© DEC 2021 | IRE Journals | Volume 5 Issue 6 | ISSN: 2456-8880

Modelling And Simulation of Grid-Tied Inverter for Interfacing Solar Power Supply to Distribution Networks

IJOMAH, O. P.[1], ILOH, J. P. I.[2], OKONKWO, I. I.[3]
[1, 2, 3] Department of Electrical and Electronic Engineering, Chukwuemeka Odumegwu Ojukwu University, Uli, Nigeria

Abstract-* As technology advances, the cost for photovoltaic cell decreases in the market and demand for photovoltaic cells increases. The excess energy that is generated can be sold back into the distribution company. This energy when managed can help to mitigate the problem of insufficient energy from the grid and maximize profit. To get this done, the output voltage and frequency of the solar inverter must match with the variations in the voltage and frequency of the grid. Unlike stand-alone photovoltaic systems, grid connected PV systems feed generated electricity into utility grids. The grid connected systems rarely include an integrated battery solution. At present, some works have been done on the simulation tools for PV power systems. This research deals with Simulation of Grid tied inverter for interfacing power availability to the distribution network. In this study, a mathematical model for synchronizing two generators was developed. The system was simulated in MATLAB/SIMULINK environment using maximum power point tracker, boost converter, Voltage source converter, phase locked loop, current reference and voltage regulator. With the output voltage been keep constant at 11KV, the system was designed so that it can follow up the grid variations. These variations were simulated within the statutory frequency limits of 49.6Hz to 50.4Hz because the system is intended to work only at steady state. The result showed that the system synchronized with the variations of the voltage and frequency of the grid to 100% degree. The work aids to mitigate, reduce electricity bills and increases amount of energy in the utility grid. It was also recommended that net-metering should be used together with the grid-tied inverter.

***Indexed Terms-* Distributed network, Grid-tied, Inverter, Photovoltaic, Power system**

I. INTRODUCTION

Unfortunately, the utilization and development of solar energy are faced with low pace of development and utilization in Nigeria. This low pace of development is due to the associated problems such as purchasing power, the technology of installation and fabrications, awareness, governmental policy politics and culture, Nigerian factor, among many other variables [1]. According to Akinboro et al. [2] more than 75% of Nigerian populations are rural dwellers, and less than 20% of Nigeria are connected to the National grid, and more than 70% of Nigeria's population of about 140 million live in more than 80% of land mass of Nigeria which is not connected to the national grid. Since the energy production level of any community dictates her pace of development and hence her poverty level, it is possible to alleviate poverty of the large community of Nigerians by providing alternative renewable energy (solar) for them. Recently, the Federal Government of Nigeria announced the kickoff of presidential initiative to deliver solar power to 20,000 homes [3]. Okechukwu [4] reported that two communities in Kaduna, Guami and Pakau in July 2017 celebrated two years of uninterrupted power from the 90kW solar photovoltaic (PV) off-grid system installed in the areas. Ayodeji O Deji, CEO of Protergia Energy, an Abuja based renewable energy company reinforces this fact, "Renewable energy is the way modern society is going, fear in some quarters that solar energy cannot power high power demanding machinery and appliances is baseless as it is capable of powering all that the conventional grid electricity can power" [5].

Presently in Nigeria, there is this general problem of underutilization of solar energy and as a result, the conventional national grid had been subjected to severe stress and damage because of overload. Moreover, even the little amount of energies generated from solar energy is being wasted because of lack of adequate infrastructure and technical know-how in place to harness them. Owing to the ongoing awareness on the need for additional power supply leveraging on renewable energy, there are good number of individuals, agencies, companies installing standalone solar power supply. Averagely, the excess energy generated, though not much compared to the level of growth in population and energy demand, when properly harnessed and channeled, can be sold to the energy industries and consequently help to mitigate the mirage of energy problems bedeviling the country's distribution networks. For greater efficiency and adequate supply of energy to the power distribution networks, there is need for developing a system for interfacing the outputs of multiple solar powered inverters to the distribution networks.

This paper is designed to model and simulate grid-tied inverter for interfacing solar power supply to distribution networks.

II. MATERIALS AND METHOD

A. *Materials*

The materials used are Solar panel, Maximum power point tracker, Boost converter, Voltage source converter, Voltage source control main controller, Harmonic filter, Transformers, distribution unit (utility grid). These materials where virtually deployed in Matlab/ Simulink environment where simulations where carried out. The software tools are Matlab/ Simulink.

B. *Method*

The software tools are Matlab/ Simulink. The block diagram of the proposed grid tied inverter is shown in Fig. 1.

