PV Solar Energy integration to the grid

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***Abstract* — Solar energy has experienced significant advancements in recent years, becoming an increasingly viable and sustainable power source. This paper investigates integration of a PV solar energy system into an existing power grid, via the simulation of a two-stage system consisting of a PV array, two level 3phase inverter, DC-DC boost converter with a maximum power point tracking controller system. A comprehensive control strategy was implemented such as pulse width modification and inductive filters to ensure seamless operation of the PV system to the grid. Also, avoidance of power quality issues was further achieved using phase lock loop (PLL) control to maintain 50Hz. The performance of the PV system was evaluated via two Simulink(R2023a) simulations. The results demonstrated the effectiveness of the model to provide reactive power support to the grid and provision of 40kW with a voltage compatible to the grid voltage of 400V.**

1. Introduction

Solar energy is considered one of the most accessible, and pollution-free renewable sources. In recent times, the supply of PV power to the electric grid has been increasingly visible, largely due to various government incentives. The development and growth of grid-connected systems require enhanced assessments of system performance under fault conditions, as well as power quality control.

1.1 Types of PV systems

Broadly, PV systems are classified into three types: grid-connected PV systems, stand-alone PV systems, and hybrid PV systems [1]. PV systems that generate electricity to be used locally at the generation center without being injected into a utility grid are called stand-alone PV systems. Here, mostly the energy generated is consumed and any available excess will be stored in batteries [1].

PV systems whose power is directly fed into the utility or electric grid are generally known as grid-connected PV systems. These are also called on-grid or grid-tied PV systems. These PV systems are capable of only feeding energy into the grid [1].

The hybrid solar PV systems typically represent the combination of both grid-tied and stand-alone. In the hybrid configuration, the PV system can generate electrical power, which is locally consumed or stored in batteries, and the excess is injected into the grid by means of net metering [1].

This paper examines the simulation modeling of a two-stage, grid-connected solar system. Figure 1 illustrates a typical schematic of a grid-tied photovoltaic (PV) system. The PV mechanism harnesses solar energy, transforming it into electricity. A sophisticated Maximum Power Point Tracking (MPPT) algorithm establishes the optimal power point for the solar system's operation, attained through the implementation of the Perturb and Observe algorithm. Furthermore, a DC-DC boost converter guarantees that the output voltage consistently surpasses the grid's peak voltage. Additionally, a DC-AC inverter and a current control unit produces an alternating voltage in compliance with the grid's prerequisites for secure connection and seamless synchronization.

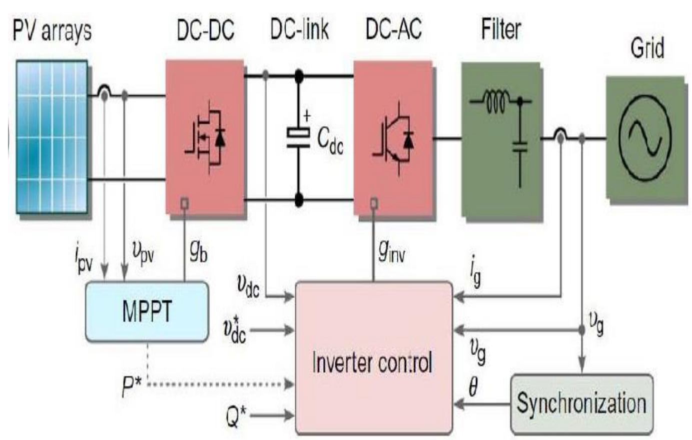

Figure 1. Schematic of a typical PV grid connected system design

A. Modelling of the DC-DC Boost converter

To connect solar system to the utility grid we have to increase the magnitude of the output voltage [2]. Which can be done with the use of a DC-DC converter. For this simulation

Voltage input ($V_{in)}$= 151V
Voltage out (V_{out})= 700V
Apparent power (S) = 40kW
Line to Line voltage (Vac_{LL})=400V
Switching frequency (Fsw)=10000Hz

This voltage increase is achieved by employing a DC-DC converter, specifically a Boost converter, to elevate the source voltage to the required levels. The DC-DC boost converter is an essential component that works in conjunction with the MPPT. Its primary function is to increase the voltage level from the solar panel (151V) to the required output voltage, which, in this simulation, is approx. 700V DC. The MPPT communicates with the DC-DC boost converter and adjusts its duty cycle, enabling the solar panel to operate at the Maximum Power Point. This ensures that the maximum available power is extracted from the solar panel under varying environmental conditions.

