Plug and Play control of Inverter-interfaced DERs for Power Management in Smart Grid

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Abstract

Productive and compelling utilization of sustainable energy resources, decentralized power generation, and energy storage can possibly take care of worldwide issues, such as the unavailability of energy and environmental change. A promising answer for interconnecting these Distributed Energy Resources (DERs) with the utility grid is the Microgrid. A key issue is the manner by which parallel inverters are being controlled in islanding mode and in grid-connected mode in order to operate these DERs at their maximum efficiency contributing power to electrical networks. This paper introduces a control strategy for productively working at least two single-phase parallel inverter-connected Distributed Energy Resources without any physical communication between them. This study will demonstrate the Photovoltaic (PV) interface of the microgrid under varying conditions, such as significant fluctuations in radiation levels, implementation of Maximum Power Point Tracking (MPPT), localized control for dynamic active power, coordinated dynamic control of active and reactive power with the decentralized operation, and multi-level control functionality of the PV source in conjunction with other microgrid sources and variable power demands. Simulation results will recommend the best control strategy for a single inverter's active power control and voltage level.

Keywords—MPPT, Distributed Energy Resources, Power control, Hierarchical Control, Microgrid, Inverter, Photovoltaic, Renewable Energy Source

1 Introduction

These days, sustainable power sources, for example, wind, solar energy, wave tidal, and energy components, assume imperative parts in energy regions. The greater part of the sustainable power sources is included AC sources with variable frequency, (for example, wind turbines), DC sources, (for example, solar PVs), or AC sources with high frequency, (for example, wind gas turbines). The converters (DC/AC), also called inverters, are expected to attach the grid with the mentioned sustainable power sources [1]. Even though sustainable power sources are very well known, inverter control still faces a few difficulties when joining networks. For instance, sustainable power sources, such as PV panels and wind power are not steady energies in daylight conditions or various breeze conditions; the current infused into the grid to be perfectly sinusoidal to retain network stability and network agreeable [1]; the Grid variation (frequency variation or voltage variation), even though the influence the grid soundness. Figure 1 displays the labeled block diagram of the PV inverter system, which incorporates PV arrays, support inverter, MPPT, DC to DC boost converter, and droop control block.

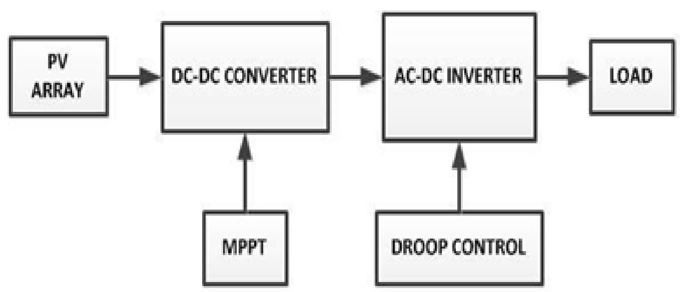


Fig. 1: Integrated PV system

ISSN: 2523-0379 (Online), ISSN: 1605-8607 (Print)
DOI: https://doi.org/10.52584/QRJ.2201.03

The boost converter is responsible for managing the power flow by regulating the voltage at the PV output. Additionally, the stability of power and voltage is maintained through the control of this converter. As a result, large energy storage systems are not required on the inverter's DC side to anticipate extreme scenarios where the storage system might fail in terms of power management [3].

The PV generation connected to this system effectively balances load demand, as opposed to operating in either load-driven or source-driven modes. The power produced by the PV arrays is smoothed by the boost converter, which then transfers this power to the AC bus via an enhanced DC-link capacitor voltage and droop control. This approach ensures the PV generator's functionality through AC bus voltage regulation, thereby improving the stability, reliability, and resilience of islanded microgrids [3].

The inverters used for grid interfacing are broadly categorized into two types: Current Source Inverters (CSI) and Voltage Source Inverters (VSI). Additionally, inverters based on control mechanisms can be classified as Voltage Controlled (VC) and Current Controlled (CC), as shown in Figure 2.

In a VSI, the DC side functions as the voltage source for the inverter. VSIs include a capacitor in parallel with the input, while current source inverters (CSIs) feature an inductor in series with the DC input. In a CSI, the DC source operates as a current source for the inverter [4].

A microgrid may include an assortment of inverters-(interfaced Distributed Energy Resources, for example, photovoltaics system, wind turbines, fuel cells, micro-turbines, energy storage devices, (for example, batteries supercapacitors) and controllable loads [2]. A promising answer for interconnecting distributed energy resources with the network is the microgrid a case of which is appeared in Figure 3.

In the micro-grid system, the output reactive power and active power of the inverter are calculated as below, respectively.

$$P = \frac{V^2 cos\phi_z - VV_{com} cos(\phi + \phi_z)}{z} \tag{1}$$

$$P = \frac{V^2 cos\phi_z - VV_{com} sin(\phi + \phi_z)}{z} \tag{2}$$

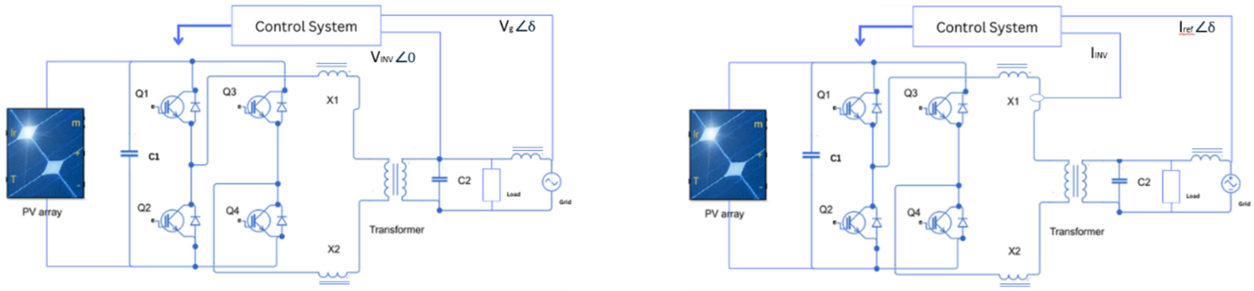
Where V is the inverter's output voltage, ϕ_z is the impendence angle, ϕ is the phase angle of the inverter's output voltage, and V_{com} is the bus voltage of the microgrid [5].

From the control and communication perspective, the microgrid is the exceedingly best system. It is essential to manage control for local loads while also efficiently and accurately regulating all converters, especially when the microgrid operates in islanded mode. This mode of operation ensures an uninterrupted power supply to local loads during grid outages. The performance of the islanded microgrid is governed by IEEE Standard 1547.4. With an expanding number of Renewable Energy Recourses (RES) applications, working parallel, near one another few km, and with created islanded operational mode, the MGs become the perfect solution for Reintegration.