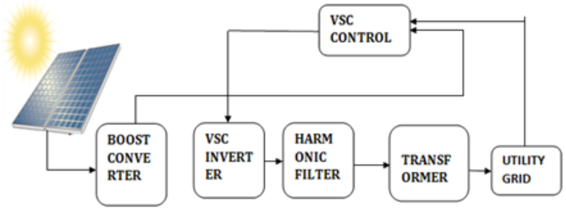


Fig. 1 Block diagram of a proposed grid tied inverter

Description of the Proposed Grid-Tied Inverter: The grid tied inverter must match the phase of the grid and maintain the output voltage, the same as the grid voltage at any instant. If the inverter's output is higher than the utility voltage, the grid tied inverter will be overloaded. If it is lower, the grid tied inverter sinks current rather than sourcing it. Its phase angle is within one degree of the AC power grid. The output voltage and current are perfectly lined up. It is also designed to quickly disconnect from the grid if the utility grid goes down. In this dissertation, there is an additional coupling inductor (Lgrid) between the grid tied inverter and mains that acts as a shim that absorbs the extra voltage, it also reduces the current harmonics generated by the pwm.

A 100-kW PV array is connected to an 11-kV grid via a DC-DC boost converter and a three-phase three-level Voltage Source Converter. Maximum Power Point Tracking (MPPT) is implemented in the boost converter by means of a Simulink model using the 'Incremental Conductance + Integral Regulator' technique. There are some that use average models for the DC-DC and VSC converters. The detailed model contains the following components:

i PV array which delivers a maximum of 100 kW at 1000 W/m^2 sun irradiance.

ii 5 KHz DC-DC boost converter increasing voltage from PV natural voltage (273 V DC at maximum power) to 500 V DC. Switching duty cycle is optimized by a MPPT controller that uses the 'Incremental Conductance + Integral Regulator' technique. This MPPT system automatically varies the duty cycle in order to generate the required voltage to extract maximum power.

iii 3-level 3-phase Voltage Source Control. The VSC converts the 500Vdc link voltages to 240 Vac and keeps unity power factor. The VSC control system uses two control loops: an external control loop which regulates DC link voltage to +/- 250 V and an internal control loop which regulates I_d and I_q grid currents (active and reactive current components). I_d current reference is the output of the DC voltage external controller. I_q current reference is set to zero in order to maintain unity power factor. V_d and V_q voltage outputs of the current controller are converted to three modulating signals $U_{abc\ ref}$ used by the PWM Generator. The control system uses a sample time of 100 microseconds for voltage and current controllers as well as for the PLL synchronization unit. Pulse generators of Boost and VSC converters use a fast sample time of 1 microsecond in order to get an appropriate resolution of PWM waveforms.

iv 10-kvar capacitor bank filtering harmonics produced by VSC.

v 100-kVA 260V/11kV three-phase coupling transformer.

vi Utility grid (11kV distribution feeder + 33kV equivalent transmission system). The 100-kW PV array uses 330 Sun Power modules (SPR-305E-WHT-D). The array consists of 66 strings of 5 series-connected modules connected in parallel. Hence, The Power Output of the PV = 66 x 5 x 305.2 W = 100.7 kW.

The 'Module' parameter of the PV Array block allows the designer to choose from among various array types of the NREL System Advisor Model. The manufacturer specifications for one module are:

Number of series-connected cells = 96

Open-circuit voltage: Voc = 64.2 V

Short-circuit current: Isc = 5.96 A

Voltage and current at maximum power: Vmp = 54.7 V, Imp= 5.58 A

The PV array block menu allows the designer to plot the I-V and P-V characteristics for one module and for the whole array. The PV array block has two inputs for varying sun irradiance (input 1 in W/m^2) and temperature (input 25℃). The irradiance and temperature profiles are defined by a Signal Builder block which is connected to the PV array inputs. The Simulink model of the proposed grid-tied inverter is shown in Fig. 2.