The converter is composed of an input direct current (DC) voltage source, an IGBT as the control switch, a diode, an inductor coil, and two capacitors [2].

During the ON state of the switch, the inductor current experiences a linear increase, while the diode remains in the OFF state. Conversely, when the switch is in the OFF state, the energy accumulated in the inductor is discharged through the diode towards the resistor-capacitor (RC) circuit. The output voltage is directly proportional to the duty cycle of the converter [2]

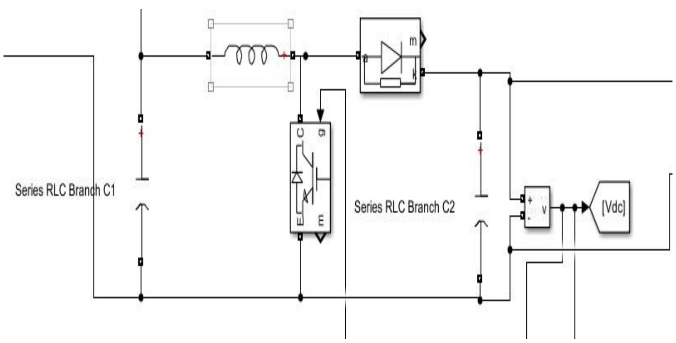

Figure 2. illustrates the Simulink model of the Boost converter.

B. Inverter

The inverter and its control unit for grid synchronization are a crucial component of a grid-connected photovoltaic (PV) system [2]. In this simulation the control unit incorporates a Phase Locked Loop (PLL) controller that synchronizes the PV system with the grid at 50Hz. The inverter is a two-level power inverter that comprises of six switching arms in total, with two arms per phase. Each arm contains two switching devices, in this case IGBTs connected in series, with one device in the high-side position and the other in the low-side position. The switching frequency of the VSC is 10e3Hz.

The current controller of the inverter comprises a PLL, a Vdc regulator, a current regulator, a reference generator, and a Pulse Width Modulation (PWM) generator. The Vdc regulator measures the DC voltage and compares it to the reference voltage. The PLL control unit converts the grid voltage and current from abc to dq reference frame using Park's transformation [3]. The grid-tied inverter interfaces via an AC filter to mitigate high-frequency harmonic injection into the grid system. Comprising inner current and voltage control loops, the inverter's control system employs a Proportional-Integral (PI) controller within the current loop for grid current regulation and DC link voltage stabilization, while managing the DC link voltage (Vdc) in the voltage loop.

2. PV SYSTEM DESIGN

2.1 Simulink Model of Grid Connected system.

The basis for this case study entails a grid connected PV system designed to supplement the daily load requirement and to supply the surplus energy to the grid. In this study grid connection is the focus and as such the daily load requirements were ignored.

The grid requirement is:

- Supply of 40kW
- Provision of reactive power support
- Supply of power at 50Hz
- Low harmonics

The line-to-line 400V is verified via simulation and also by calculations whereby the Modulation index (M_a) was also found from Vdc=700V, Vac_{LL}=400v

$$Ma=\frac{\sqrt{2}}{\sqrt{3}}\cdot\frac{2Vac\ LL}{Vdc} = 1.224 \cdot (800/700) = 0.9326$$

The modulation index is used to further in this simulation to contribute to the inductive filter design.

