

Design and Simulation of a Grid-Connected PV Inverter with High-Gain DC–DC Converter Using ANSYS Twin Builder

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Abstract

Rising global energy demand, the depletion of fossil fuels and environmental concerns have significantly increased interest in renewable energy systems; in this context, photovoltaic (PV) systems have emerged as one of the leading solutions. However, in grid-connected PV systems, the conversion of low-level and variable DC voltage into AC power that meets grid standards with high efficiency is one of the fundamental engineering challenges. In this study, a grid-connected PV inverter system integrated with a high-gain DC-DC boost converter was designed in the ANSYS Twin Builder environment and modelled in detail using a multi-domain approach. A Perturb and Observe (P&O) based maximum power point tracking algorithm was applied to obtain maximum power from the PV panels, and a phase-locked loop (PLL) based control structure was used for grid synchronization. Furthermore, an LCL filter structure was designed to reduce harmonic distortion at the output. The proposed system was analyzed under various radiation and temperature conditions; simulation results demonstrated that the DC bus voltage was maintained stably at 400 V with low ripple, that the output waveform was of high-quality sinusoidal nature, and that effective synchronization with the grid was achieved. It was determined that the total harmonic distortion ratio for voltage and current is approximately 0.8%, remaining below international standards. This study offers a unique and practical contribution to the literature by addressing power electronics, control systems and multi-domain modelling in an integrated manner on a single platform.

Keywords: photovoltaic systems; inverter; DC–DC converter; ANSYS Twin Builder.

1. Introduction

The limited nature of fossil fuel reserves, rising greenhouse gas emissions and the continuous increase in global energy demand make it imperative to develop sustainable and environmentally friendly alternatives for energy production. In this context, renewable energy sources, particularly photovoltaic (PV) systems, have become a major focus of research in both academic and industrial circles in recent years. Cost reductions in PV technologies and improvements in cell efficiency have accelerated the widespread adoption of grid-connected systems. Indeed, recent reports indicate that global installed PV capacity is increasing annually, reaching a critical share within the energy production portfolio. [1-3].

In grid-connected PV systems, the fundamental technical challenge lies in the high-efficiency conversion of low-level and variable direct current (DC) voltage into alternating current (AC) that complies with grid

standards. In this conversion process, DC-DC converters, maximum power point tracking (MPPT) algorithms, DC-AC inverters and filtering structures play a critical role [4–7]. In particular, advanced inverter topologies and LCL filter structures are widely used to reduce total harmonic distortion (THD) and ensure system stability within the scope of power quality requirements [7–9]. In this context, the development of converter topologies capable of providing high voltage gain and operating with low ripple stands out as an important research topic in terms of system efficiency [9].

Recent studies have focused on hybrid, multilevel and parallel converter topologies with the aim of overcoming the limitations of conventional boost converters. These configurations offer advantages such as lower switching losses, reduced electromagnetic interference (EMI) and higher power density [10–12]. However, in grid-connected inverter design, it is not only power conversion efficiency that is decisive; criteria such as total harmonic distortion (THD), power quality, synchronization (PLL) and compliance with grid codes are also key factors [13].

At this stage, multiphysics simulation tools play a significant role in the design and validation processes of these systems. Platforms such as ANSYS Twin Builder, in particular, enable the integrated modelling of electromagnetic, power electronics and control systems, thereby accelerating the prototype development process and reducing costs. Recent studies have shown that the digital twin approach and real-time simulation techniques are being used increasingly in PV system design [14–16].

Although there are numerous studies in the literature on grid-connected PV inverter designs, there are few studies in which high-efficiency DC-DC converters are integrated with the inverter and modelled and analyzed holistically within the ANSYS Twin Builder environment. Furthermore, a significant proportion of existing studies focus either solely on control algorithms or solely on hardware topology, leaving a gap in integrated system-level analysis.

The primary objective of this study is to design and analysis a high-efficiency, grid-connected inverter configuration for photovoltaic systems within the ANSYS Twin Builder environment. In this context:

- A DC-DC boost converter topology providing high voltage gain has been developed,
- An MPPT algorithm has been implemented to maximize the output power of the PV system,
- A PLL-based control structure was utilized for grid synchronization,
- Appropriate filter structures were designed to reduce harmonic distortion at the inverter output,
- The entire system was modelled as an integrated system within the ANSYS Twin Builder environment,

and performance analyses were carried out.

Unlike existing studies in the literature, this work stands out due to:

- The integration of simulation, control and power electronics on a single platform,
- The joint optimization of the high-gain converter and the inverter,
- A multi-domain modelling approach that produces results close to real-world system behavior,

stands out for.

2. Materials and Methods

2.1. Single-phase grid-connected PV systems

The general structure of a single-phase grid-connected PV system is shown in Figure 1.

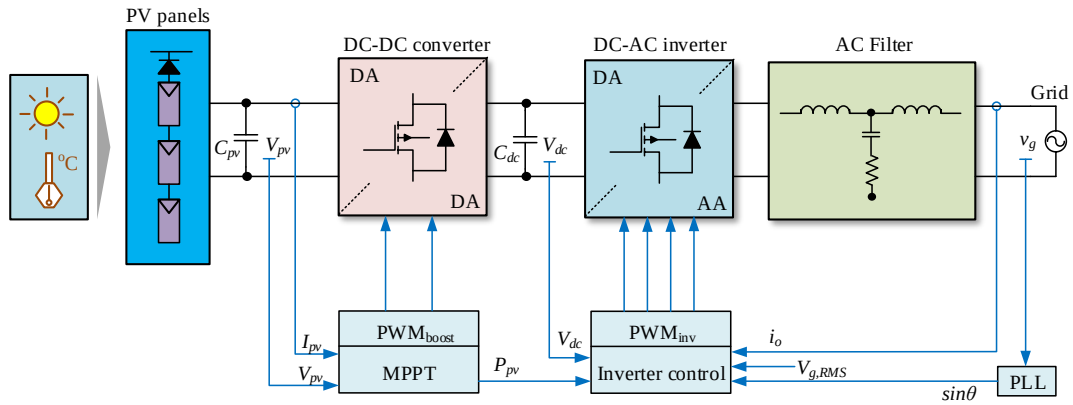


Figure 1. General structure of a single-phase grid-connected PV system.

The control of the single-phase grid-connected PV system shown in Figure 1 can be divided into two main sections. The first of these involves the control of the PV panels and the DC-DC converter, with the aim of obtaining maximum power from the PV panels; the second involves the control of the inverter, which is carried out to supply energy of the required quality to the grid.