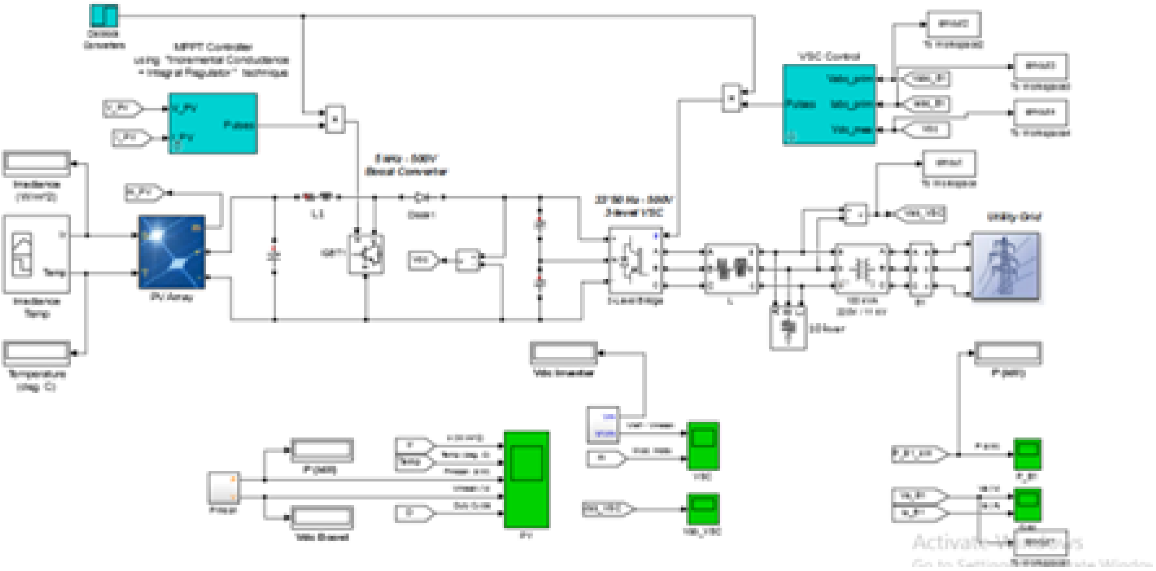
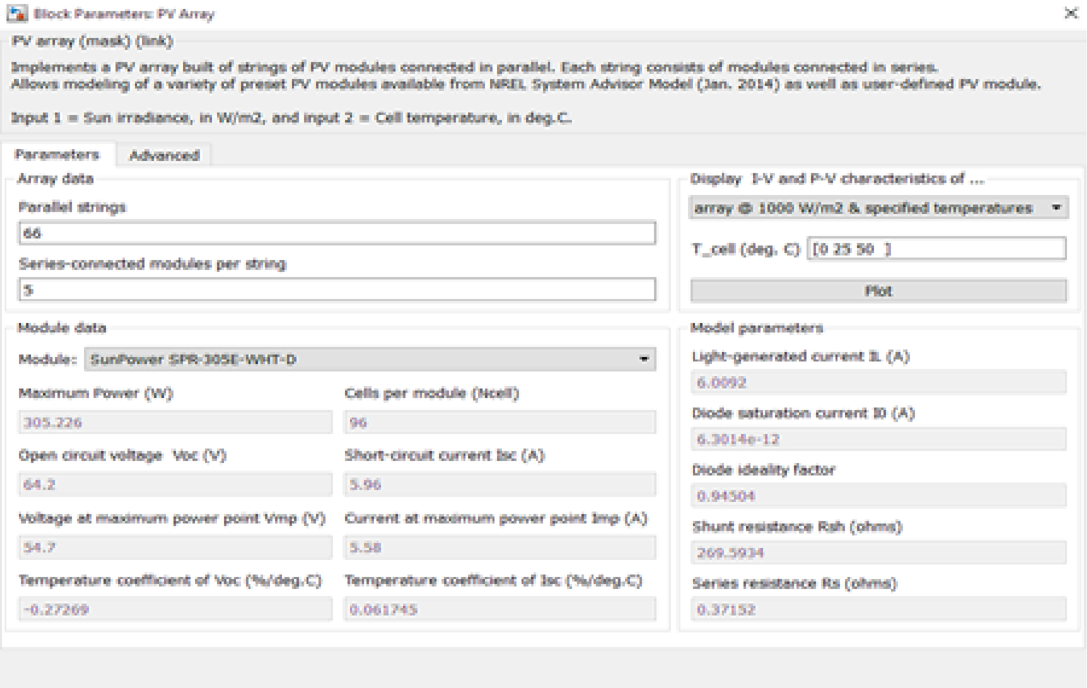


Fig. 2 The model of the proposed grid tied inverter

C. Photovoltaic Cell

The detailed parameters of the photovoltaic array block diagram are done in the module depending on the type of the PV cell choose in the MATLAB from National renewable energy laboratory (NREL). The block parameters are shown in Fig. 3.



PV array (mask) (link)

Implements a PV array built of strings of PV modules connected in parallel. Each string consists of modules connected in series.
Allows modeling of a variety of preset PV modules available from NREL System Advisor Model (Jan. 2014) as well as user-defined PV module.

Input 1 = Sun irradiance, in W/m2, and input 2 = Cell temperature, in deg.C.

Array data
Parallel strings: 66
Series-connected modules per string: 5

Display I-V and P-V characteristics of ...: array @ 1000 W/m2 & specified temperatures
T_cell (deg. C): [0 25 50]

Module data
Module: SunPower SPR-305E-WHT-D
Maximum Power (W): 305.226
Cells per module (Ncell): 96
Open circuit voltage Voc (V): 64.2
Short-circuit current Isc (A): 5.96
Voltage at maximum power point Vmp (V): 54.7
Current at maximum power point Imp (A): 5.58
Temperature coefficient of Voc (%/deg.C): -0.27269
Temperature coefficient of Isc (%/deg.C): 0.061745

Model parameters
Light-generated current IL (A): 6.0092
Diode saturation current I0 (A): 6.3014e-12
Diode ideality factor: 0.94504
Shunt resistance Rsh (ohms): 269.5934
Series resistance Rs (ohms): 0.37152