Ripple current =0.005· (S/Vac)

L= (2/3) · ((ma·Vdc· (1-ma))/ (ripple current·2*fsw)) = 0.0029

Due to the large switching frequency (10e3Hz) of the inverter a small L filter which was calculated is more sufficient to reduce the harmonics.

The PV array operates according to the standard test conditions, providing output power at a module temperature of 298 K (25 °C) and an irradiance of 1000 W/m². A boost converter facilitates the elevation of the PV voltage from 151V to 700 V, and its duty cycle is governed by a maximum power point tracking (MPPT) controller. The inverter subsequently transforms the 700V direct current (DC) into an alternating current (AC) 400V (230Vrms).

The power conversion stage of the PV systems injects harmonics into the grid [4]. To reduce the harmonic distortion generated by the inverter a low pass filter is used whereby 40kW can be sufficiently supplied to the grid. Figure 3 illustrates a simulated representation of a two-stage, grid-integrated photovoltaic (PV) system.

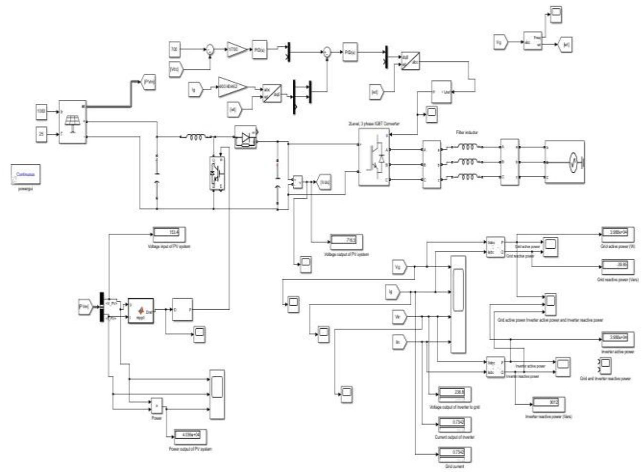

Figure 3. Simulink model of the 40kW grid connected PV system.

Provision of reactive power is required by this system. Balancing of reactive power supply and demand is a key requirement for reliable electric power system operation. Lack of sufficient reactive power supplies can end with voltage instability [5]. For this paper a separate model is created as illustrated in figure 4. to simulate and measure the reactive power, active power, power factor and power factor angle.

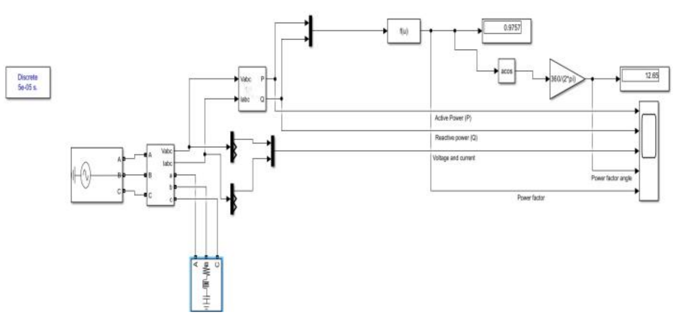

Figure 4. Simulink model of reactive power support of the 40kW PV system.

4. Results and Discussions

Fig 5 to 11 shows all the experimental results of the proposed system, starting with the output power of the PV array which is 40kW followed by the output voltage (151V) and current (268A) of the PV array, switching pulse of boost converter and output voltage (700V) of boost converter, inverter switching pulses and output of inverter which is grid compatible and last, the filtered waveform of the three phase voltage supplied to the utility grid.

4.1 Waveforms of the PV power output, PV current and voltage input.

The 268 amperes generated by the solar panels is proportional to the solar irradiance and is also affected by the temperature. When solar radiation strikes a solar cell, part of the photons can be absorbed by the cell, resulting in the production electron hole pairs in the cell. If an external circuit is formed, the voltage difference drives the electrons from the n-side to the p-side of the junction. Consequently, the electric current is formed in the external circuit [9].