Grid Tied Inverter (GTI) is used to exchange AC power coming productivity, which is the ability to inject power from the PV array and transmit that power into the grid with the most between local load and grid. GTI is required to have high minimal power losses. Other than the capacity of full PV power extraction, the ideal grid-tied PV inverter is additionally required to agree to all applicable grid codes and regulations [7]. The estimation of energy reserves in the distribution grid using a smart grid-enabled Conservation Voltage Regulation (CVR) approach has been investigated by Singh and S. Singh [6].

To achieve higher energy reserves, CVR is implemented with more stringent voltage regulation in conjunction with PV systems by maintaining bus voltages within a specified range. The additional reactive power support is provided by PV inverters, which are managed using a droop control technique. The PV inverter injects the droop-controlled reactive power within limits during instances of low voltage violations. The impact of inverter losses during reactive power support has also been analyzed. It is concluded that the CVR operation combined with the PV system results in a greater reduction in energy consumption, peak load demand, and system losses within the ANSI voltage range compared to CVR alone [6].

M. Metcalfe, S. Nowak, W. Eberle, and L. Wang [8] introduces a reactive power control technique for PV inverters that is designed to be adaptive. The proposed PI controller adjusts the reactive power injection of the solar inverters in real time to regulate the voltage at the Point of Common Coupling (PCC) to a desired value. This voltage control strategy effectively drives the voltage at the PCC to specified target levels. The performance of this method was evaluated using the IEEE 34 test feeder under various power injections and PV inverter ratings. P. Monica, M. Kowsalya, and K. Subramanian [9] examine the droop-based decoupling control of a neutral point clamped 3-level inverter in the islanded method of activity of microgrid. The



(a) VSI, Voltage Controlled (b) VSI, Current Controlled

Fig. 2: VSI, Voltage/Current controlled

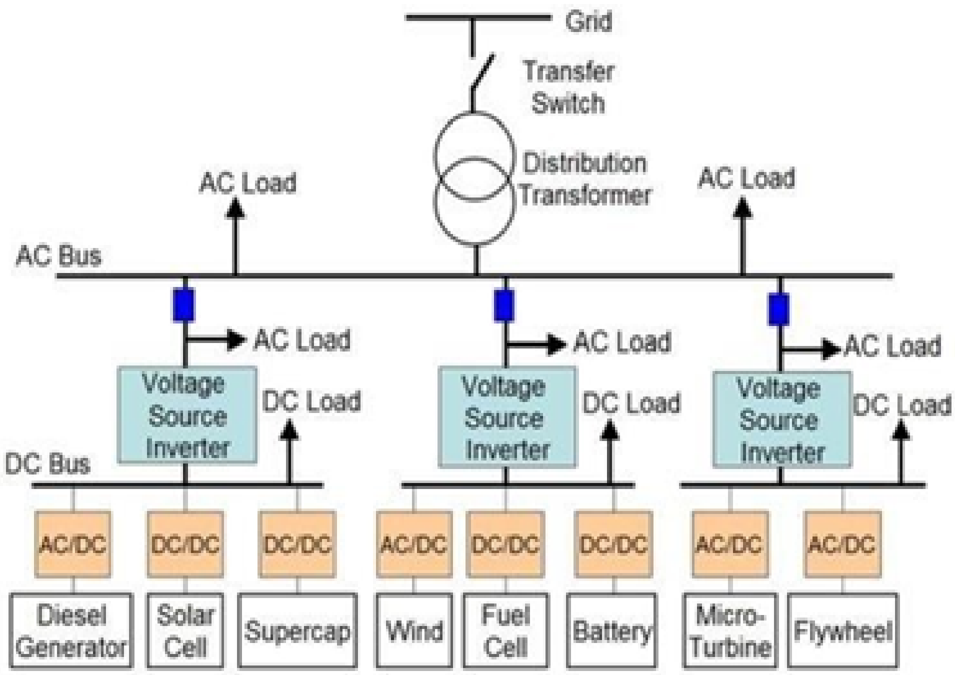


Fig. 3: Inverter interfaced MicroGrid

paper examines the decoupling control of 3-levelnNPC inverter with a predefined reference by methods for droop control algorithm thinking about the active and reactive power of the system [9]. D. Lei, T. Haolei, and X. Furong [10] proposed an enhanced droop-based control for single-stage two-stage PV inverters. With this strategy, the PV inverter can work in either MPPT mode or dispatched control mode when associated with the grid.

Additionally, this control strategy can be utilized for understanding the operational control in an islanded mode without significant control reconfiguration.

T. Tawil, J. Charpentier, M. Benbouzid, and G. Yao [11] proposed a multi-source network for an independent site for various control systems. Specifically, a power control, a voltage and frequency control, and an inverter virtual synchronous generator control systems are embraced and assessed. After that, two explicit multi-source control techniques, in particular, the conventional droop control and a virtual synchronous generator control are simulated and assessed dependent on a comparative study. P. Das, S. Chattopadhyay, and M. Palmal [12] built up another droop technique for parallel load distribution of parallel associated inverters with no direct communication amongst these inverters.

A stability investigation was studied. Routh–Herwitz standard was utilized to figure out the droop coefficient of the system. The droops were produced by utilizing d-and q-axis current. Just d-and q-axis current was utilized; the technique was without the utilization of line impedances. Xiongwei Hu, Fang Shi, and Guiting Xue [5] proposed another power supply module joining the solar panels with an ESS, which can accomplish

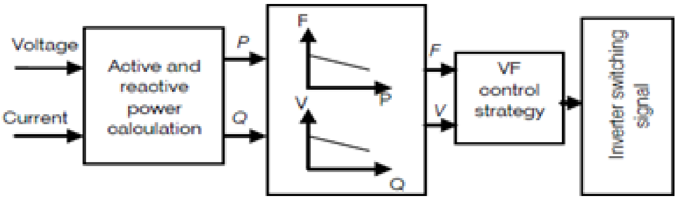


Fig. 4: V-F droop control characteristics

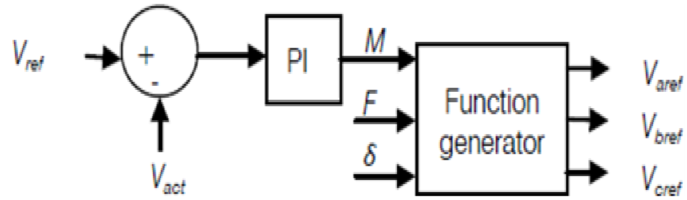


Fig. 5: Synchronous reluctance motor view of stator and rotor

the plug-and-play work. This system is anything but difficult to figure out. PV inverter controlled by the technique of MPPT and energy availability of battery inverter controlled by the droop control can make up a miniaturized scale control supply module.