Fig. 3 The detailed parameters of the photovoltaic array block

where,
Maximum Power (W) = Power obtained at maximum power point (V_{mp}, I_{mp}).
P_{max} = as $P_{max} = V_{mp} \times I_{mp}$. The default value is 305.226 W.
Cells per module (N_{cell}) = Number of cells per module. The default value is 96.
Open circuit voltage V_{oc} (V) = Voltage obtained when array terminals are left open. The default value is 36.3V.
Short-circuit current I_{sc} (A) = Current obtained when array terminals are short circuited. The default value is 7.84A.
Voltage at maximum power point V_{mp} (V) = Voltage at maximum power point. The default value is 29V.
Current at maximum power point I_{mp} (A) = Current at maximum power point. The default value is 7.35A.
Temperature coefficient of V_{oc} (%/deg.C) = variation of V_{oc} as a function of temperature. The open-circuit voltage at temperature T is obtained as $V_{ocT} = V_{oc}$ (1 + beta_V_{oc} (T–25),
V_{ocT} = open-circuit voltage at temperature T (in degrees C),
Voc = temperature coefficient (in %/degrees C)
T = temperature in degrees C. The default value is -0.27269 %/deg.C.
Temperature coefficient of I_{sc} (%/deg.C) = variation of I_{sc} as a function of temperature. The short-circuit current at temperature T is obtained as Isc_T = Isc (1 + alpha_Isc(T–25),
I_{sc} = short-circuit current at 25 degrees C,
I_{scT} = short-circuit current at temperature T (in degrees C),
alpha_Isc is the temperature coefficient (in %/degrees C), The default value is 0.102 %/deg.C.
T_{cell} (deg. C)
Light-generated current I_L (A) = Current for one module under STC, flowing out of the controllable current source that models the light-generated current. An optimization function determines this parameter to fit the module data. The default value is 6.0092A.

Diode saturation current I_0 (A) = Saturation current of the diode modeling the PV array for one module under STC. An optimization function determines this parameter to fit the module data. The default value is 6.3014e-12A.

Diode ideality factor = Ideality factor of the diode modeling the PV array. An optimization function determines this parameter to fit the module data. The default value is 0.94504.

Shunt resistance Rsh (ohms) = Shunt resistance of the model for one module under STC. An optimization function determines this parameter to fit the module data. The default value is 269.5934Ω.

Series resistance Rs (ohms) = Series resistance of the model for one module under STC. An optimization function determines this parameter to fit the module data. The default value is 0.37152Ω.

D. Boost Converter

Specifications:
V_{in} = Input power voltage
V_{out} = Nominal output voltage
I_{out} = Maximum output current and
Integrated circuit (IGBT) used to build the boost converter; the parameter of the calculation is gotten from the data sheet (IGBT data sheet). If the parameters are known the calculation of the boost converter is done. The Schematic diagram of the boost converter is shown in Fig. 4

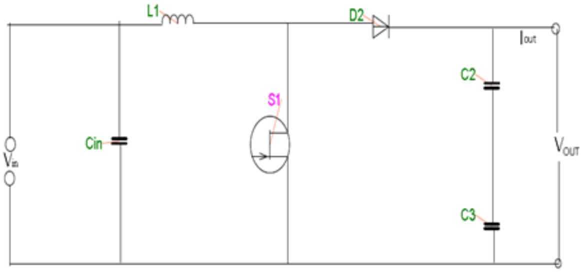


Fig. 4 Schematic diagram of boost converter

From the photovoltaic array parameters, Series connected panel = 5
Parallel connected panel = 66
The output Voltage = Voltage in series + Voltage in parallel
Also, the maximum voltage per cell = 54.7V.
Voltage in series = 54.754.7 $\times 5 = 273.5V$
Voltage in Parallel =$\frac{1}{54.7\times66} = 0.000276V$
The output Voltage = 273.5 + 0.000276 = 273.50027V.
Applying equation (2.8),
$V_R = \frac{1}{1-D} \times V_{dc}$, our duty cycle = 0.5,
Output voltage of the boost converter = $\frac{1}{1-0.5} \times 273.5$
$= 2 \times 273.5 = 547V.$

E. Voltage Source Converter Connected to the Grid

The circuit diagram of voltage source converter is shown in figure 3.6. The parameters of the voltage source main controller is also shown in figure 3.7, while the three level bridge mask for the voltage source is shown in Fig. 5.

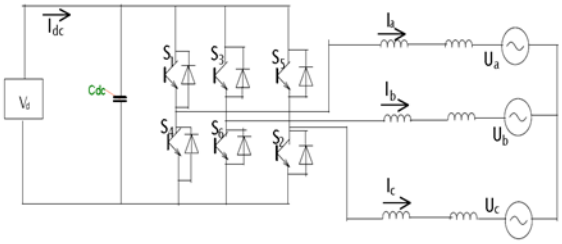
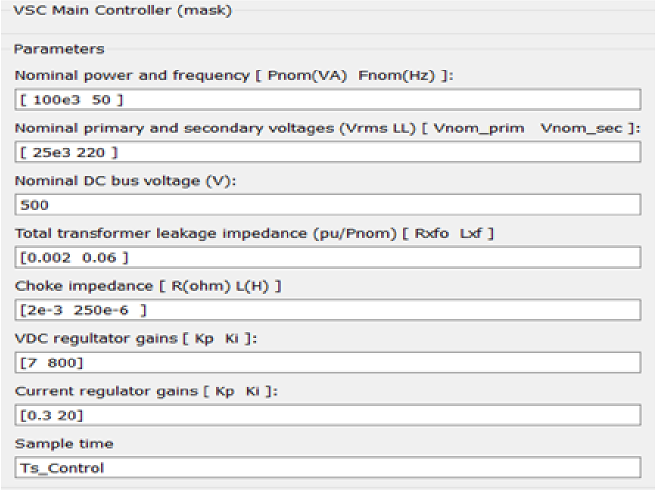