The 151-voltage generated by the solar panels is affected by the number of series-connected PV cells, as well as temperature and irradiance. The open-circuit voltage (Voc) of a PV cell increases logarithmically with increasing irradiance and decreases linearly with increasing temperature. The PV input voltage waveform can provide insights into the array configuration and performance under varying conditions. Analyzing the Vpv waveform can also help detect issues like partial shading or mismatched modules, which can affect the overall efficiency of the system.

The power generated by the PV system is the product of the input current and voltage (Pout = Ipv × Vpv). The power output waveform reflects the combined effects of solar irradiance, temperature, and the PV array's electrical characteristics. In an ideal system, the power output waveform would closely follow the solar irradiance pattern. However, real-world systems can have losses and inefficiencies, causing deviations from the expected pattern. Examining the power output waveform can help identify areas of improvement, such as optimizing the maximum power point tracking (MPPT) algorithm or addressing mismatch losses. Figure 5 provides a summary of the three waveforms.

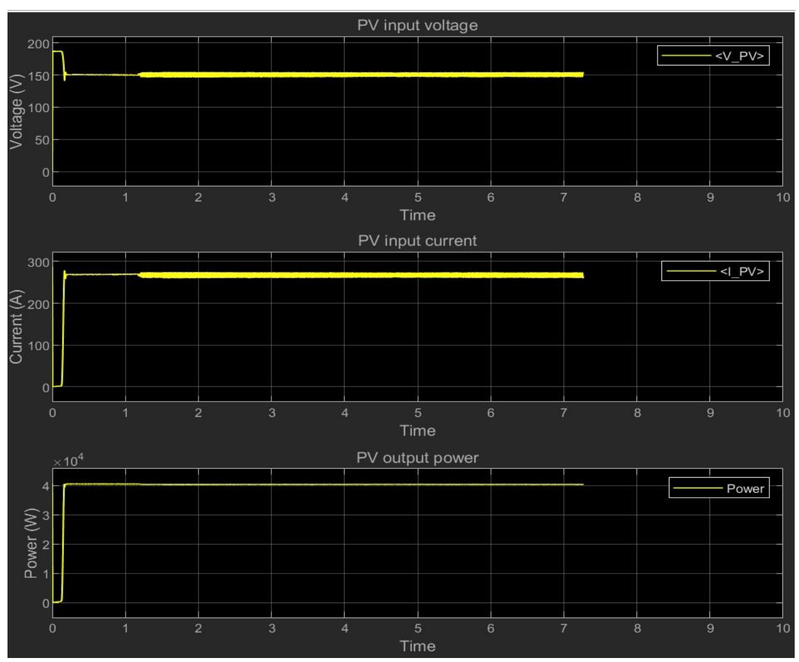

Figure 5. Simulink waveforms of PV input voltage, PV input current and PV output power.

4.2 Switching frequencies of boost converter and 2level 3phase inverter.

In the case of both the DC-DC boost converter and the 2level 3phase inverter a switching frequency of 10 kHz is used for the PWM signal. The switching frequency determines how frequently the power electronic switches change their state [7]. A higher switching frequency allows for better control and faster response but may lead to increased switching losses in the converter [7]. The PWM waveform has a constant frequency of 10 kHz which means that the time period of one complete cycle is 100 µs. The duty cycle of the PWM waveform represents the fraction of the time the signal is "on" or "high" within one cycle. It varies between 0% (always off) and 100% (always on) [7].

The PWM waveform's shape is very similar to a series of rectangular pulses with varying widths, depending on the duty cycle determined by the MPPT P&O algorithm. The waveform in these simulations exhibits rapid transitions between the high and low states, corresponding to the switching frequency of 10 kHz. By analyzing the PWM waveform, one can infer the performance of the MPPT algorithm and the overall efficiency of the grid-connected PV system.