2.2. Control structure of the PV panel and DC-DC converter

Various MPPT methods are used to obtain maximum power from PV panels. The P&O MPPT method has been selected for PV panel control due to its applicability, ease of implementation, ability to track the maximum power point with high accuracy, low computational load, and potential for further development. Figure 2 shows the block diagram of the algorithm for this method.

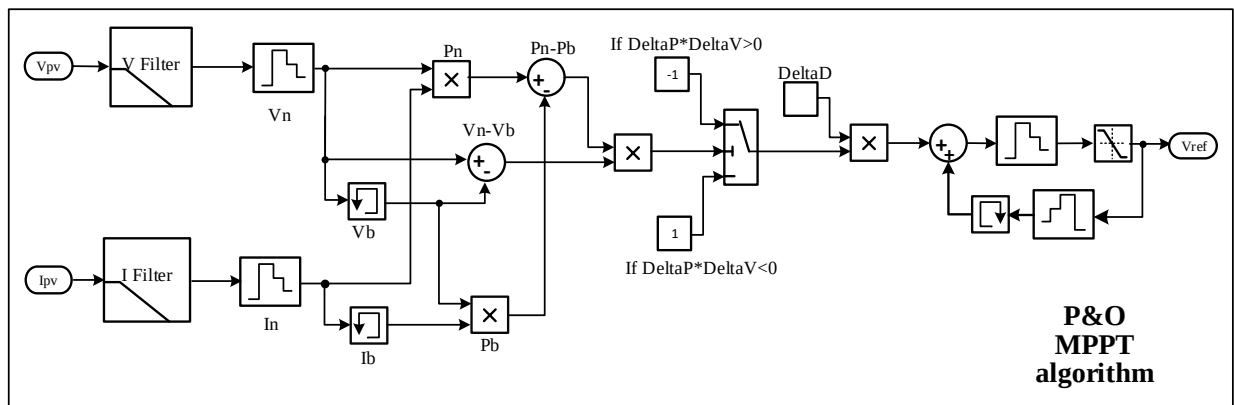


Figure 2. Block diagram of the P&O MPPT algorithm.

The P&O MPPT method is based on the property that the derivative of the PV module's power-voltage characteristic is positive on the left-hand side and negative on the right-hand side. If the derivative of the power-voltage characteristic is zero, as shown in Equation 1, the reference signal (V_{ref}) is held constant [16].

$$\frac{\partial P_{pv}}{\partial V_{pv}} = 0 \quad (1)$$

As shown in the flowchart in Figure 3, during the execution of the P&O MPPT process, the output voltage and current of the PV module are periodically sampled in successive sampling steps to calculate the corresponding output power and the power-voltage derivative. The MPPT process is carried out by adjusting

the reference signal of the PWM controller. The V_{ref} signal can be determined based on the equation in Equation 2 [16].

$$V_{ref}(n) = V_{ref}(n-1) + \Delta d \cdot \text{sign}\left(\frac{\partial P_{pv}}{\partial V_{pv}}(n)\right) \quad (2)$$

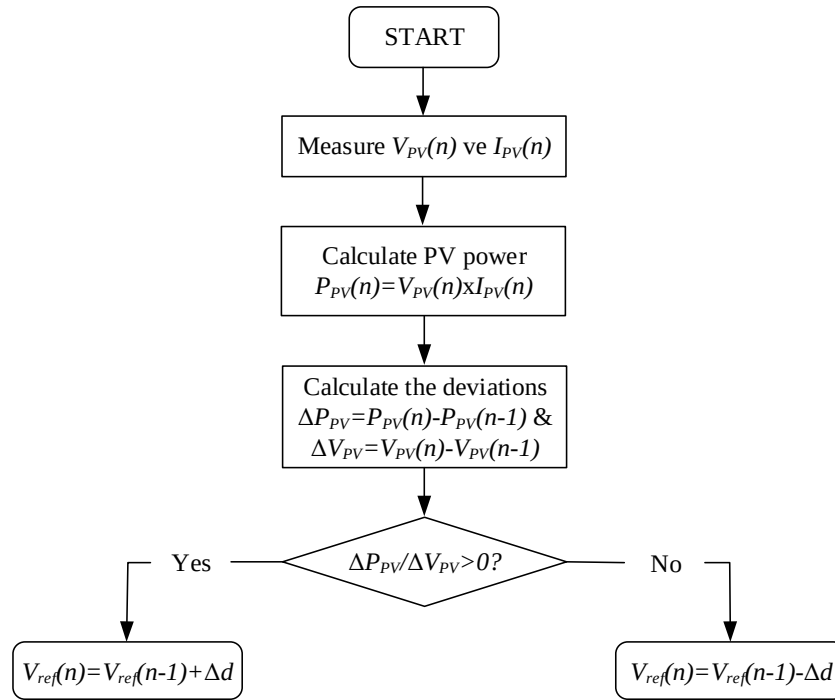


Figure 3. Flowchart of the P&O MPPT method [17].

The PWM signals required for the proposed DC-DC boost converter circuit are obtained by comparing a reference signal with a carrier signal. This is illustrated in Figure 4.

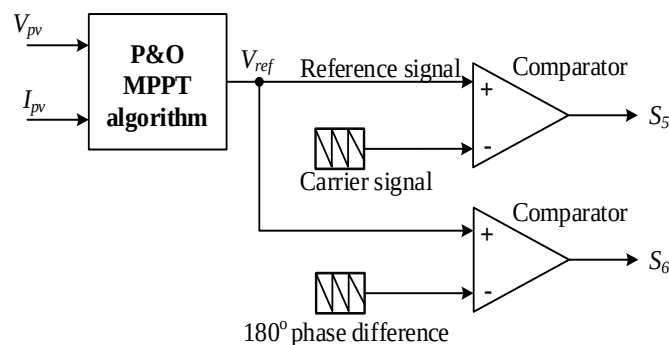


Figure 4. PWM_{boost} control architecture.

2.3. Inverter control structure

The control architecture shown in Figure 5 has been used in the inverter control of the PV system. Inverter PWM signals are generated by sampling the DC bus voltage (V_{dc}), PV panel power (P_{pv}), instantaneous grid voltage (v_g), instantaneous grid current (i_g) and RMS grid voltage ($V_{g,RMS}$).

As there is only a single variable (grid voltage) for synchronization in grid-connected single-phase PV systems, grid synchronization is a challenging task. In recent studies, various methods have been developed to

obtain grid voltage information, such as the zero-crossing method, filtered grid voltage methods, and phase-locked loop (PLL) techniques [18–21].