Fig. 5 Circuit diagram of the VSC connected to a three-phase grid


VSC Main Controller (mask)

Parameters

Nominal power and frequency [Pnom(VA) Fnom(Hz)]:
[100e3 50]

Nominal primary and secondary voltages (Vrms LL) [Vnom_prim Vnom_sec]:
[25e3 220]

Nominal DC bus voltage (V):
500

Total transformer leakage impedance (pu/Pnom) [Rxfo Lxf]
[0.002 0.06]

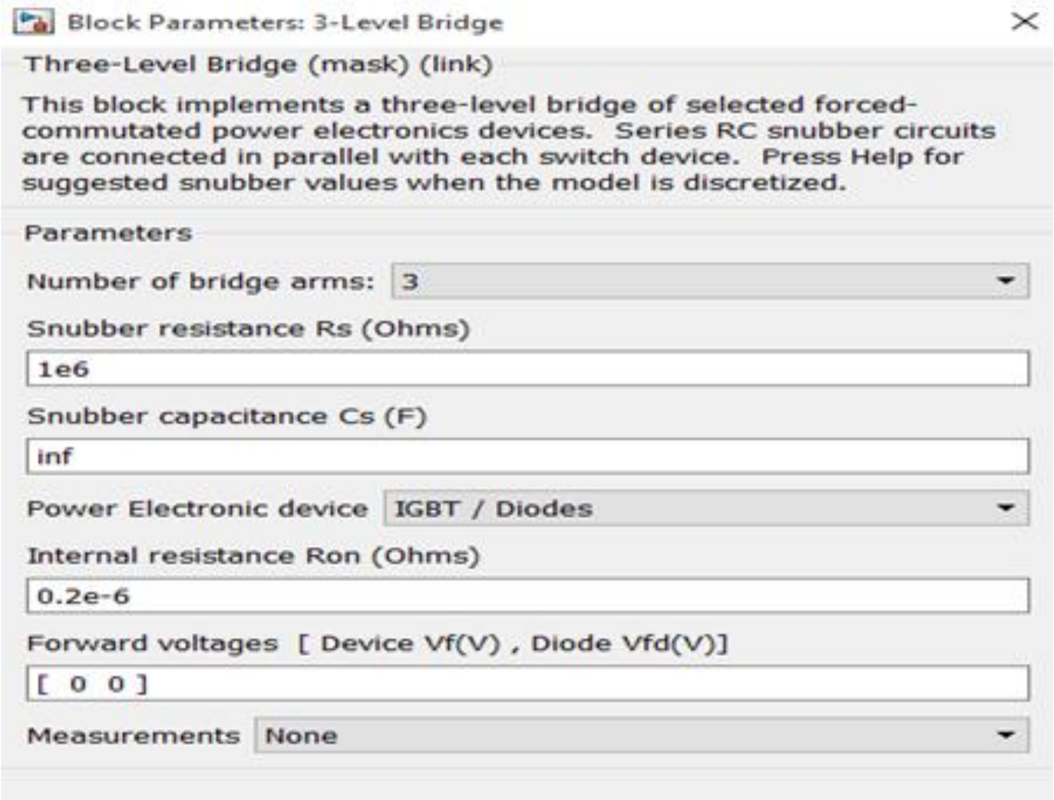
Choke impedance [R(ohm) L(H)]
[2e-3 250e-6]

VDC regultator gains [Kp Ki]:
[7 800]

Current regulator gains [Kp Ki]:
[0.3 20]

Sample time
Ts_Control

Fig. 6 Parameters of Voltage Source Main Controller



Three-Level Bridge (mask) (link)

This block implements a three-level bridge of selected forced-commutated power electronics devices. Series RC snubber circuits are connected in parallel with each switch device. Press Help for suggested snubber values when the model is discretized.

Parameters

Number of bridge arms: 3

Snubber resistance Rs (Ohms): 1e6

Snubber capacitance Cs (F): inf

Power Electronic device: IGBT / Diodes

Internal resistance Ron (Ohms): 0.2e-6

Forward voltages [Device Vf(V) , Diode Vfd(V)]: [0 0]

Measurements: None

Fig. 7 The three level bridge mask

Number of bridge arms determines the bridge topology: one, two, or three arms.

The snubber resistance, in ohms (Ω): Set the Snubber resistance Rs parameter to inf to eliminate the snubbers from the model.

The snubber capacitance, in farads (F): Set the Snubber capacitance Cs parameter to 0 to eliminate the snubbers or to inf to get a resistive snubber. When you are you using a continuous solver you can completely eliminate snubbers,

Select Enable use of ideal switching devices in the Configure parameters section of the Powergui block dialog box. To disable snubbers in all power electronic devices select Disable snubbers in switching devices. Snubbers are enabled in this model.