The PWM waveform for the 2-level, 3-phase IGBT inverter involves the comparison of high-frequency carrier signals with 3-phase sinusoidal modulating signals derived from the MPPT P&O algorithm. The resulting PWM signals control the IGBT switches to generate a stepped output voltage waveform that approximates the sinusoidal modulating signals [7]. The resulting PWM output voltage waveform contains harmonics due to the high-frequency switching. These harmonics are reduced by this increased switching frequency of 10kHz and by using filtering techniques such as using inductive filters as represented in the model.

Figures 6 and 7 illustrates the shape of the PWM for both devices.

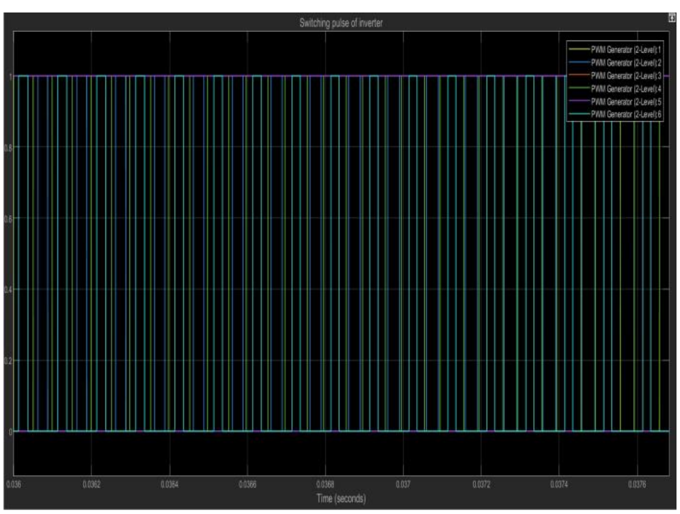

Figure 6. Switching pulse of 2level, 3phase inverter.

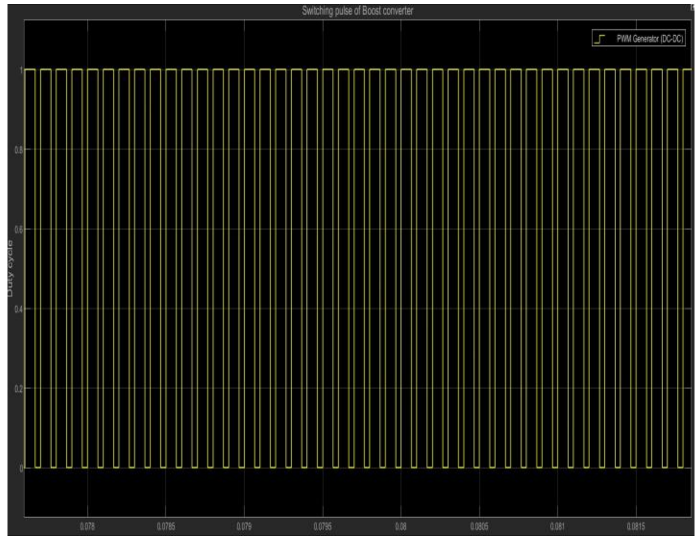

Figure 7. Switching pulse of DC-DC boost converter

4.3 Output voltage of DC-DC boost converter

The voltage is initially 151 V, and it is boosted to 700 V at the output of the boost converter. Boosting the voltage to 700 V before transferring it to the inverter which steps it down to 477 V (326V) allows for a more manageable current (approximately 57 A) during the intermediate stages of power conversion, reducing the stress on components and conductors. Also, A higher intermediate voltage (700 V) ensures better voltage regulation and stability at the final grid voltage of 400 V. This is because the voltage controller and inverter can more easily compensate for fluctuations in the input voltage or load variations, providing a stable voltage supply to the grid. Figure 8 illustrates the waveform of the DC-DC boost converter output voltage:

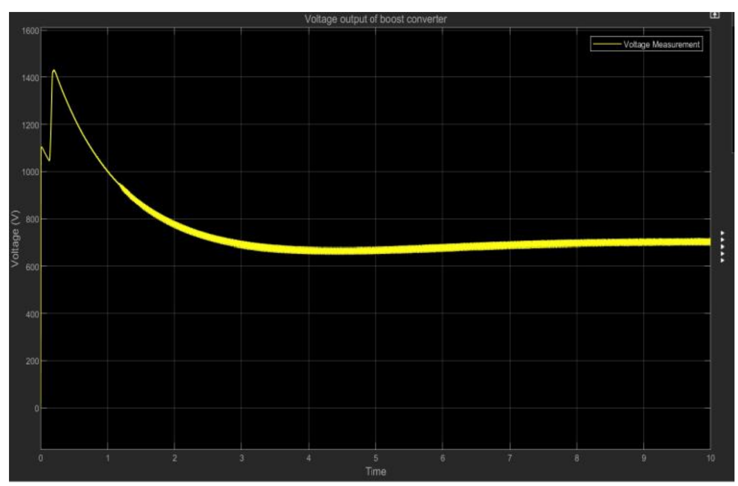

Figure 8. Output voltage waveform of DC-DC boost converter

4.4 Grid voltage, Grid current and Inverter voltage waveforms

From this simulation it is seen that the inverter voltage output of 477V (line-to-line voltage) indicates the peak voltage output of the inverter. However the voltage supplied to the grid is 326V (peak value) and 230V RMS which suggests that the inverter is successfully providing power at lower, grid-compatible voltage. This is important because the inverter must be able to synchronize with the grid's voltage and frequency to prevent power quality issues. The inverter's current and grid current output is 84A (peak value) and 57A RMS as seen in figure 9.

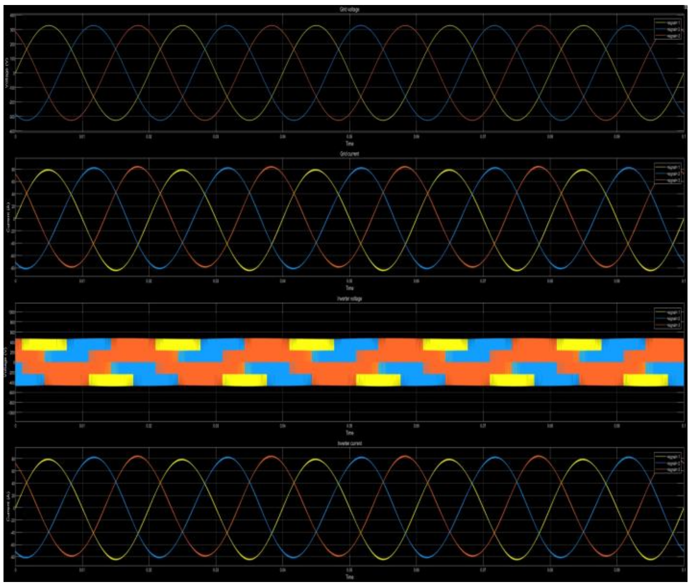

Figure 9. illustration of Grid voltage, Grid current and Inverter voltage waveforms

The voltage drop is also indicative of reactive power being supplied to the grid. This is essential for maintaining voltage stability in the grid. By providing reactive power, the inverter helps support the grid, reduce voltage fluctuations, and improve overall power quality [6].

4.4 Phase lock loop (PLL) for frequency control and grid synchronization

In the context of the grid-connected inverter, the PLL control system is employed to synchronize the inverter's output frequency (10e3Hz) with the grid's voltage waveform and frequency (50Hz), ensuring seamless power transfer and maintaining grid stability**.** For this purpose, synchronization between the inverter and the grid was performed via a feedback system. A built-in Simulink PLL block was used. The purpose of the PLL block is to generate the grid's frequency, voltages, and phase angle,

which are then fed into the PWM block [8]**.** No frequency issues are observed as the values are well between 50.1Hz and 49.9 Hz as seen in figure 10.