The microgrid is an advanced system for RES featuring an integrated control mechanism. Typically, droop control is implemented at the fundamental level for progressive control. In islanded operation, it is crucial to manage reactive power sharing while allowing the RES to operate at maximum active power. Consequently, a new reactive power-sharing mechanism was proposed, focusing on the analysis of power distribution among converters within the microgrid. This innovative approach maintains the reactive power flow and prevents the disconnection or failure of any converter in the microgrid [13].

2 DROOP CONTROL MECHANISMS IN ISOLATED, GRID-CONNECTED, AND PARALLEL INVERTER SYSTEM

Frequency-Voltage (f-V) control system is used in most traditional approaches in isolated operations for single inverters, in grid-connected operations active power–reactive power (P-Q) control pattern is used. The reactive power–voltage droop control and active power–frequency droop control may be used for parallel inverters to share the reactive power and active power in isolated processes.

2.1 V-F Droop control

The voltage and frequency droop control appearances are shown realistically in Figure 4. The output voltage and current of the inverter are measured to calculate its reactive and active power.

By utilizing the voltage and frequency droop control strategy, the inverters can understand the "plug-and-play" idea: share the power consequently by utilizing just the nearby data, i.e. the voltage, and frequency, rather than the interchange with the other inverter or the microgrid focal control system [15].

$$f = f_0 + K_{pf}(P_0 - P) \tag{3}$$

$$V = V_0 + K_{QV}(Q_0 - Q) \tag{4}$$

The PI controller processed the error by comparing the voltage reference, V, with the actual bus voltage, V_{act}, to generate the modulation index, M.

The three-phase inverter's reference voltage V_{aref}, V_{bref}, and V_{cref} are generated using the modulation index and with the reference frequency, F, and phase shift, δ. The SPWM is chosen for its straightforward executable property. The waveforms of the reference voltages are synchronized with the carrier signal to result in the switching signals for the inverter.

2.2 P-Q DROOP CONTROL

In a grid-connected system, the PQ control method is used to control every DG unit as the frequency and the voltage of the scheme have been adjusted by an infinite power grid. The PQ-controlled inverter functions by injecting a predetermined amount of power into the grid. This power is defined either locally or centrally. Figure 6 depicts the block diagram of the droop-based control system for managing load power. [15].

The following equations represent the droop:

$$P = P_0 + K_{pf}(f_0 - f) \tag{5}$$

$$Q = Q_0 + K_{VQ}(V_0 - V) \tag{6}$$

The reference signals for the reactive and active power, Q and P are generated by using the actual voltage and frequency, that are input to the droop unit.

PI controllers produce the reference direct axis and quadrature axis currents, I_{dref} and I_{qref}, respectively, by processing the resulting errors after the comparison of references to their actual values.

The inverse Park transform, dq/abc is used to obtain the three-phase reference currents, I_{aref}, I_{bref},

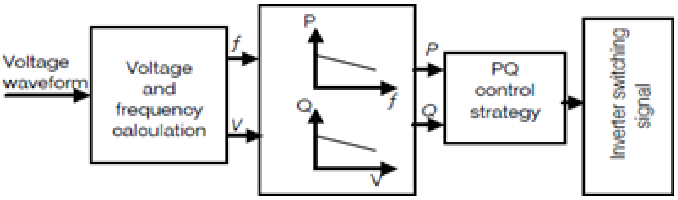


Fig. 6: P-Q droop control characteristics

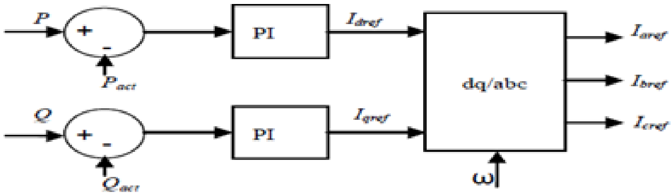


Fig. 7: P-Q droop control characteristics

and I_{cref}. Furthermore, the Hysteresis Current Control (HCC) technique is utilized to generate the appropriate switching signals for the inverters.

2.3 Q-V & P-F DROOP CONTROL

In a parallel inverter system, the inverters independently determine their real-time active and reactive power. This idea has been created utilizing reactive power voltage and dynamic frequency droop for the inverter's power control as shown in Figure 8.

The voltage source's reactive power Q and active power P can be determined as follows:

$$P_1 = \frac{U_{1,eff}.U_{2,eff}}{\omega_N(L_1 + L_2)} sin\delta \quad (7)$$

$$Q_1 = \frac{U^2{}_{1,eff}}{\omega_N(L_1 + L_2)} - \frac{U_{1,eff}.U_{2,eff}}{\omega_N(L_1 + L_2)} cos\delta \quad (8)$$

The inverters are coupled using the inductances coming about because of their filters and for the pulse concealment. The reason why inverters are controlled by fixed voltage and fixed frequency is sensitivity that's why they can't operate in parallel. The decoupling and droops control is shown in Figure. 9.

2.4 OPPOSITE DROOP CONTROL

Reactive power flows due to the difference of phases between the voltage sources.

$$Q_{inv} = \frac{U_{inv,eff}.U_{grid,eff}}{R_{line}} Sin\delta \quad (9)$$

Grid having low voltage is linked with voltages and active power flow.

$$P_{inv} = \frac{U^2{}_{inv,eff}}{R_{line}} - \frac{U_{inv,eff}.U_{grid,eff}}{R_{line}} Cos\delta \quad (10)$$

This observation indicates the use of reactive power/frequency and active power/voltage (Q-F & P-V) droops, referred to as inverse droops. Low voltage profiles in the grid are linked to active power levels, while reactive power is not effective for voltage regulation. In initiating a response scheme, the primary control challenges involve managing voltage and dispatching active power.

As evident from the primary advantage of inverse droops, rapid voltage control is a key benefit. However, if one were to regulate voltage in this manner, power dispatch would not be feasible, as each load would be entirely supplied by the nearest generator. This approach, while effective, falls outside the scope of creative energy, leading to voltage deviations within the system. Utilizing standard droops allows the system to reach higher voltage levels, facilitates coordinated control with synchronous generators, and enables accurate power dispatch. The extent of voltage deviations within the system is influenced by the grid's design.

3 SIMULATIONS SCENARIOS

A simulation scenario has been chosen to evaluate this system based on the reactive and active power handling capabilities of these inverters based on the above-discussed droop control mechanisms. Scenario I is shown in Figure 10.
In Grid-connected mode P-Q droop is used, V-F droop is used in the system when the grid is off and BI and PVI act as parallel inverters.

4 MATLAB SIMULATIONS

A complete MATLAB simulation scenario is shown in Figure 11. It consists of three power sources Grid, PV inverter, and battery-based inverter. Similarly, three control switches are used to control the ON/OFF state of these power sources.

