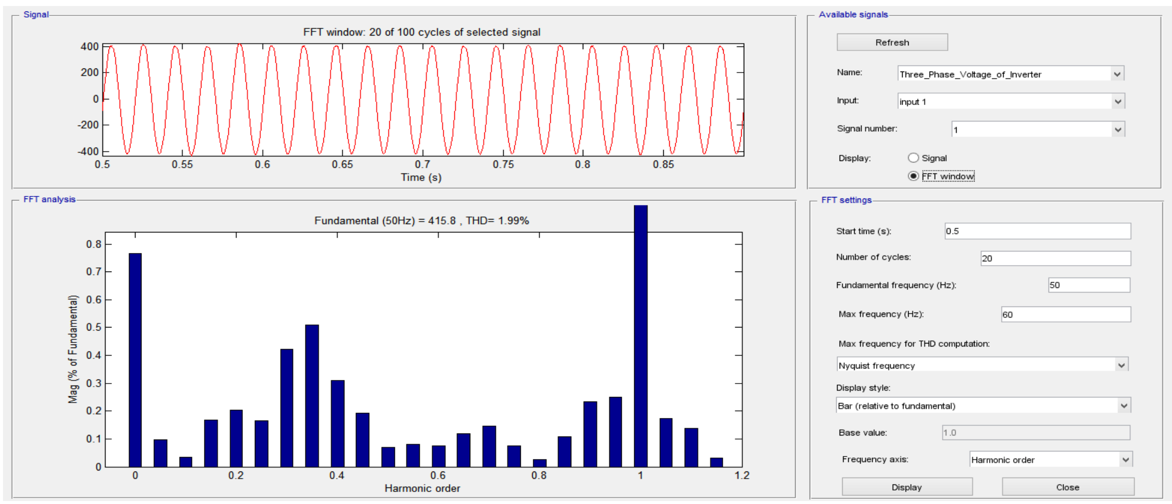

Fig. 22: Bar representation of VTHD relative to the fundamental

Results validation

To validate the result obtained in this Paper, result of performance parameter (CTHD and VTHD) was compared with some similar work done in the past and the comparison is as follows Result of a research conducted in 2013 by Altin and Ozdemir, shows that the system produces CTHD of 3.75 which is above the standard set out by IEEE519-1992. Result of a research conducted in 2014 shows that the developed system produces different average CTHD at different input voltage levels, the least value was found to be 2.73% which is within the acceptable level of standard set out by IEEE519-1992. Result of a research conducted in 2014 by Ahuja and Kumar, the result shows that the developed system produces different average CTHD at different frequencies levels, the least value was found to be 1.43% at frequency of 13KHZ, which is within the acceptable level of standard set out by IEEE519-1992. The validation of the result has shown that the proposed topology gives better result which is far below the standard set out by IEEE519-1992 of below 3 and 5% in current and voltage, respectively.

Conclusion

Based on the review of similar research work conducted, it was found that most of the research work could not meet up with the minimum CTHD and VTHD set out by IEEE519-1992 of below 3 and 5% in current and voltage, respectively. This research work presented a model of a PV array which considers some factors that constrained PV module output power based on Sun-power datasheet, it has also modelled a boost DC-DC converter, an inverter and presented a simulation model of the PV array, DC-DC converter as a standalone and finally the complete system (PV array, DC-DC converter and inverter) and the control unit. However, results obtained from the simulation which comprises a PV array, DC-DC converter, an Inverter, the Controller unit results were presented and discussed. Validation of the simulated result based on total harmonic distortion were carried out and the validation has shown that the proposed topology gives better result with an error of 1.06 and 1.99% for current and voltage, respectively which is far below the standard set out by IEEE519-1992. This research work has presented an effective approach for simulating a grid tie inverter for photovoltaic applications. It was evident from the results obtained that multi-level grid tie inverter improves power quality by reducing the total harmonic distortions below the specified minimum. Also, if grid tie inverter like this can be design and connected to the grid, it can improve power availability in Nigerian grid and can specifically promote increase in sustainability of hybrid energy systems which is a cost effective and environmentally friendly green source of energy.

Conflict of Interest

Authors declare that there are no conflicts of interest.

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