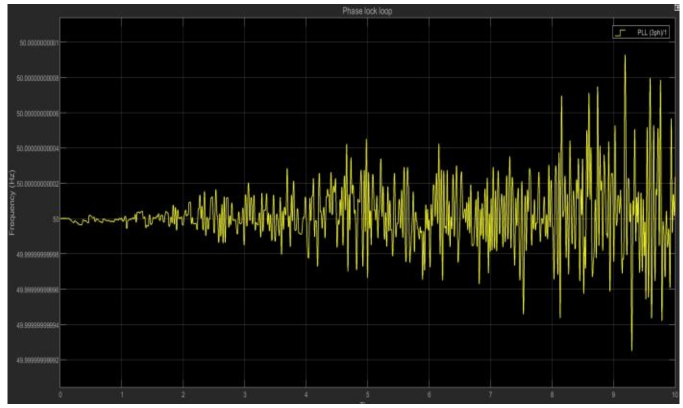

Figure 10 illustrates the waveform of the PLL controlled output frequency to the grid of 50Hz.

4.5 Active power, reactive power, power factor and power factor angle.

The PV inverter supplies an active power of 3.99e4 W (approx. 40kW) to the grid, alongside a reactive power support of 8,976 VAr. It also consumes a small reactive power of 35.92 VAr from the grid. The inverter consumes a small amount of reactive power (35.92 VAr) from the grid due to factors such as switching losses, component losses and/or its control strategy [6].

The system exhibits a power factor angle of 12.64 degrees and an overall power factor of 0.9757. The inverter efficiently converts and synchronizes DC solar power to AC grid power while maintaining a near-unity power factor. By generating 8,976 VAr of reactive power and consuming only 35.92 VAr, it contributes to grid voltage stability and mitigates fluctuations. The 0.9757 power factor indicates an almost ideal balance between active and reactive power, minimizing power losses and optimizing grid performance

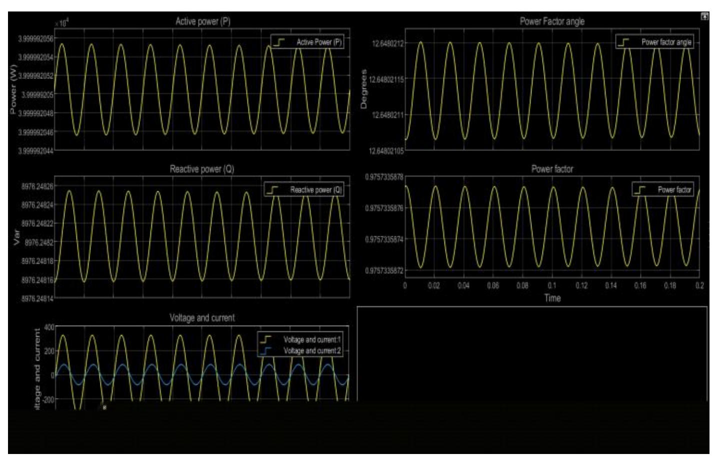

Figure 11. illustrating reactive and active power waveforms along with power factor and power factor angle

5. Conclusion

The PV system exhibits a proficient performance, converting DC solar power into grid-compatible AC power with an output voltage of 476V peak line to line and an RMS current of 57A. The system supplies 39.9 kW (approx. 40kW) of active power and 8,976 VAr of reactive power to the grid, while consuming a minimal 35.92 VAr reactive power. In this PV system, the 12.64-degree angle indicates a slightly lagging power factor, meaning the current lags the voltage. The cosine of this angle yields the power factor ($\cos(\theta) = 0.9757$), which quantifies the ratio of active power (P) to apparent power (S), or PF = P/S.

With a near-unity power factor of 0.9757, the inverter efficiently manages active and reactive power exchange, enhancing grid stability and power quality. The Phase-Locked Loop (PLL) ensures precise synchronization of the inverter output with the 50Hz grid frequency.

In summary this simulation effectively shows that this PV system is effectively capable of providing the required power needed (40kW) while providing reactive power to the grid and delivering a voltage of 326V to grid which will not cause overvoltage issues.

References

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