A common bus is developed where the load is connected. RL load is used in the load block. All measurements are made to perform on this load block. Voltages and currents of power sources are localized and measured. The measurement section primarily consists of the voltage/current and active/ reactive power of all three power sources. Waveform displaying availability is also performed to better understand of

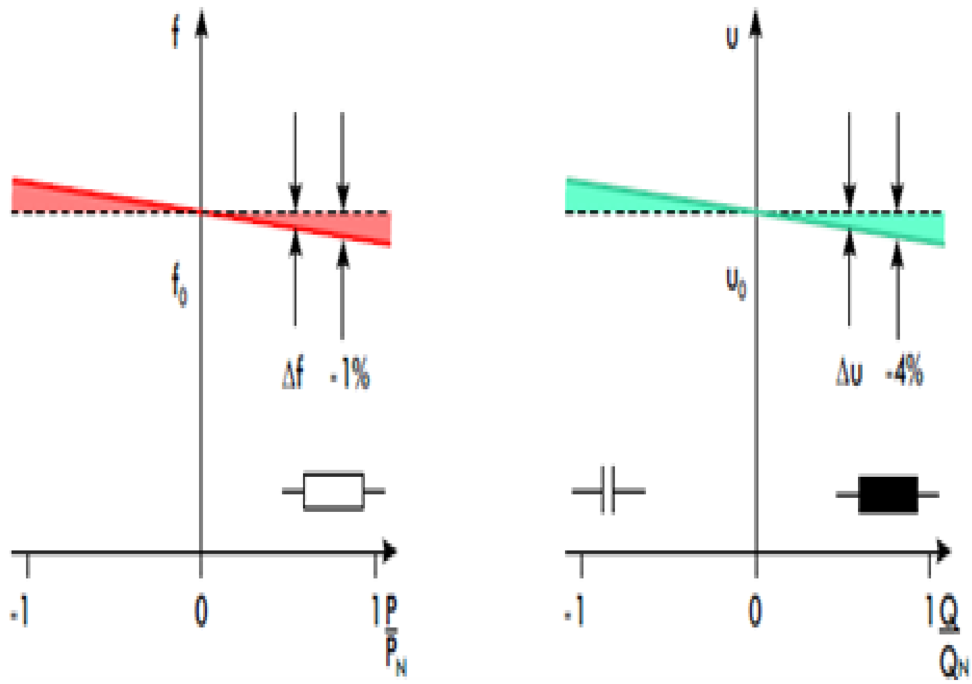


Fig. 8: Q-V & P-F droop control characteristics

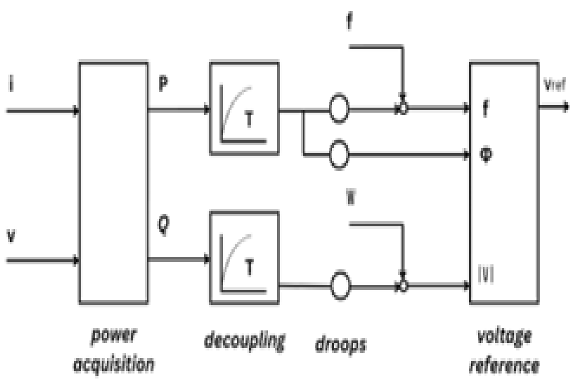


Fig. 9: P-F & Q-V Droop control characteristics

phase angles of currents and investigate the current-sharing capability of these individual inverters and grids. Two control parameters defined for better coordination between inverters are Modulation index and phase shift.

5 SIMULATIONS RESULTS

Figure 12 shows the interval when solar irradiations are not enough to produce any power from the PV inverter. All the demand of load is catered by grid power. Usually, this interval is a basic viewpoint of low or no solar conditions. Figure 12a shows showing currents of load and grid while Figure 12b represents the actual quantities of the active//reactive power along with currents and voltages.

After reaching the better solar irradiation interval power generated from the PV inverter is higher than the load demands. In this case, the excess power is injected into the grid.

Figure 13b illustrates this where the grid is taking the power from the PV inverter. And load behavior is the same which means the load is taking the same power as in the case of individual grid cases.

As the GTI are tied with grid voltages, when the grid goes the PV inverter is also switched off because it was tied with grid voltages. In this scenario, all the power required by the load is delivered by the Battery inverter. Figure 14a illustrates where only BI is ON and it is the only limited energy resource available.

The PV inverter is designed in such a way that it is capable of resynchronizing with BI. So as Figure 14b, now PV inverter is also supplying its power to load with BI. But in this case, PV is operated in a precise way that it does not supply any power to BI.

After rejoining the grid voltages, as in Figure 15, the PV inverter is again tied with the grid voltages. And power sharing nature of PV inverter is again developed to contribute its power to the grid.

Figure 16 shows the detailed analysis on the basis of this entire simulation, where the time-dependent nature of this inverter and grid availability is illustrated. In the absence of grid voltages, the PV inverter is also sharing its power with the load.