Discretized the system and simulate power electronic devices with virtually no snubbers by specifying purely resistive snubbers with a very large resistance, thus producing negligible leakage currents. The bridge operates satisfactorily with purely resistive snubbers. Selecting the Tustin/Backward Euler (TBE) discretization method (default solver in the Configure parameters section of the Powergui block dialog box).

III. SYSTEM DESIGN ANALYSIS

Simulation starts with standard test conditions (25 deg. C, 1000 W/m^2).
From t = 0 sec to t = 0.05 sec, pulses to Boost and VSC converters are blocked.
PV voltage corresponds to open-circuit voltage
(Nser x Voc) = 5 x 64.2 = 321V. (1)
The three-level bridge operates as a diode rectifier and DC link capacitors are charged above 500 V.
At t = 0.05 sec,
Boost and VSC converters are de-blocked. DC link voltage is regulated at V_{dc} = 500V.
Duty cycle of boost converter is fixed (D= 0.5 as shown on PV scope).
Steady state is reached at t = 0.25 sec.
Resulting PV voltage is therefore,
PV(v) = (1-D) x V_{dc} = (1 - 0.5) x 500 = 250 V. (2)
The PV array output power = 96 kW
Whereas specified maximum power with a 1000 W/m^2 irradiance = 100.7 kW.

From Scope Grid, phase A voltage and current at 25 kV bus are in phase (unity power factor). At t = 0.4sec, MPPT is enabled. The MPPT regulator starts regulating PV voltage by varying duty cycle in order to extract maximum power. Maximum power (100.4 kW) is obtained when duty cycle is D = 0.454.

At t = 0.6 sec, PV array mean voltage = 274 V as expected from PV module specifications (Nser x Vmp = 5 x 54.7 = 273.5 V).

From t = 0.6 sec to t = 1.1 sec, sun irradiance is ramped down from 1000 W/m^2 to 250 W/m^2. MPPT continues tracking maximum power.

At t = 1.2 sec when irradiance has decreased to 250 W/m^2, duty cycle is D = 0.461. Corresponding PV voltage and power are Vmean = 268 V and Pmean = 24.3 kW.

Again, the MPPT continues tracking maximum power during this fast irradiance change.

From t = 1.2 sec to t = 2.5 sec sun irradiance is restored back to 1000 W/m^2 and then temperature is increased to 50℃ in order to observe impact of temperature increase.

Note that when temperature increases from 25℃ to 50℃, the array output power decreases from 100.7 kW to 93 kW.

IV. SIMULATION RESULTS

Having known that frequency is number of cycles per second. Hence, F=1/T. Taking case study of varying the frequency of the grid in a fluctuating mode and monitor on the scope of the grid and voltage source inverter output on MATLABSIMOUT environment to view the variations, also, seeing that it meets the condition of synchronizing two generators. According to Zeyad et al (2018), frequency in a power system is a real-time changing variable that indicates the balance between generation and demand. The system operation in Nigeria power system is responsible for maintaining the frequency response of the power system within acceptable limits. Two main levels that defines this limits are operational limit which is equal to ± 0.2Hz (i.e. 49.8Hz to 50.4Hz), and the statutory limit which is ±0.4Hz (i.e. 49.6 and 50.4Hz). Under a significant drop in the frequency (i.e. below 49.2Hz), a disconnection by low- frequency relays is provided for frequency control of both generators and demand. Taking a case study of varying frequency at 49.6, 49.8, 50, 50.2, and 50.4Hz, the Nigerian standard frequency is 50Hz likewise the model system. The Simulation results are done with time at 0.05sec.

A. Simulation Result when the Grid Frequency Fluctuates to 49.6Hz

Figure 8 is the graph of the Grid Phase voltage at 49.6Hz and Fig. 9 shows the graph of the inverter output of the same frequency before interfacing. Figure 10 shows the output voltage and frequency at 49.5Hz of the synchronized grid to inverter. Checking the number of oscillations, we can see that the system adjusts and obtain the exact frequency of the grid on the VSC output at a steady voltage.