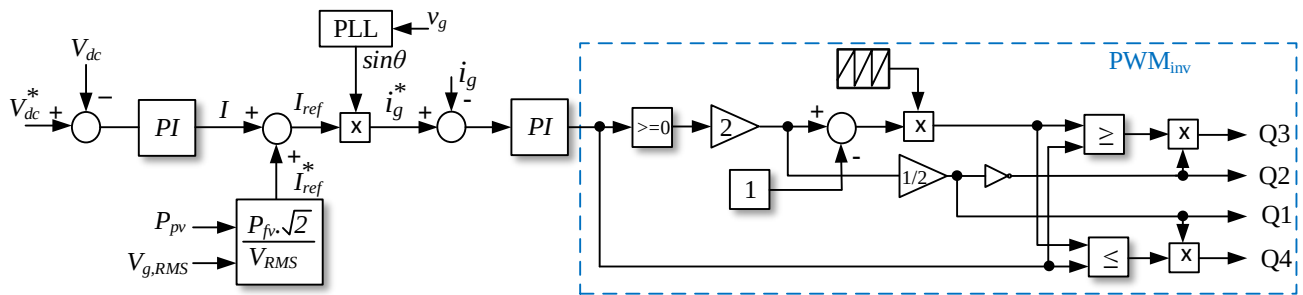


Figure 5. Inverter control architecture of a grid-connected single-phase PV system.

The mains voltage data was obtained using the single-phase PLL system, the general structure of which is shown in Figure 6. The SOGI-PLL structure shown in Figure 7.c was also used as the orthogonal system generation architecture.

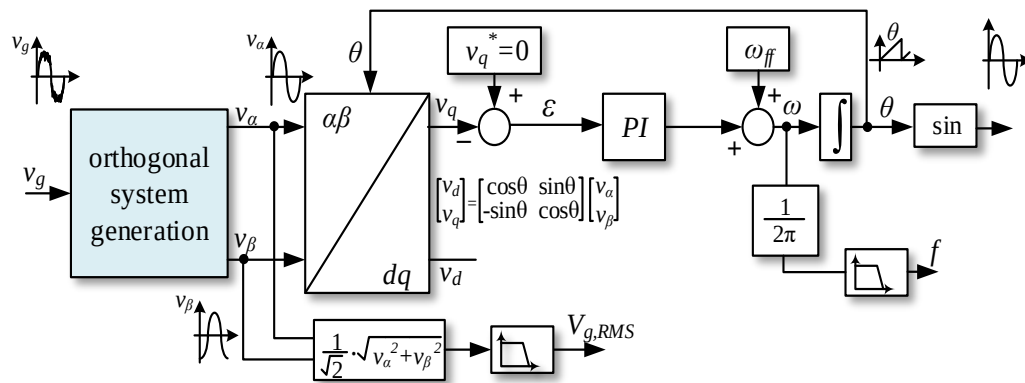


Figure 6. General structure of a single-phase PLL system [22].

The primary function of a PLL circuit is to ensure that the inverter output current operates at a unity power factor which involves synchronizing it with the mains voltage and to provide a pure sinusoidal current reference [23].

The PLL is used to detect the phase of the mains voltage; to this end, an orthogonal voltage system must be established. In single-phase systems, as there is less information regarding the grid state compared to three-phase systems, more advanced methods must be considered to create an orthogonal voltage system. Generally, the fundamental difference between various single-phase PLL methods lies in the structure of the orthogonal voltage system generation [22,23].

Figure 7 shows phase detection structures based on the T/4-delayed PLL [24], the enhanced PLL (EPLL) [25] and the second-order generalized integrator (SOGI) [23]. Studies on these three structures demonstrate that the SOGI-PLL offers a good solution for single-phase applications in terms of high tracking accuracy and fast dynamic response, particularly in situations where the grid voltage may experience various disturbances such as voltage sags and frequency variations [21].

In particular, using the SOGI-PLL architecture shown in Figure 7.c, the following three main tasks can be performed:

- Generation of the orthogonal voltage system;

- Delay-free filtering of the orthogonal voltage system;
- Decoupling the frequency of the overall structure (Figure 6).

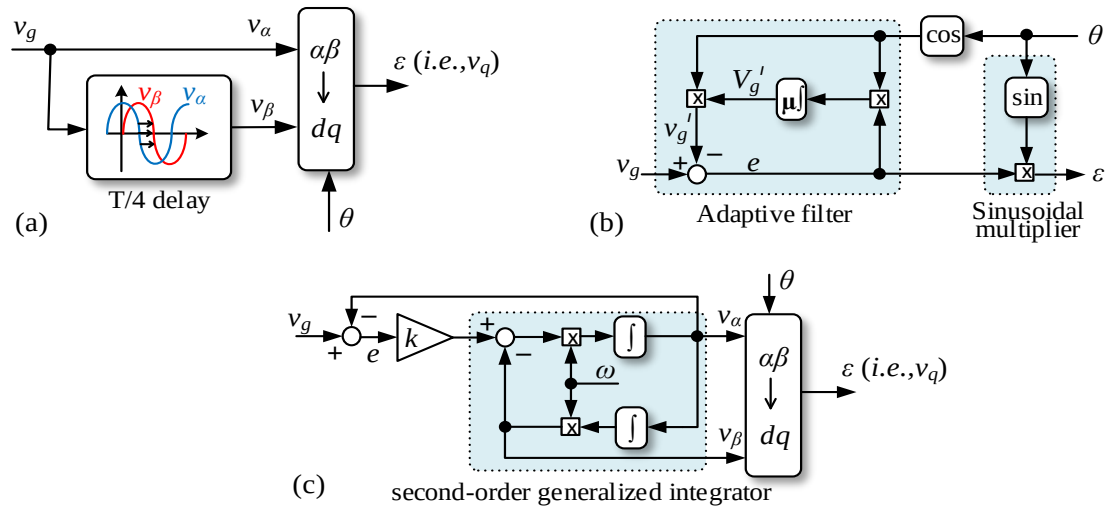


Figure 7. Phase detection architectures of single-phase PLL systems; (a) T/4 delay PLL (b) EPLL (c) SOGI-PLL.

In the SOGI-PLL architecture, the mains voltage (v_g) is filtered into two pure orthogonal waveforms, v_α and v_β , at the mains frequency (f) due to the SOGI resonance frequency. The level of filtering can be adjusted via the gain value k . If k decreases, the filtering becomes heavier, causing the filter's bandwidth to narrow

2.4. PV panel model

In the ANSYS Twin Builder simulation software, a PV panel model was created, as shown in Figure 8, using the SKYBASESOLAR SK125*125-M-72-195W PV panel employed in experimental studies as a reference.

