

PQ-Control Strategy for Distributed Power Generation Systems (DG) Connected to the Grid

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ABSTRACT

A great number of renewable energy generations such as fuel cells, photovoltaic and wind power generations can be directly tied to grid forming distributed generation systems. These interconnections often cause problems with control, protection, security and safety. It is therefore crucial to employ adequate control and synchronization systems to arrest the challenges between the grid and the distributed generations. This paper implements a control strategy for Distributed generation containing photovoltaic renewable energy generation. The control strategy consists of active and reactive control for distributed generation systems. The challenge of grid synchronization was addressed by implementing phase lock loop (PLL) to synchronize the frequency and phase of DG with the main grid. Simulation results have proven that the implemented control strategy works well for distributed generation containing renewable energy generations.

Keywords: Distributed Generation (DG), Photovoltaic (PV) cell, PV generator model, PI controller, Power flow control.

1. INTRODUCTION

Distributed Generation (DG) systems implies a range of technologies that produce electrical energy around where it will be utilized, such energy sources include solar power, wind energy and combined heat and power. Distributed Generation (DGs) may supply a single entity, for example a household, company, or may be a part of larger unit known as a micro grid, for example a large campus, major industry facilities or a military base. When coupled to the grid utility's low voltage distribution lines, DGs can deliver reliable, clean power to more consumers with decreased electricity losses along the transmission and distribution lines.

DG technologies consists of a wide range of technologies, such as wind power, micro turbines, internal combustion engines, gas turbines, photovoltaics (PV), fuel cells, and storage systems. However there are challenges in controlling a potentially huge number of DGs, and operating the

network safely and efficiently. This challenge can be partially addressed by the proper implementation of control schemes.

In order to improve the power supply, Renewable energy sources are connected to the existing power generation system to form a Distributed Power Generation Systems (DPGs). As more DGs are connected to the system, the power system begins to experience instability and in severe situations, power outage. System instability is mainly caused by problems with the synchronization of these systems to the utility network and/or improper controls of DGs in place [1].

The objective of this work is to enhance the synchronization of the DGs to the grid network so as to increase the stability of the grid in order to reduce system failure to a very reasonable low level.

Grid-connected PV controller systems are broadly divided into two categories: Input-side controllers and grid-side controllers. The Input-side controllers mainly consists of MPPT with the main property to extract the maximum power from the input source. On the other hand, Grid-side controllers include control of voltage, current and active & reactive power generated to the grid.

This work is based on implementation of active & reactive (PQ) control based on Rivers State University (RSU-Nigeria) substation distributed network integrated with solar PV systems.

2. DISTRIBUTED GENERATION AND HARDWARE STRUCTURES FOR PV SYSTEM

This section presents literatures on distributed generation and hardware structures for PV systems.

2.1. Distributed Generation

Usually, distributed generations (DGs) denote environment friendly renewable power generation devices such as solar energy, wind energy, fuel cells and others which are often located near the loads. DGs have been proven to improve the quality of power and system reliability mainly due to the fact that they decrease the cost of construction and maintenance, decrease power system losses in transmission and help to improve the system efficiency. Researchers have shown that to a large extent, DGs are exempted from faults in transformation and transmission system which in turn improves power system reliability and quality [1].

A renewable energy technology that has gained huge acceptance over the years as a way of sustaining and continuously improving the standards of living devoid of causing harm to the environment is the Solar (PV) technology. Solar energy system also known as Photovoltaic generation (PV), simply based on the photo-voltaic effect of PV cells in converting solar energy to DC power, has features of environmental-friendly, ease of maintenance, zero-emission, and small cost. PVs mainly have two operation modes which are: (1) islanding mode, where electrical systems incorporated with PV are not tied to public power grid, and they are commonly used in areas far-off from the public power grid, for example an island; (2) parallel-in mode, that PV is paralleled to public power grid. This mode can use photovoltaic generations as mass power production and is the most used mode in the world [2-3].

2.2. Hardware Structure for PV Systems

A two-stage energy conversion system is applied in the PV system. The first stage consists of a PV array with a DC-DC converter, this helps to boost the comparatively low PV system voltage to equal the input voltage rating of the inverter. The second stage comprises of a voltage source converter (VSC) tied to the power grid through an L-filter plus a step-up transformer, to raise the voltage of the inverter in order to match the rated voltage of grid [4]. The MPPT for the PV is implemented on the boost converter for extracting maximum power under normal condition [5].