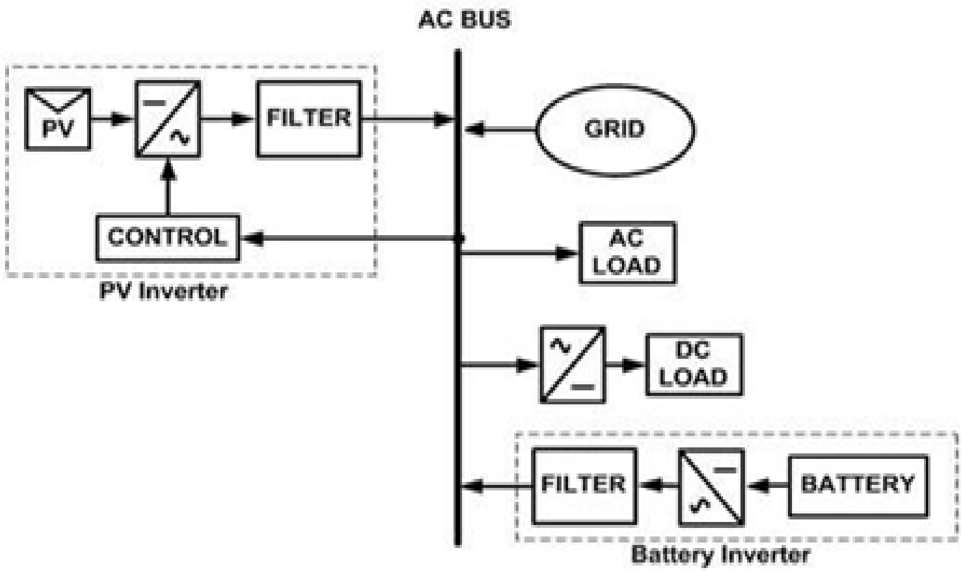


Fig. 10: Simulation scenario

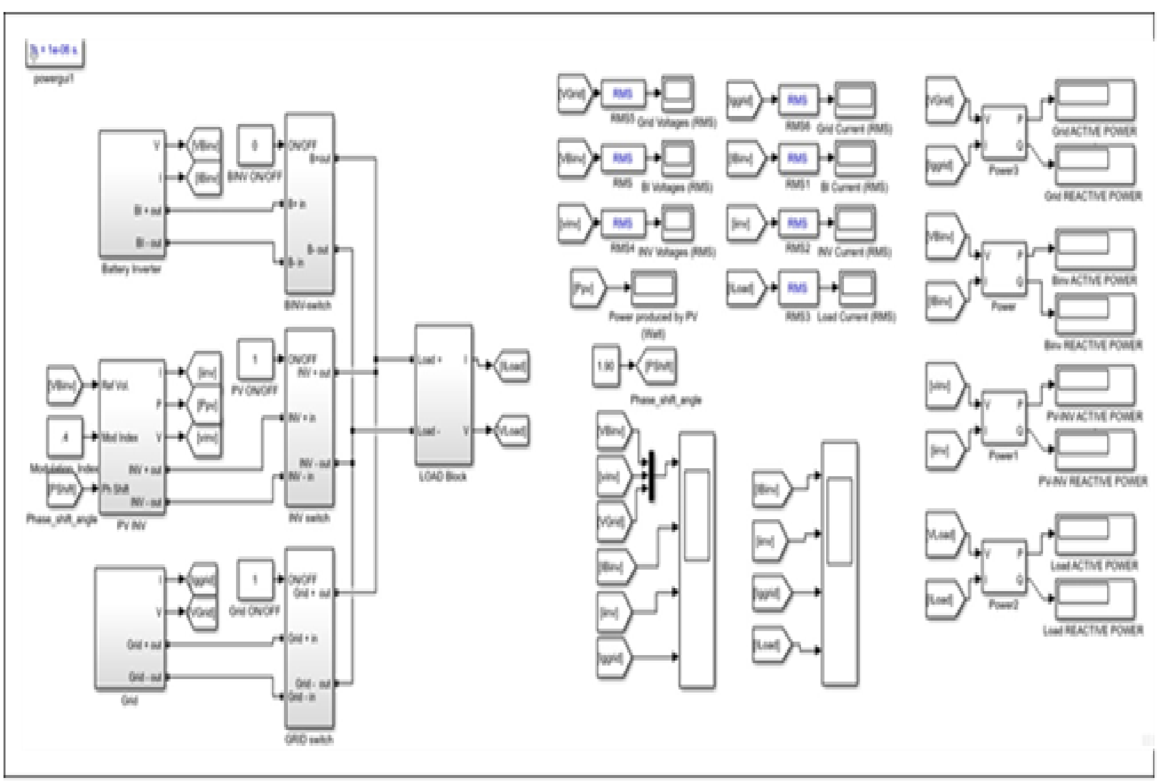
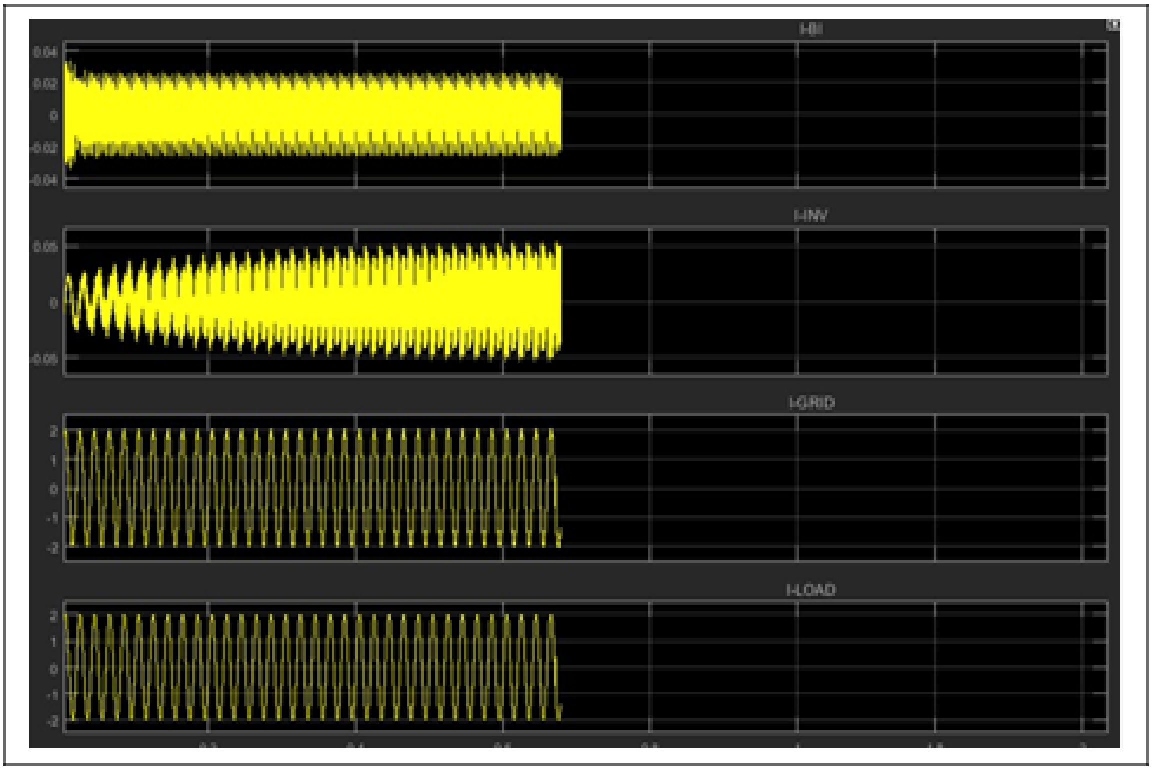
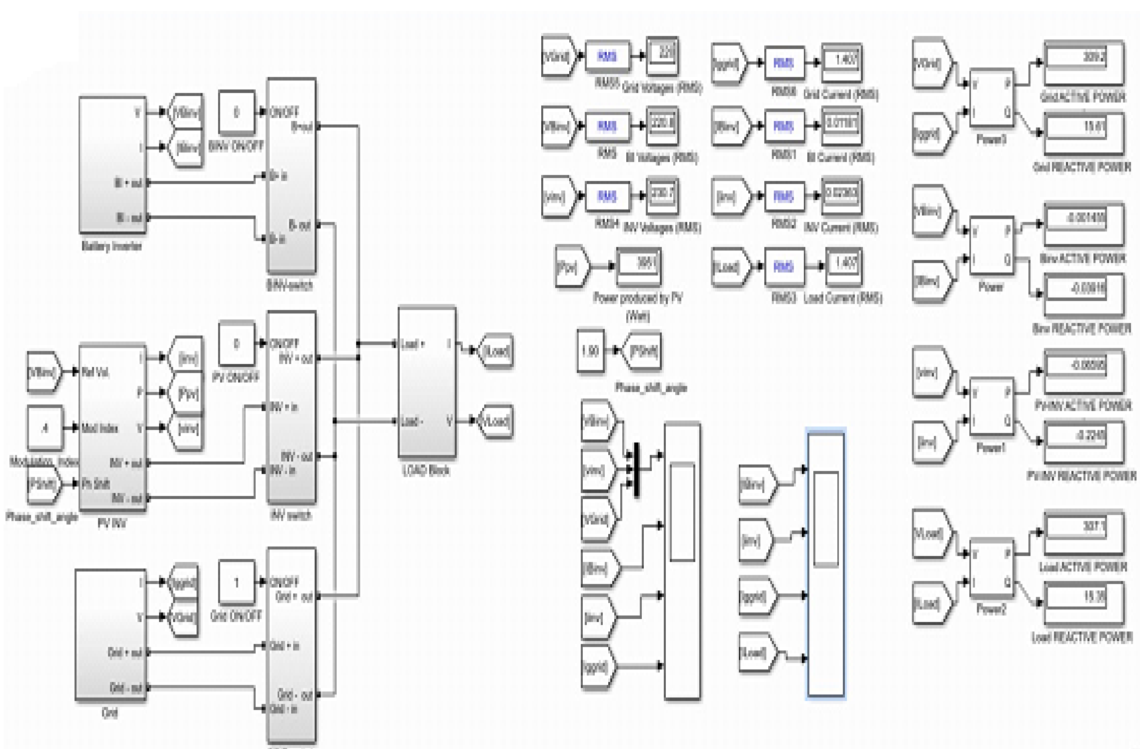