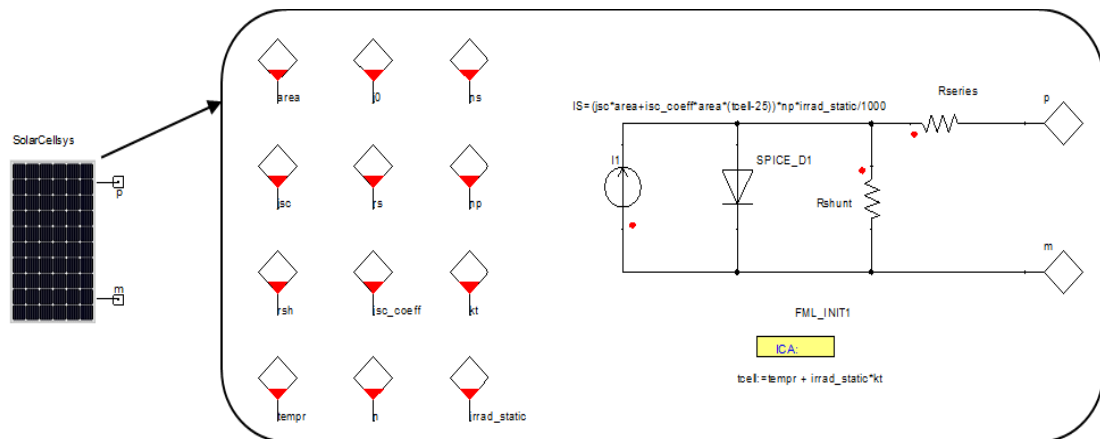


Figure 8. PV panel modelling workflow using ANSYS Twin Builder.

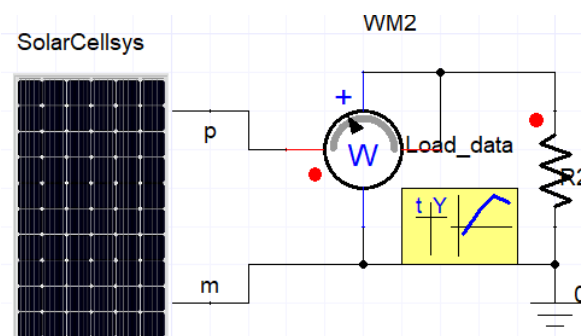


Figure 9. Circuit diagram for measuring the I-V and P-V characteristics of a PV panel.

The current-voltage (I-V) and power-voltage (P-V) characteristics of the circuit simulated in the ANSYS Twin Builder program, as shown in Figure 9, for the PV panel model under different irradiance and temperature conditions were observed. The characteristic curves obtained for the PV model are shown in Figures 10 and 11. The specifications of the reference PV panel are given in Table 1. These values were obtained by the manufacturer under standard test conditions, namely 1000 W/m² solar irradiance, 25 °C temperature and air mass 1.5.

Table 1. Specifications of the SK125*125-M-72-195W FV panel used as a reference.

Feature	Symbol	Value
Maximum Power	$P_{\max}$	195 W
Open-Circuit Voltage	V_{oc}	45.2 V
Maximum Power Voltage	V_{mpp}	37.3 V
Short-Circuit Current	I_{sc}	5.64 A
Maximum Power Current	I_{mpp}	5.23 A
Number of Cells in the Module	N_{cell}	72
I_{sc} Temperature Coefficient	α_{Isc}	0.05% / °C

Figure 10 shows the I-V and P-V characteristic curves at a constant irradiance of 1000 W/m² (G) and temperatures ranging from 10 to 70 °C. As can be seen, it can be said that the change in temperature has no significant effect on the current, but does cause a change in the voltage. An increase in temperature causes a decrease in the open-circuit voltage (V_{oc}), whilst resulting in a negligible increase in the short-circuit current (I_{sc}). At 10 °C, the open-circuit voltage is approximately 47 V, whereas at 70 °C it is approximately 40 V. The voltage suffers a loss of approximately 1.5–2 mV per degree of temperature change for each cell. This causes the maximum power point of the PV panel to shift. At 10 °C, the maximum power ($P_{\max}$) is 205 W, whereas at 70 °C it is 163 W.

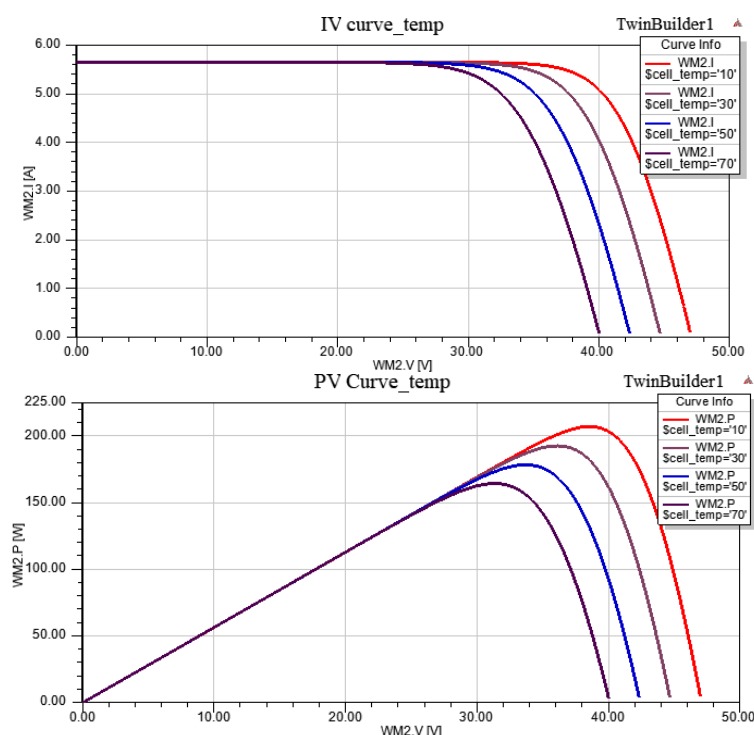


Figure 10. Variation in the I-V and P-V characteristics of the PV model at an irradiance of 1000 W/m² as a function of temperature (10, 30, 50, 70 °C).

Figure 11 shows the I-V and P-V characteristic curves at a constant temperature of 25 °C and varying irradiance levels of 400–1000 W/m². As can be seen, it was observed that the current varies significantly with irradiance, whilst the voltage changes very little. As solar irradiance increases, the short-circuit current increases in direct proportion, whilst the increase in open-circuit voltage is relatively smaller. Consequently, these changes also cause a shift in the PV panel's maximum power point. At an irradiance of 1000 W/m², the maximum power is 195 W, whereas at 400 W/m² it is 78 W.