In Nigeria, quite a number of research works have been conducted with the aim of solving the electricity challenge in the country. One of such works is seen in the literature by [6] who presented a passageway to a completely sustainable power supply for Nigeria in the nearest future [7]. On another scale,[8] did some works on the poverty of a country's energy. They studied into the implications of smart strategies and structure in order to realize a smart Nigerian electrical energy network. A lot of researchers have also done work on the techno-economic study of the applications of solar and wind energies in Nigeria [5].

[10], stated in their work that apart from the low efficiency, the major drawback of distributed generation systems (DGs) based on both wind and solar energies is their controllability. As a result, their connection to the utility network can lead to instability of the grid and in some cases even failure, if these systems are not properly controlled. Furthermore, [11] states that the standards for connecting the renewable systems to the utility grid are stressing progressively more the ability of the DGs to operate over short grid instabilities. Consequently, the control strategies applied to DGs have become of high interest.

[13], discussed the controls of a DG, hardware structures for the DGs, control structures for the grid-side converters and control strategies under faults. It has been established that Grid synchronization algorithms plays a major role and influences the control of a DGs on normal and faulty grid conditions. [13].

2.3. Photovoltaic Generator Model

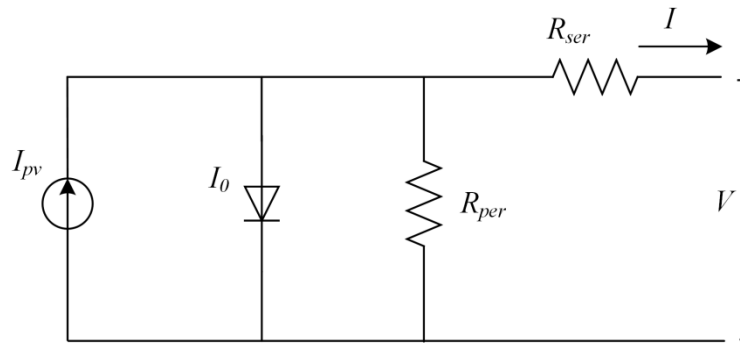


Figure 1: Equivalent circuit of Single cell PV

Figure 1 shows the equivalent circuit of a single cell PV. The simplified PV generator model is given by equation (1).

$$I = I_{pv} - I_0 [e^{-qV/akT} - 1] \quad (1)$$

I , denotes the net-current from a unit solar cell; I_{pv} denotes the total current produced by the solar irradiation; " I_0 " denotes the reverse saturation current (leakage current) of a diode; " a " is the diode's ideality factor, which signifies the modification necessary to meet the theoretical P-N junction characteristics of a solar cell to the measured values; T denotes the temperature in Kelvin of a diode; q is an electron charge given by 1.602×10^{-19} C; and k denotes the Boltzmann constant given by 1.380×10^{-23} J/K.

Equation (1) is insufficient to define the characteristics of an applied solar cell. The insertion of a series & parallel resistance values alongside the observation of the terminal voltage makes the model ideal for the practical conditions.

$$I = I_{pv} - I_0 \left[\exp\left(\frac{V + R_{ser}I}{V_{ta}}\right) - 1 \right] - \frac{V + R_{ser}I}{R_{per}} \quad (2)$$

As above-mentioned, PV systems generally have low voltage inputs provided by the photovoltaic panels, however several of such units can be interconnected to attain the requisite power and voltage. Typically, power conditioning systems, such as dc-dc converters, inverters and the likes, are often essential to supply normal consumer load demand or send electrical energy into the utility grid. In order to smoothen the produced current, LCL filters are usually installed between these inverter systems and the grid network. In addition, input and output power isolation for DGs is a prerequisite in many nations. There are two ways this isolation can be achieved viz; a) dc-dc converter b) isolation transformers next to the dc-ac stage. In this work, we have implemented the isolation transformer after the dc-ac stage.