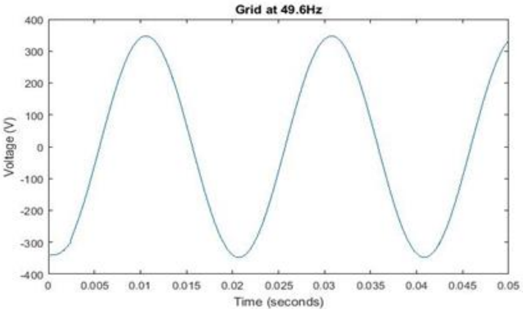


Fig. 8 The Grid phase Voltage at 49.6Hz

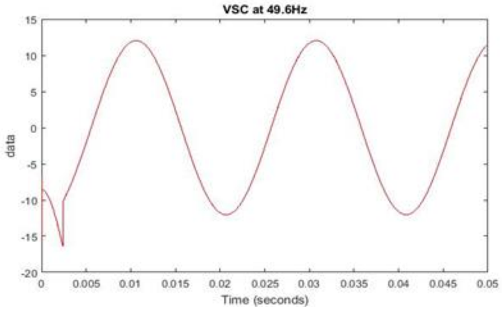


Fig. 9 VSC waveform at 49.6Hz

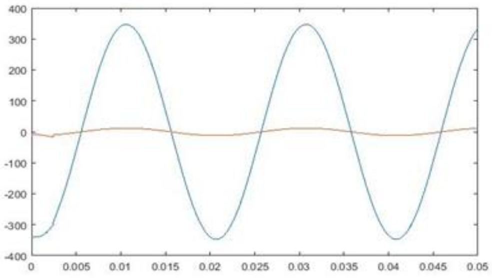


Fig. 10 Waveform of inverter voltage Synchronized to Vgrid at 49.6Hz

B. Simulation Result when the Grid Frequency Fluctuates to 50Hz

The system adjusts to give stable frequency on the inverter output just as in 49.8Hz. Figure 11 shows the grid voltage and frequency at 50Hz and Fig. 12 shows the inverter output at the same frequency and voltage. Figure 13 shows the output voltage and frequency at 50Hz, of the synchronized grid to inverter. Checking the number of oscillations, we can see that the system adjusts and obtain the exact frequency of the grid on the VSC output at a steady voltage.

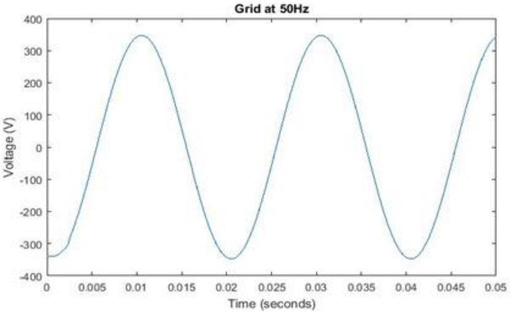


Fig. 11 The grid phase voltage at 50Hz

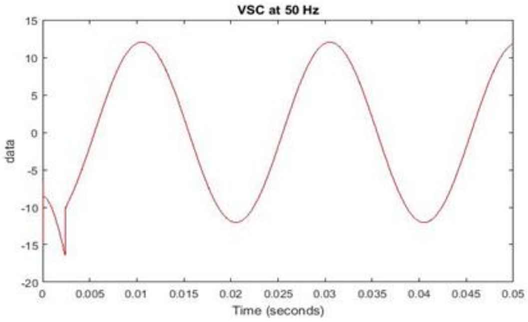


Fig. 12 The waveform at 50Hz

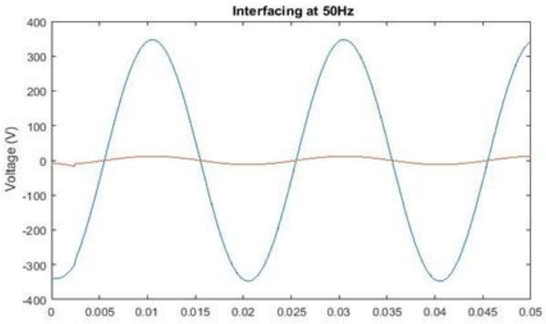


Fig. 13 Waveform of inverter synchronized to Vgrid at 50Hz

C. Simulation Result when the Grid Frequency Fluctuates to 50.2Hz

The system gives a stable frequency on the inverter output just as in 50Hz. Figure 14 shows the grid voltage and frequency at 50.2Hz and Fig. 15 shows the inverter output at the same frequency and voltage. Figure 16 shows the output voltage and frequency at 50.2Hz, of the synchronized grid to inverter. Checking the number of oscillations, we can see that the system adjusts and obtain the exact frequency of the grid on the VSC output at a steady voltage.