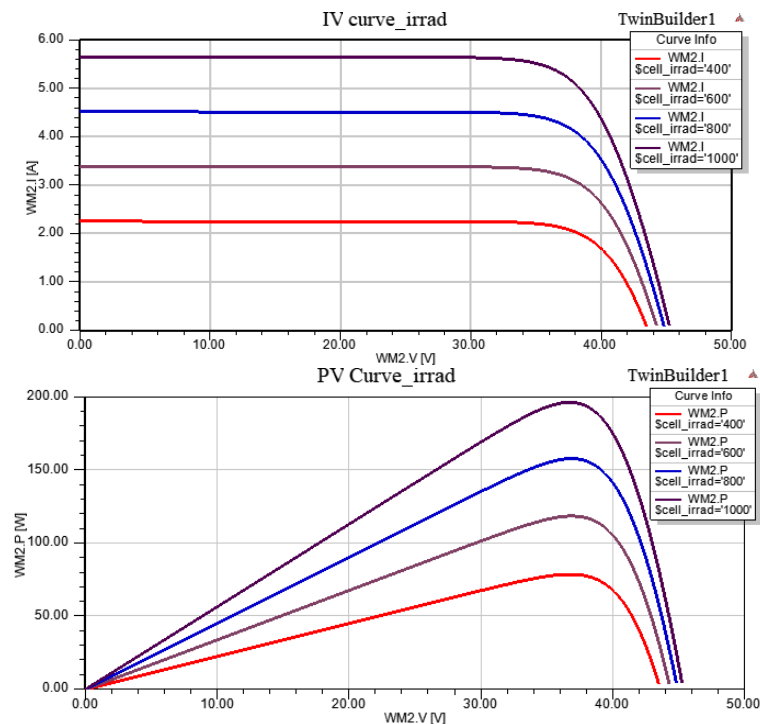


Figure 11. Variation in the I-V and P-V characteristics of the PV model at a temperature of 25 °C as a function of irradiance (400, 600, 800, 1000 W/m²).

Consequently, it can be seen from the characteristic curves of the PV panel that temperature changes affect the voltage; an increase in temperature reduces the panel voltage and, consequently, lowers the maximum power output that can be obtained from the panel. Changes in solar irradiance, however, cause a significant change in panel current whilst the change in voltage is minimal. An increase in irradiance leads to a substantial rise in current, whereas the voltage increases only slightly in comparison. Unlike temperature, an increase in solar irradiance increases the panel's maximum power output.

Table 2. Comparison of model values with reference PV panel values.

Characteristic	Reference panel values	The model's simulation values	Relative error (%)
$P_{\max}$ (W)	195	194.9948	0.0027
V_{oc} (V)	45.2	45.17	0.066
V_{mpp} (V)	37.3	36.62	1.82
I_{sc} (A)	5.64	5.64	0
I_{mpp} (A)	5.23	5.325	1.82
Efficiency (η %)	15.27	15.274	0.026

Table 2 presents a comparison of the values obtained from the PV model, which was simulated using the results of various performance parameters of the reference model under standard test conditions. As can be

seen, a good agreement has been observed between the reference SKYBASESOLAR SK125*125-M-72-195W panel and the simulation model. The relative error for all parameters of the solar PV model ranges from 0% to 1.82%. This simulation study confirms that there is consistency between the characteristic curves and the performance of the PV panel model.

2.5. Simulation circuit of a single-phase grid-connected PV system in ANSYS Twin Builder

The simulation circuit of the single-phase grid-connected PV system, which incorporates the proposed DC-DC boost converter and forms the subject of this thesis, is shown in Figure 12. The circuit parameters used in the simulation studies conducted for the entire PV system are given in Table 3.

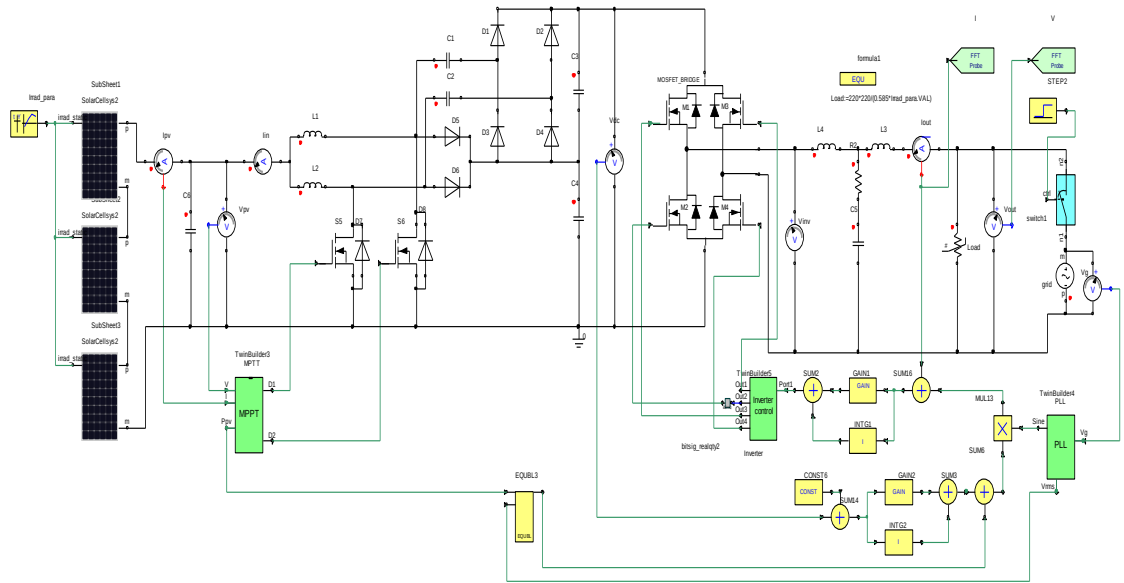


Figure 12. Simulation circuit of a single-phase grid-connected PV system in ANSYS Twin Builder.

Table 3. Parameters of the circuit used in the simulation of the entire PV system

Parameters	Value
PV panel maximum power, $P_{\max}$	585 W
Input voltage, V_{in}	110V
DC bus voltage, V_{dc}	400 V
Output voltage, V_o	220 V
Inverter switching frequency, $f_{s_{\text{boost}}}$	20 kHz
Inverter switching frequency, $f_{s_{\text{inverter}}}$	40 kHz
Inductors, L_1, L_2	1 mH
Filter inductors, L_i, L_g	4.52 mH - 100 μ H
Filter capacitor, C_f	1.8 μ F
Damping resistor, R_d	1.9 Ω
Capacitors, C_1, C_2	47 μ F
Output capacitors, C_3, C_4	470 μ F
DC-DC converter switches, S_5, S_6	IRFP460
Inverter switches, S_1, S_2, S_3, S_4	IRFP460
Diodes, $D_1, D_2, D_3, D_4, D_5, D_6$	DSEI30-06A
Solar irradiance, G	1000 W/m ²

In the simulation circuit, existing elements within the ANSYS Twin Builder program were utilized when creating the control blocks. Where a numerical link needed to be established between the input signals and the block-dependent variables at the block's output, an equation block (EQUBL) was used. The control diagram of the MPPT block used in the simulation circuit is shown in Figure 13. The Prove and Observe (P&O) algorithm was used as the MPPT algorithm. Existing blocks in Twin Builder were utilized when creating the control algorithm. In this control algorithm, the instantaneous voltage and current values of the PV panel were sampled to calculate the instantaneous power value. The instantaneous power value is compared with the previous power value to obtain the ΔP value. Accordingly, to ensure that the generated output power is always at its maximum value, the output voltage or current is increased or decreased. As a result of these operations, the reference voltage signal is compared with two sawtooth signals that are 180° out of phase, thereby generating two PWM signals that are 180° out of phase for the switching elements in each power stage.