2.4. Maximum power point tracking (MPPT)

A solar cell generally has very low efficiency; nevertheless, if the PV system and the load can be harmonized accurately, the efficiency will be improved. One of such methods is called the maximum power point tracking (MPPT). In the P-V & I-V curve, once the output voltage rises, the system power increases first and then drops, therefore there exists a voltage conforming to the maximum power output. This particular voltage is often spotted and sustained by applying a special kind of converter known as a boost converter whose duty-cycle is regulated by the MPPT algorithm. Perturb and Observe (P&O) method [8] is used to achieve the MPPT, and the algorithm is based on the calculation of the current & voltage of the PV array. For varying values of temperatures and irradiance, the PV system will reveal diverse characteristic curves with each curve having its MPPT. The peak voltage equivalent to this point is delivered to the converter as the reference voltage.

2.5. PI Control

A standard PI control methodology is applied for inverter control purpose that involves the usage of the comparative gain and integrator for regulating the physical system's specific state. The outer loop of the proposed controller is the active power flow control. The error signal of the system is multiplied with the reference voltage to find the average active power reference.

The demanded voltages u_d and u_q are existing in the rotating reference frame, which requires to be transformed into abc voltages by applying the back-reference frame transformation conversion process. The conversion from d_q components to $\alpha\beta$ can be achieved using (3).

$$\begin{pmatrix} V_\alpha \\ V_\beta \end{pmatrix} = \begin{pmatrix} \sin \theta & \cos \theta \\ \cos \theta & -\sin \theta \end{pmatrix} \begin{pmatrix} V_d \\ V_q \end{pmatrix} \quad (3)$$

Having obtained the stationary reference frame components, the three-phase components are calculated using;

$$V_a = V_\alpha \quad (4)$$

$$V_b = \frac{-V_\alpha}{2} - \frac{\sqrt{3}}{2} V_\beta \quad (5)$$

$$V_b = \frac{-V_\alpha}{2} - \frac{\sqrt{3}}{2} V_\beta \quad (5)$$

$$V_c = \frac{\sqrt{3}}{2} V_\beta - \frac{-V_\alpha}{2} \quad (6)$$

Additionally, the gating signal for the three-pole of the inverter is found by.

$$m_{a,b,c} = \frac{2V_{a,b,c}}{V_{dc}} \quad (7).$$

The modulating signal then pushes the SVPWM of the inverter to achieve the anticipated voltage at the separate poles of the inverter.

2.6. Power flow control and PQ controller design

In the grid-tied operational mode, the foremost role of a Distributed Generation is to produce the real & reactive power, such that the real power reference will be obtained from the grid energy management controller. The real & reactive power will be controlled through current regulation or voltage regulation [14].

In the real & reactive power (PQ) control, the variables controlled by the electrical converter are the real and reactive components supplied to the grid, and it is preferred to meet the real and reactive power reference values. The 3-phase produced voltage and current in the abc frame of the inverter is denoted by:

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} m_a \cos(\omega t) \\ m_a \cos(\omega t - \frac{2\pi}{3}) \\ m_a \cos(\omega t + \frac{2\pi}{3}) \end{bmatrix} \quad (8)$$

Here, m_a is the peak value of the voltage and current, ω is the angular frequency. The 3-phase stationary component system can be converted to the d-q rotating arrangement by applying transformation model proposed by Park and it is represented as:

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\ \sin(\omega t) & \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} \quad (9)$$

Having applied the Park's transformation, the real & reactive power can be represented by:

$$P = \frac{3}{2} \cdot (v_q i_q - v_d i_d) \quad (10)$$

Thus the produced current from the inverter system after applying Park's transformation model, can be evaluated. In the current regulated system, the real power control loop produces the d-axis reference current (i_{d_ref}) and the reactive power control loop produces the q-axis reference current (i_{q_ref}) in the synchronous frame [13].

2.7. PLL Technique

In recent times, the PLL system is the advanced method used to extract the phase angle of the voltages of the grid system. The PLL system is applied in d-q synchronous reference frame, and the diagram is shown in Figure 2. As noticed, this structure requires transformation of its coordinate form $abc \rightarrow d-q$.