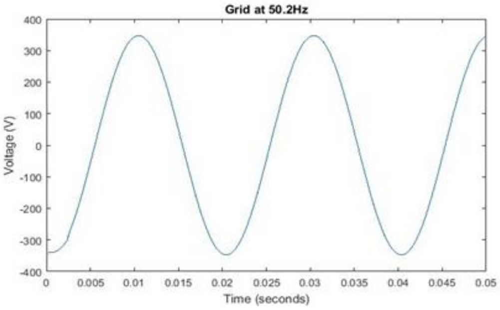


Fig. 14 The Grid phase voltage at 50.2Hz

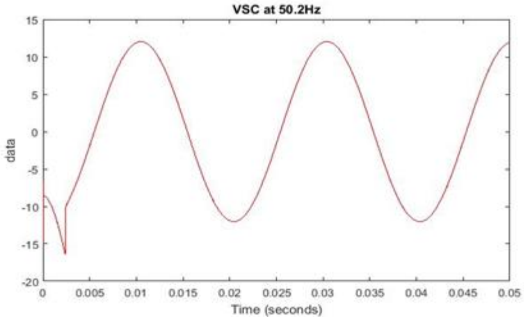


Fig. 15 The VSC waveform at 50.2Hz

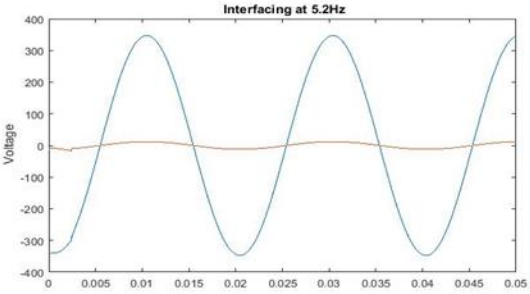


Fig. 16 Waveform of inverter synchronized to Vgrid at 50.2Hz

D. Simulation Result when the Grid Frequency Fluctuates to 50.4Hz

The system gives a stable frequency on the inverter output just as in 50.2Hz. Figure 17 shows the grid voltage and frequency at 50.4Hz and Fig. 18 shows the inverter output at the same frequency and voltage. Figure 19 shows the output voltage and frequency at 50.4Hz, of the synchronized grid to inverter. Checking the number of oscillations, we can see that the system adjusts and obtain the exact frequency of the grid on the VSC output at a steady voltage. The same as other results obtained. The spikes noticed in the voltage source waveform between 0 - 0.005 seconds is as a result of transient state, which can be negligible.

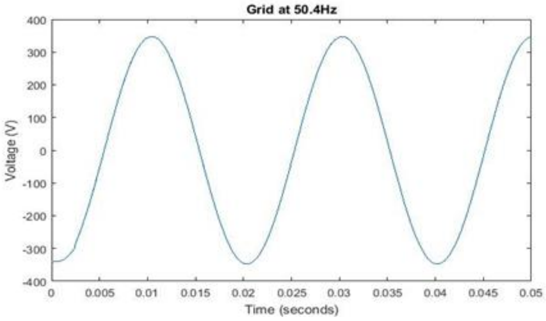


Fig. 17 The Grid phase voltage at 50.4Hz

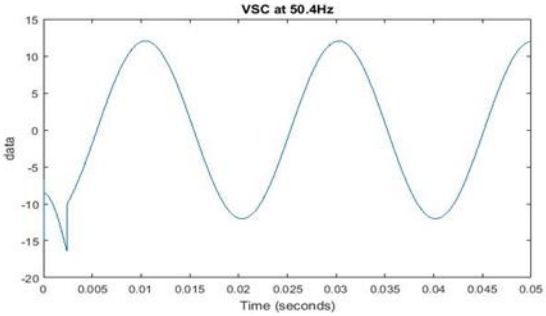


Fig. 18 The VSC waveform at 50.4Hz

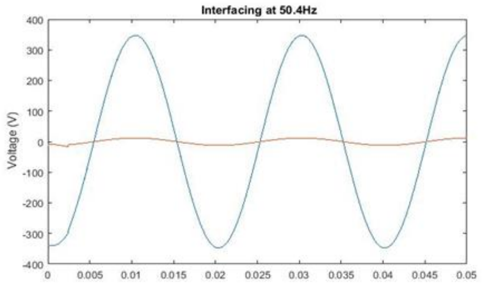


Fig. 19 Waveform of inverter synchronized to Vgrid at 50.4Hz

E. Summary of Findings

First considering ideal case condition in Fig. 10 shows the measurement positions of the Inverter Voltage (Vinv) and Vgrid. The Vinv is measured at the output terminal of the LC filter and the Vgrid is measured across the grid source and the inductor which act as the transmission line.

A case study was taken within the statutory frequency limit while the interfacing graphs in the simulation results shows the sinusoidal waveforms of the Vgrid and Vinv of the simulated model for the solar irradiance of $1000Wm^{-2}$ and temperature of 25℃. It is observed that the Vinv waveform is in phase with the Vgrid waveform to every frequency fluctuation within the statutory frequency ranger. This implies that the inverter has synchronized to the grid.

CONCLUSION

The simulation of grid tied inverter presented here shows that the Vinv and Vgrid synchronized also, within the grid statutory frequency range. The Simulink model met the conditions necessary for synchronizing two generators. When customers generate excess energy from their solar panel, they can easily maximize profit by selling it to their nearby neighbors leveraging on the grid or selling it to the grid.

REFERENCES

[1] Sambo, A.S (2009): "*Strategic Developments in Renewable Energy in Nigeria.*" International Association for Energy economics, Vol. 16, pp 9-15

[2] Akinboro, F.G, Adejumobi, L.A and Makinde, V. (2012): "*Solar energy installation in Nigeria; Observations, prospects, problems and solution*" Translational Journal of Science and Technology Vol. 2, pp 73-84.

[3] Chineme (2017): "*/nigeria's-presidential-initiative-to-provide-solar-systems-to-20,000 homes/*", www.offgridnigeria.com/

[4] Okechukwu, N. (2017). www.punchng.com/kaduna-communities-record-two-yearuninterrupted-power-supply-fg/amp/ m

[5] Akinosun G, (2017): "*Solar energy: Nigeria's best shot at eradicating its electricity problem*" http//:techpoint.africa/2017/09/06/solar-energy-nigerias-eradicating-electricity-problem/