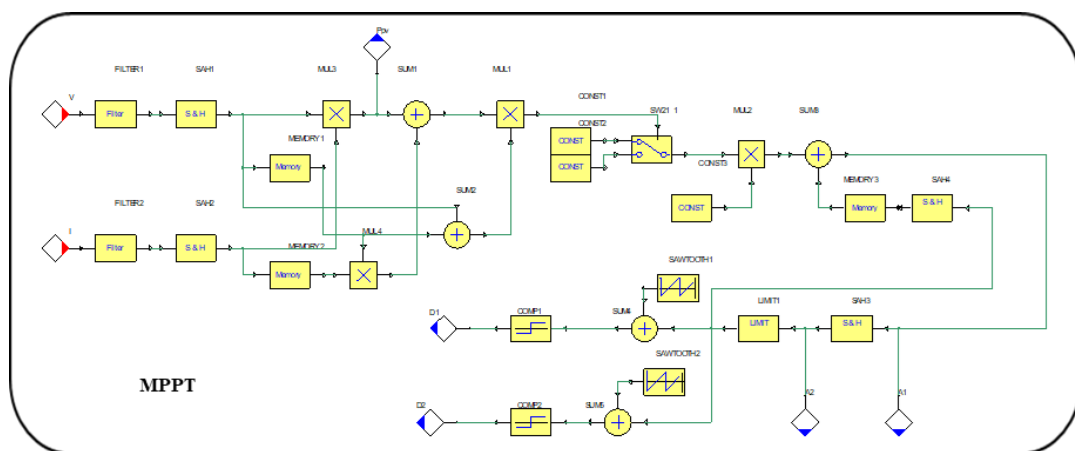


Figure 13. Block diagram of the P&O MPPT circuit.

The block diagram of the inverter control unit is shown in Figure 14.

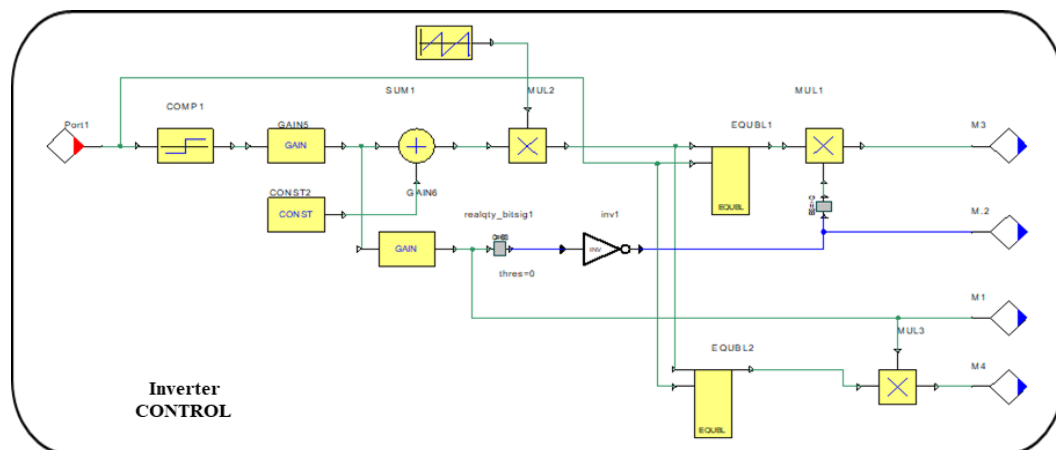


Figure 14. Block diagram of the inverter control system.

Figure 15 shows the block diagram of the PLL. As can be seen, only the instantaneous voltage (v_g) of the mains supply is sampled to determine the phase of the mains voltage, and the SOGI-PLL phase detection circuit is utilized.