Fig. 11: MATLAB Simulation

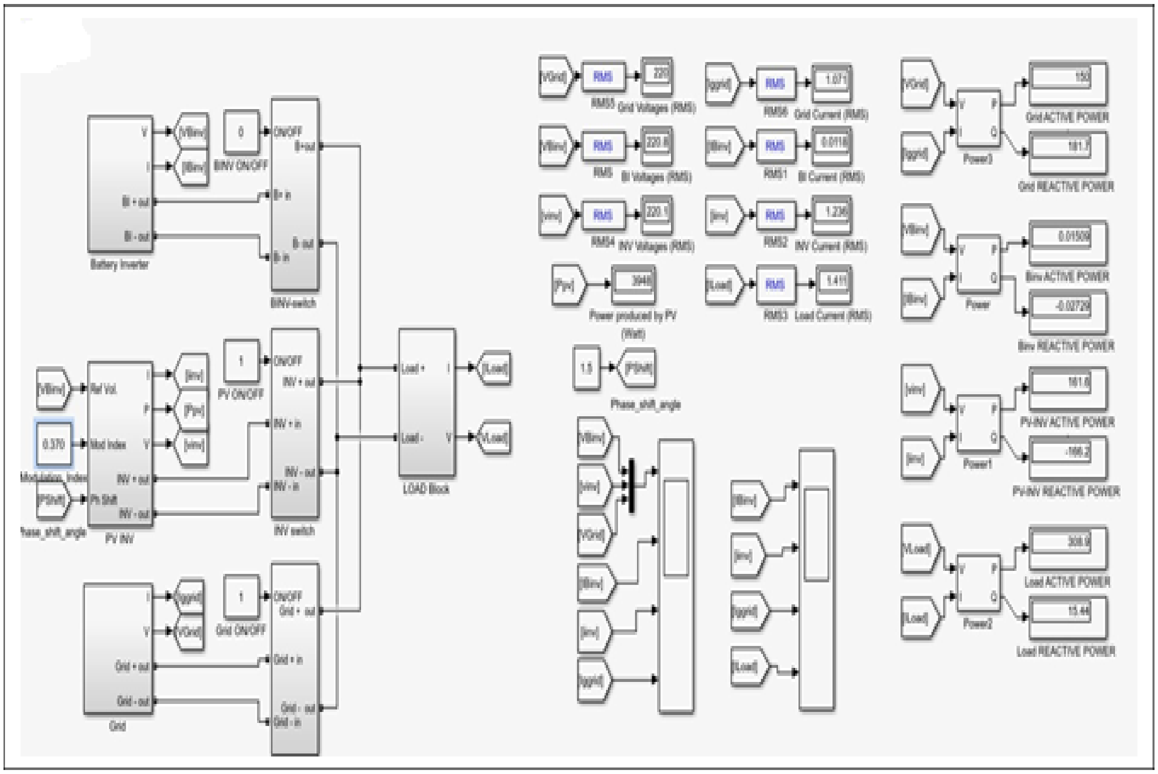


(a) currents of load and grid - Grid on, INV off & BI off

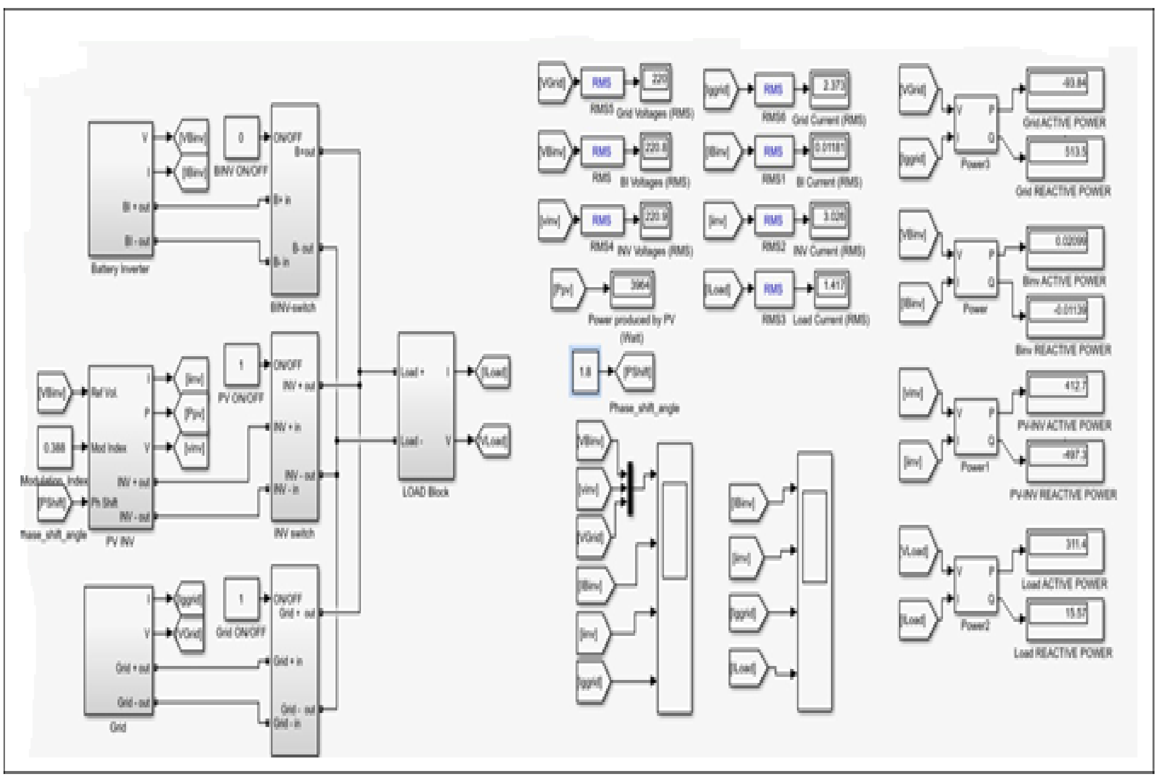


(b) Active Power and Reactive Power, Grid on, INV off & BI off

Fig. 12

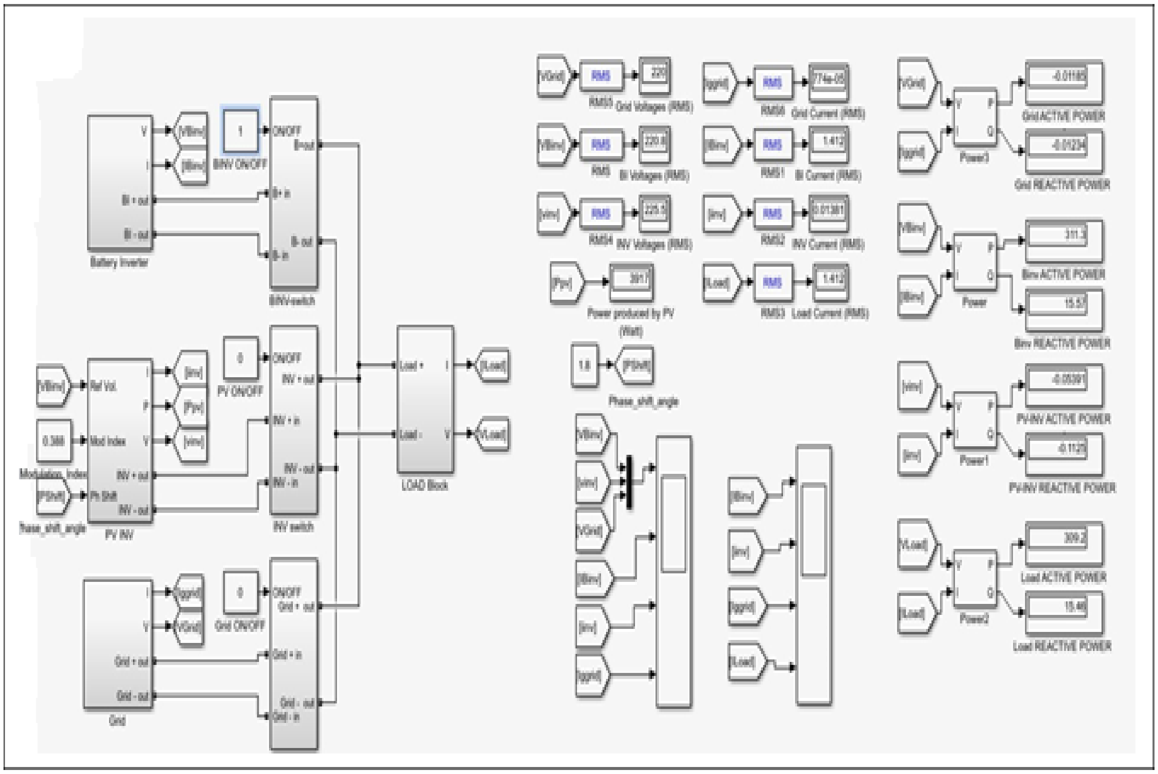


(a) Active Power and Reactive Power - Grid on, INV on & BI off

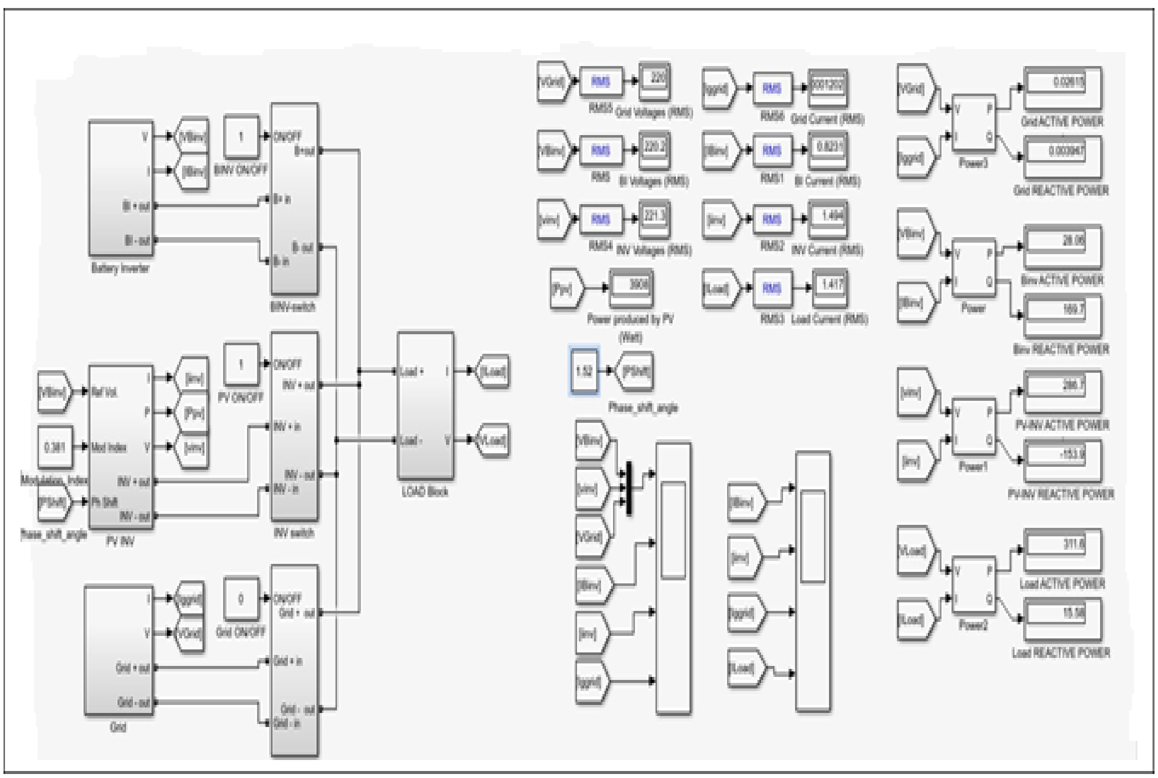


(b) Active Power and Reactive Power contribution - Grid on, INV on & BI off

Fig. 13