As noticed, this structure requires transformation of its coordinate form $abc \rightarrow d-q$, and also the lock is complete by setting the reference U_d^* to nil. A regulator device, commonly PI, is used to control this variable, and the output of this regulator is the frequency of the grid. After integrating the grid frequency, the grid voltage phase angle is found, which is fed back into the $\alpha\beta \rightarrow dq$ transformation module to convert into the synchronous rotating reference frame.

This algorithm has a better elimination of utility harmonics and other kinds of disorders, however, there is need to overcome grid imbalance by implementing additional improvements [4]. For the unsymmetrical voltage faults, the second harmonics made by the negative sequence will spread through the PLL device and will be replicated in the extracted phase angle. To beat this, totally different filtering techniques are required such that the negative sequence is filtered out. As a result, during unstable conditions, the 3-phase d-q PLL structure can approximate the phase angle of the positive sequence of the utility voltages.

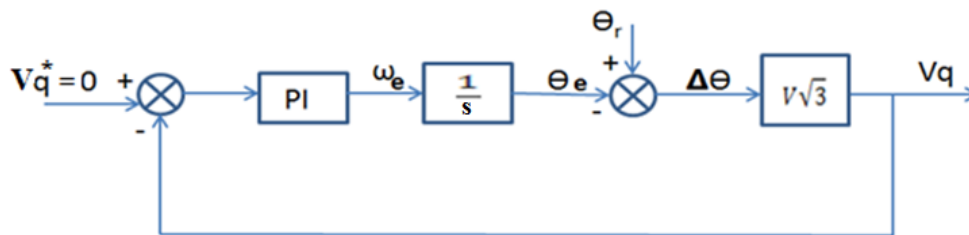


Figure 2: Basic diagram of the PLL

The transfer function of the PI controller is given by:

$$C_{p2}(s) = k_{p2} + \frac{k_{i2}}{s} \quad (11)$$

The open loop transfer-function (G) is expressed as follows:

$$G(s) = \frac{V_{qr}^*(s)}{V_{qr}(s)} = -V\sqrt{3} \cdot \left(\frac{k_{p2} + \frac{k_{i2}}{s}}{s} \right) \quad (12)$$

The closed-loop transfer function (H) is expressed as follows:

$$H(s) = \frac{G_s}{1+G_s} = \frac{-V\sqrt{3} \cdot (k_{i2} + k_{p2}s)}{s^2 - V\sqrt{3} \cdot k_{p2}s - V\sqrt{3} \cdot k_{i2}} \quad (13)$$

Further evaluating (13), we obtain (14):

$$\begin{cases} k_{p2} = \frac{-2z\omega_{i2}}{V\sqrt{3}} \\ k_{i2} = \frac{-\omega_{i2}^2}{\sqrt{3}} \end{cases} \quad (14)$$

Where $\omega_{i2} = \frac{1}{T_{i2}}$ is the cut-off frequency, T_{i2} is the time response of the system of and z is the damping factor. For this work, we used 10 ms ($T_{i2} < T_{i1}$), $z=1$ (to eradicate the oscillations) and we obtained $\omega_i = 100$ rad/s. This delivers: $k_{p2} = -0.5$ and $k_{i2} = -25$