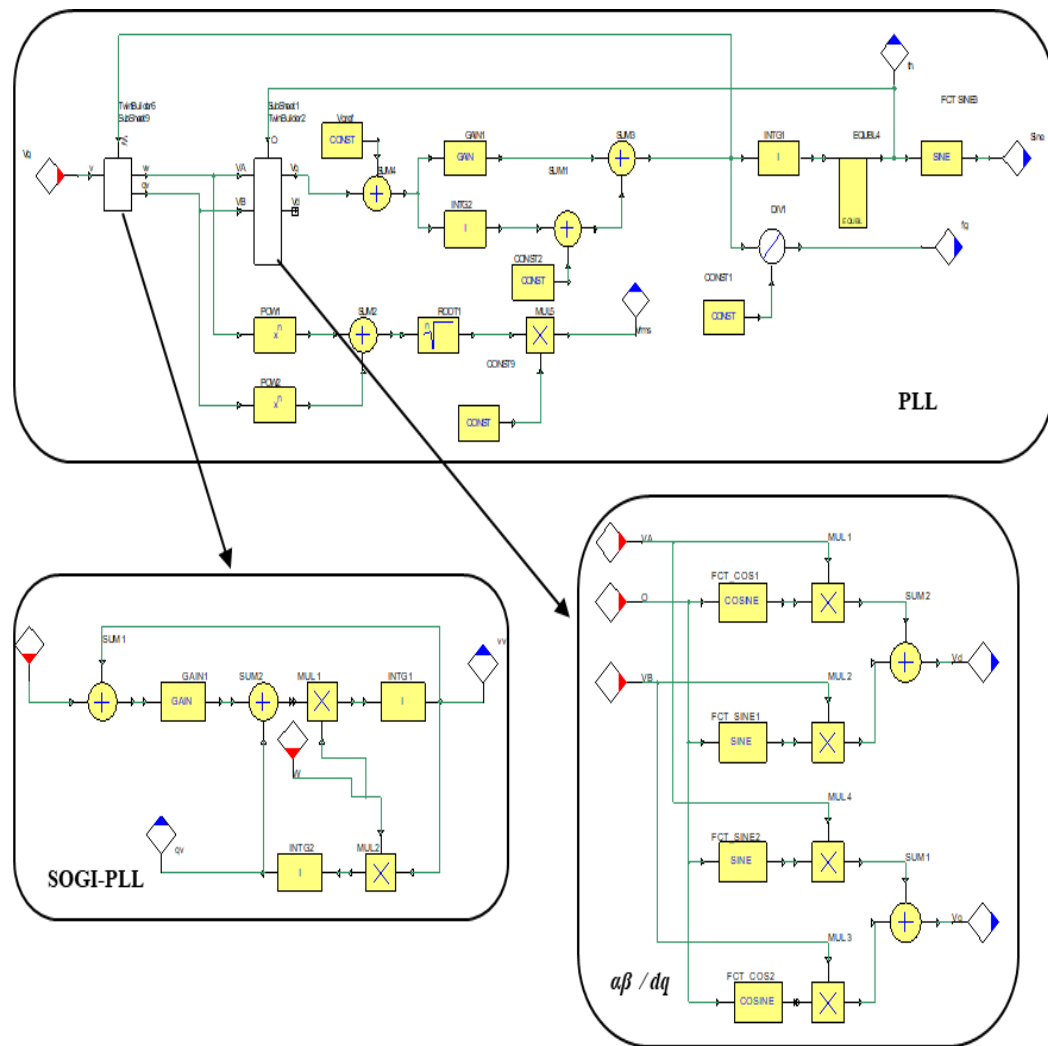


Figure 15. Block diagram of the PLL.

3. Results and Discussion

The power, current and voltage graphs for PV panels under different irradiance values are shown in Figure 16. Three PV panels, each modelled as 195 W in the simulation circuit shown in Figure 12, were connected in series. As can be seen, maximum power of 585, 435 and 290 W is obtained from the PV panels at irradiance levels of 1000, 750 and 500 W/m² (G), respectively. The maximum voltage obtained does not vary significantly as the irradiance changes and remains at approximately 110 V, whilst the maximum current takes on approximate values of 5.32, 4, and 2.67 A respectively.

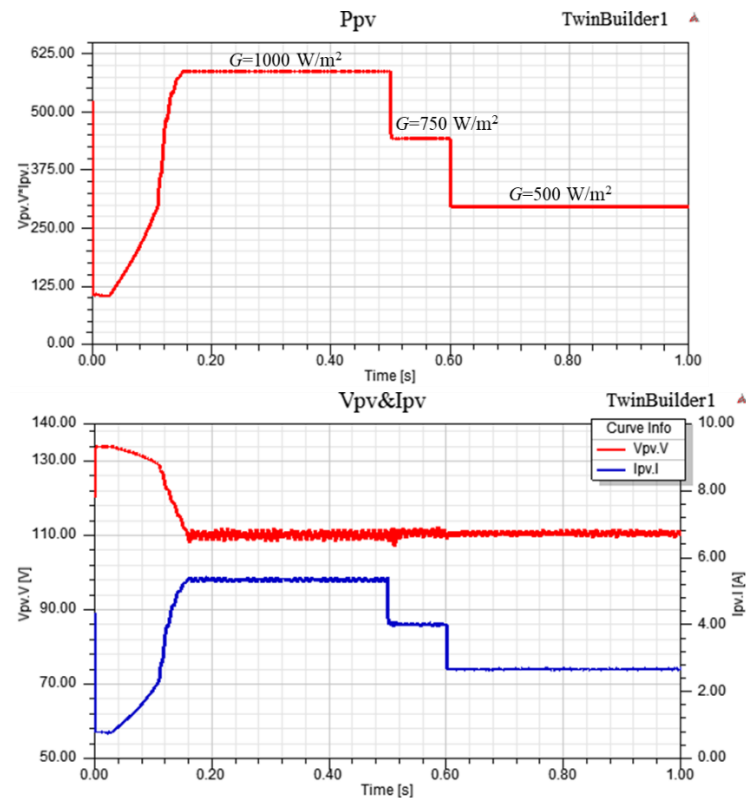


Figure 16. Graphs showing the maximum power, current and voltage of series-connected PV panels under different irradiance levels.

The waveforms of the currents flowing through the input inductors (L1, L2), to which the switching elements driven with a 180° phase difference which form the circuit's ladder structure are connected, and the resulting input current waveform are shown in Figure 17. It can be seen that the input current is distributed equally across the inductors and that the ripple ratio is low. As the current through one of the inductors in each power stage rises, the current through the other falls, resulting in an energy transfer from the inductors to the output.

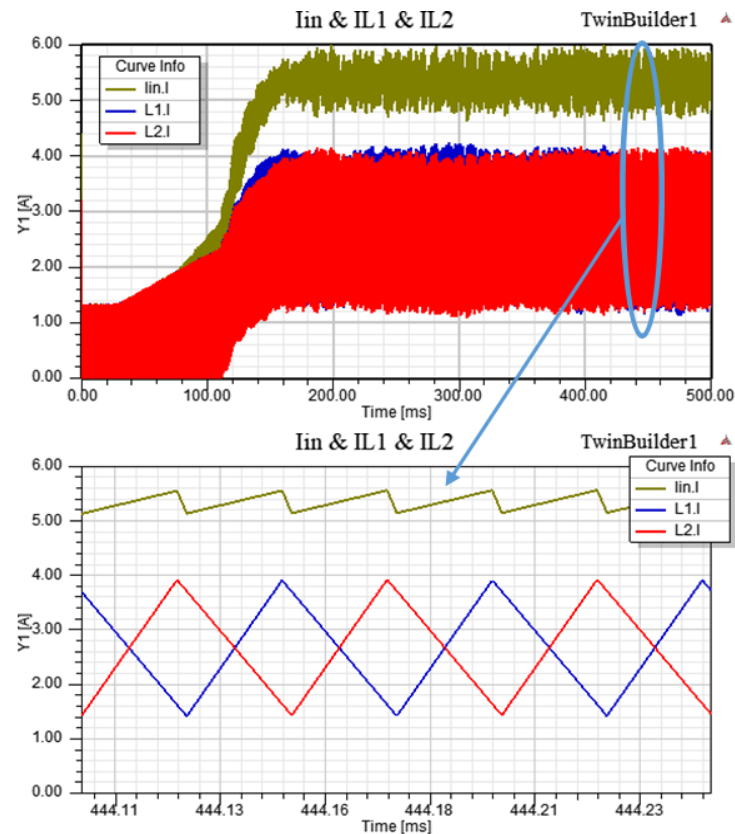


Figure 17. Waveforms of the input current (I_{in}) and the currents ($IL1$ – $IL2$) flowing through the series-connected inductors.