(a) Active Power and Reactive Power - Grid off, INV OFF & BI ON



(b) Active Power and Reactive Power - Grid off, INV on & BI on

Fig. 14

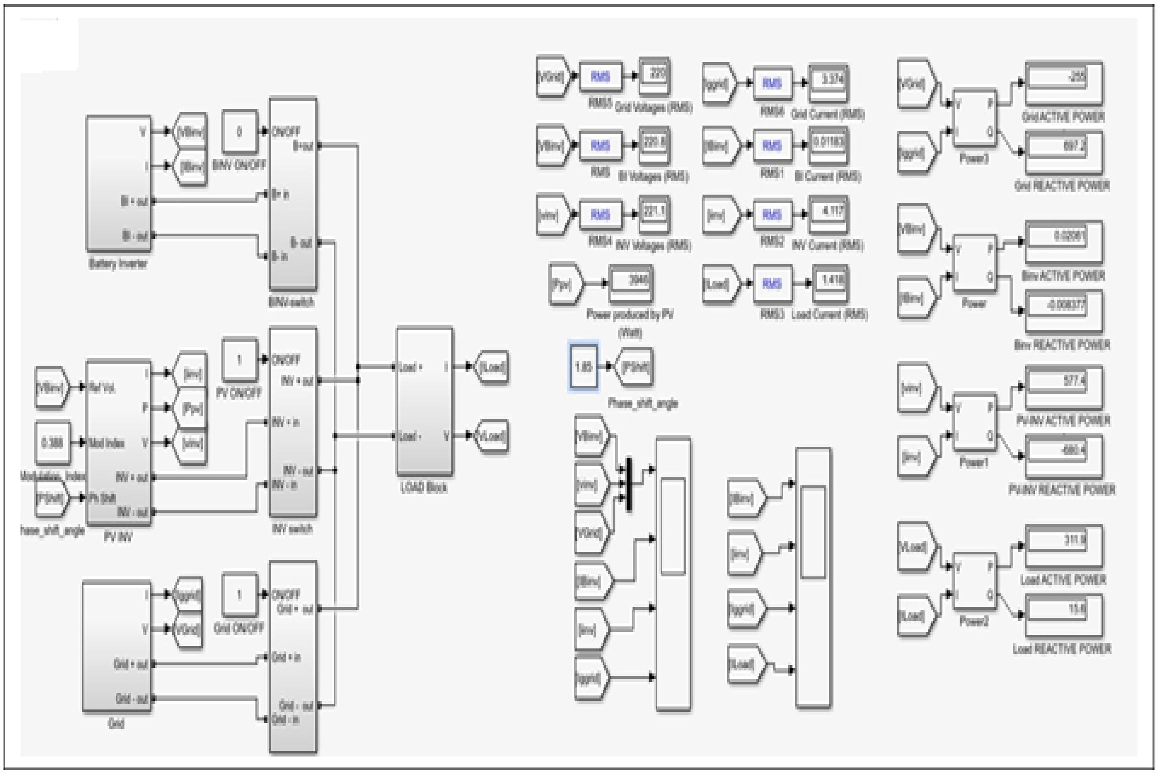


Fig. 15: Active Power and Reactive Power - Grid on, INV ON & BI OFF

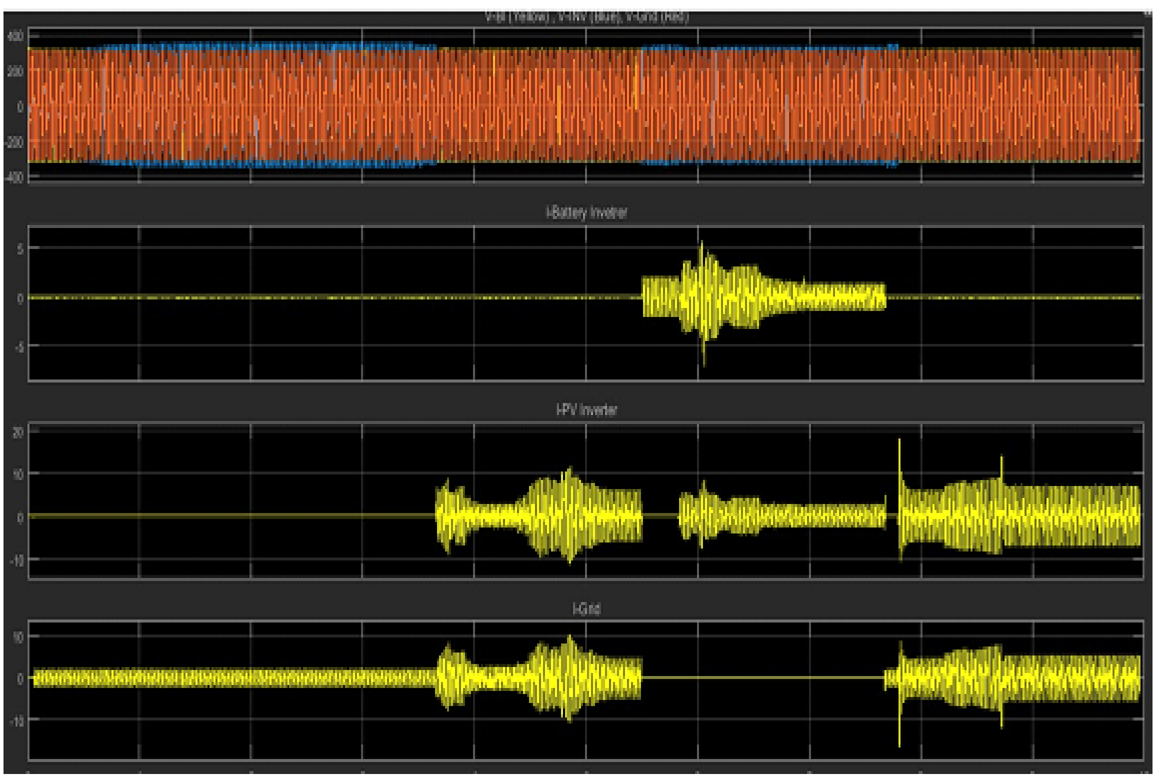


Fig. 16: Complete simulation scenario

In the absence of solar irradiations, the PV inverter does not participate in load sharing. The only available power source is the grid.

6 CONCLUSIONS

MATLAB simulations are conducted in three different modes: islanded, grid-connected, and SFnG. In the island, voltage stability is the function of active power drawn by the inverter. In Grid-connected, P-Q droop is used and active power and reactive power are the function of inverters frequency and their voltage. In the case of SFnG, the parallel inverters mode, reactive power, and active power flow are precisely controlled by voltage angle and modulation of inverters.

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