4. ADOPTED MODEL FOR IMPLEMENTATION

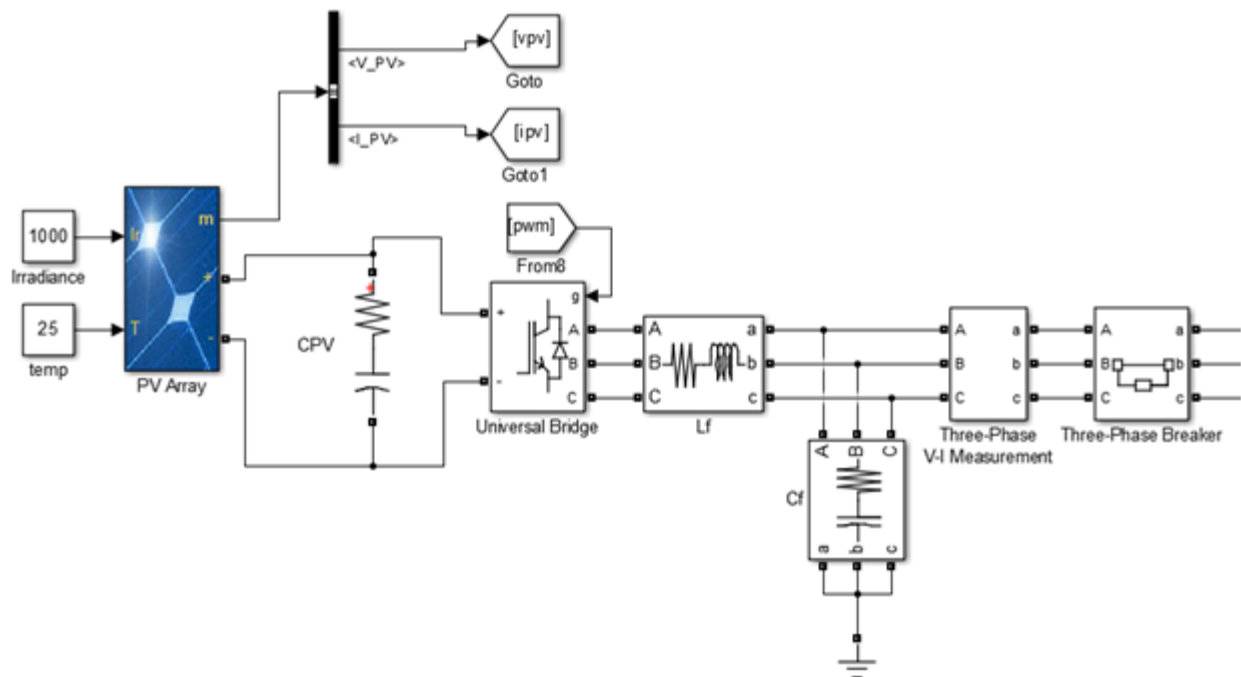


Figure 3: Simulink circuit design (PV and inverter side)

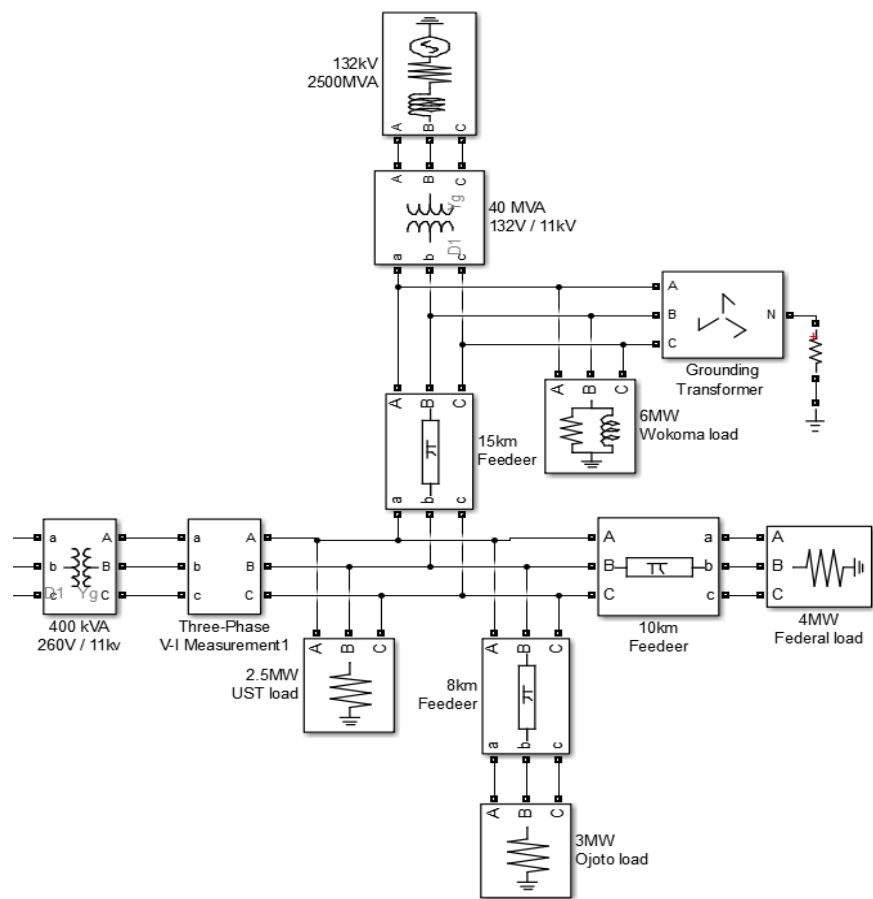


Figure 4 Simulink circuit design (grid side)

4.1. Model parametersa. Grid Loads

Table 1: Grid Load Parameters

Substation	Estimated Capacity	Estimated Line Length
Wokoma	6MW	15Km
RSU (UST)	2.5MW	-
Ojoto	3MW	8Km
Federal	4MW	10Km

Table 2: Power transformers parameters

Equipment	Rating
Step-up transformer	400KVA, 260/11KV
Step-down transformer	40MVA, 132/11KV

Inverter parameters

PV Prated =213kW, Vin = 250V, 1Soltech 1STH-215-P; 27 series modules; 4 parallel strings, temp =25°C, Irradiance =1000
 RCL filter Rf =770ohm Lf =7.7H

4.2. Simulation Results

The model for this work is built in the MATLAB/SIMULINK environment. The components comprises of a PV array, a converter, an inverter, an LCL filter, the PI and PLL controllers and the utility grid. The control algorithm of the inverter is designed in the MATLAB programming environment. Therefore as a way to test the performance of the PQ control, we varied P_ref on time (t) as follows:

- For t = [0.2] s, P_ref=10 kW
- For t = [0.2] s, P_ref=15 kW
- For t = [0.2] s, P_ref=12 kW

This is represented in fig 8.

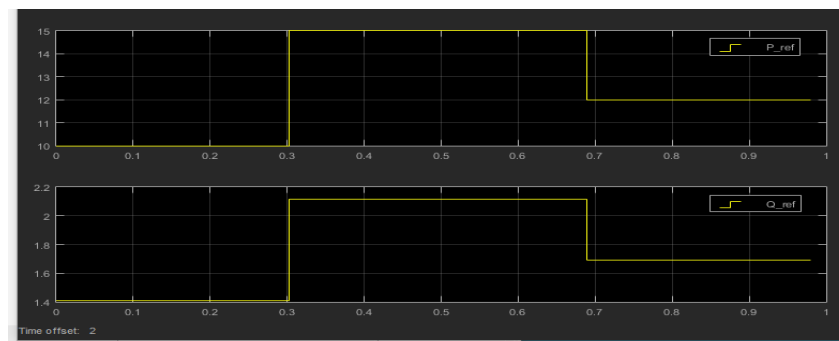


Figure 5: Active & reactive power references (P_ref & Q_ref)

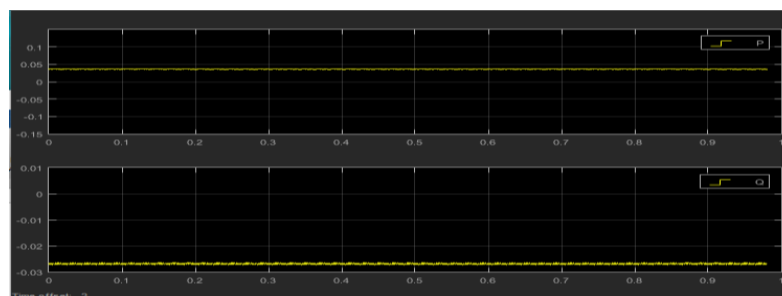


Figure 6: Active and reactive simulated power curves

5. IMPLEMENTATION OF THE V-DISPARITY MODULE AND RESULTS

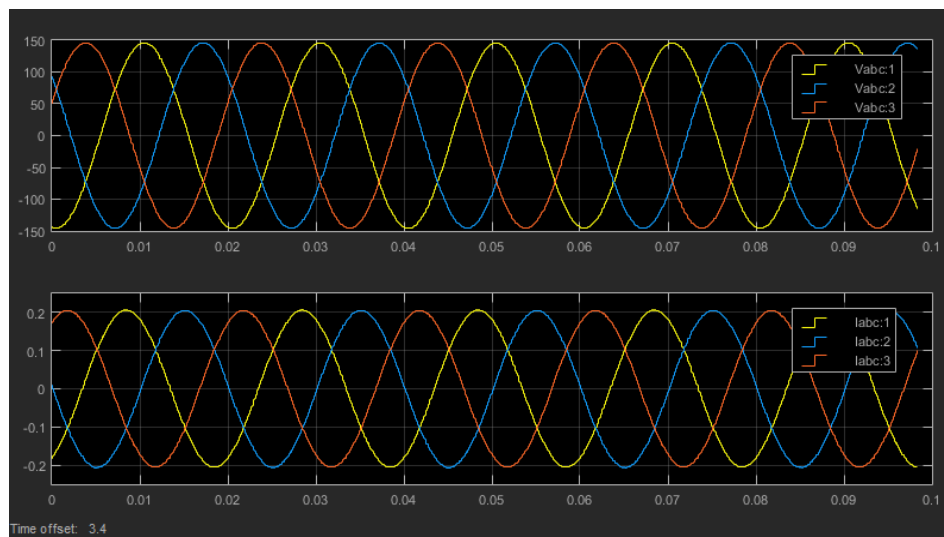


Figure 7: Three-phase inverter voltage and current

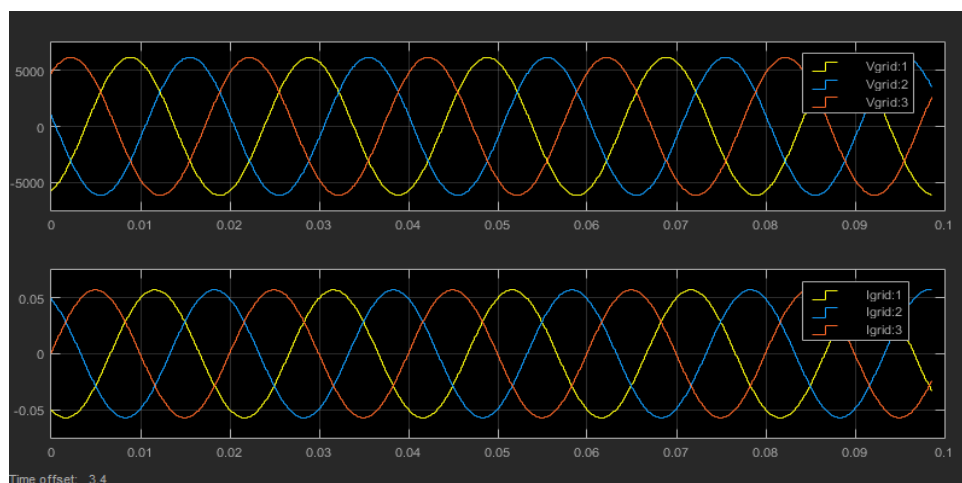


Figure 8: Three-phase grid voltage and current

In figure 8, the first graph shows the three-phase grid voltages. The colours; yellow, blue and brown indicates phase voltages 1, 2 and 3 respectively. The second graph shows the three-phase grid currents. The colours; yellow, blue and brown indicates phase currents 1, 2 and 3 respectively.

6. DISCUSSION

In this work, a PQ controller is developed for a detailed PV model with inverter interconnected to DGs. The use of PQ control guarantees that DGs can produce certain power in accordance with real and reactive power references. The PQ controller is developed with PI controllers where the artificial bee colony (ABC) is to adjust the PI parameters. Tuning PI controller parameters can be tedious and time-consuming, and to avoid such difficulty in this work, we used a heuristic method, ABC, to search for the optimal parameters. In contrast with manually-tuned parameters, ABC-tuned parameters have improved performance in terms of percentage of over-shoot and steady-state errors.

7. CONCLUSION

Similar to V-f and master-slave controls, the proposed control strategy have the capacity to operate without any online signal communication between DGs. This makes the operation economical and quicker in response to changes in load. The results

acquired from the simulation, indicate that the proposed controller is efficient in the performance of real & reactive power tracking for grid-connected PV systems. Phase Lock Loop (PLL) is applied in this work to synchronize frequency and phase of the DG with the grid system.

Recommendations

To completely exemplify the intricacy of the Distributed Generation systems, future work should include the improvement of hierarchical controllers for power systems comprising of numerous DGs and energy storage system.

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Conflict of Interest

The author declares that there are no conflicts of interests.

Data and materials availability

All data associated with this study are present in the paper.

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