In the simulation circuit, the waveform of the bus voltage (V_{dc}) obtained at the output of the proposed DC-DC boost converter is given in Figure 18. It is observed that the voltage is fixed at 400 V and has a small ripple ratio between 2–4 V depending on the changing radiation intensity.

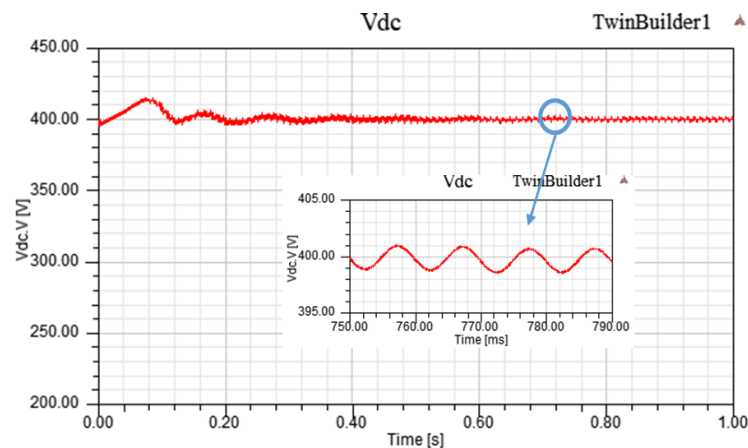


Figure 18. Graph of the DC bus voltage (V_{dc}) of the simulation circuit.

The trigger signals driving the switching elements in each power stage of the proposed DC-DC boost converter are shown in Figure 19. It can be seen that the signals have a 180° phase difference and a frequency of 20 kHz. With trigger signals having a duty cycle of less than 0.5 ($d = 0.45$) corresponding to an approximately 110 V PV panel voltage, a 400 V DC bus voltage is obtained (Figure 18).

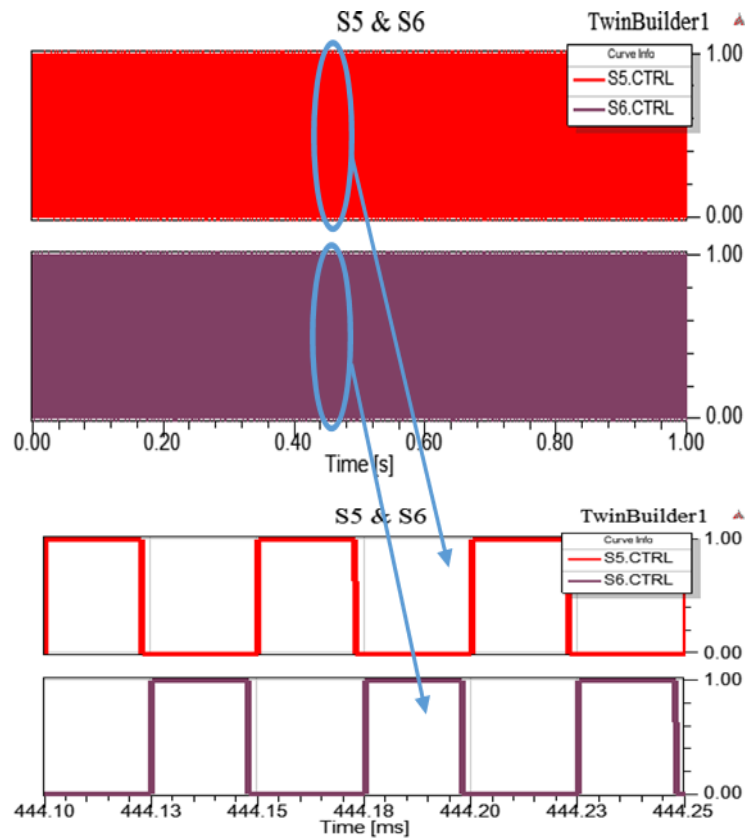


Figure 19. Trigger signals for the switching elements (S_5 , S_6) of the proposed DC-DC boost converter.

The waveforms of the output voltage (V_o), output current (I_o) and grid voltage (V_g) of the grid-connected PV system at different irradiance levels are shown in Figure 20. As can be seen, the PLL controller ensures that the inverter output current is in phase with the grid voltage. It can also be seen that the output voltage is in phase with the grid voltage and has the same amplitude. As the irradiance on the PV panel decreases, the output current of the PV system decreases; however, the output voltage remains unchanged and maintains the same amplitude as the grid voltage.

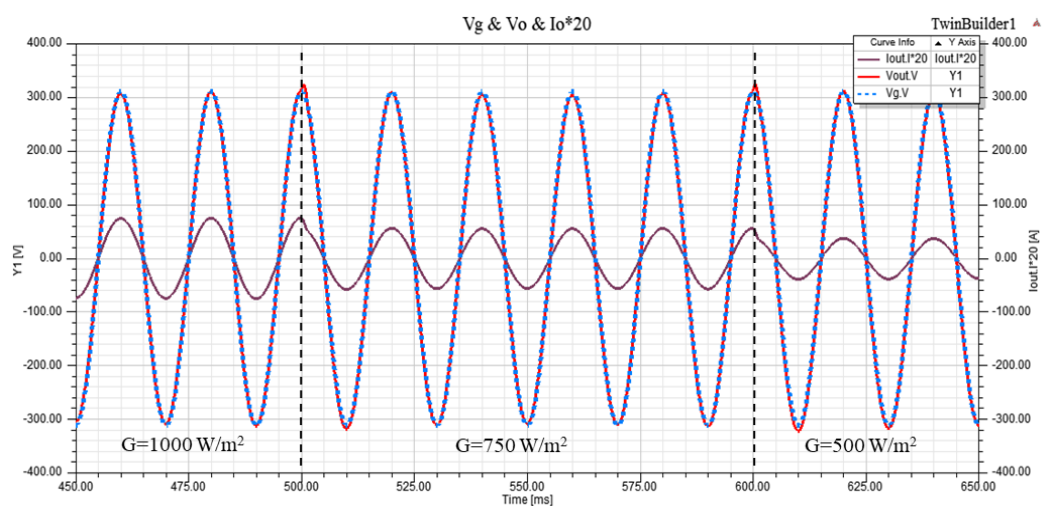


Figure 20. Waveforms of the output voltage (v_o), output current*20 (i_o*20) and grid voltage (v_g) for a grid-connected PV system at different irradiance levels

Figure 21 shows the waveforms of the inverter's pre-filter output voltage (V_{inv}) and post-filter output voltage (V_o). It can be seen that the pre-filter output voltage contains very high harmonic components. The LCL filter at

the inverter's output eliminates these harmonics, ensuring a smooth sinusoidal waveform at the circuit's output.

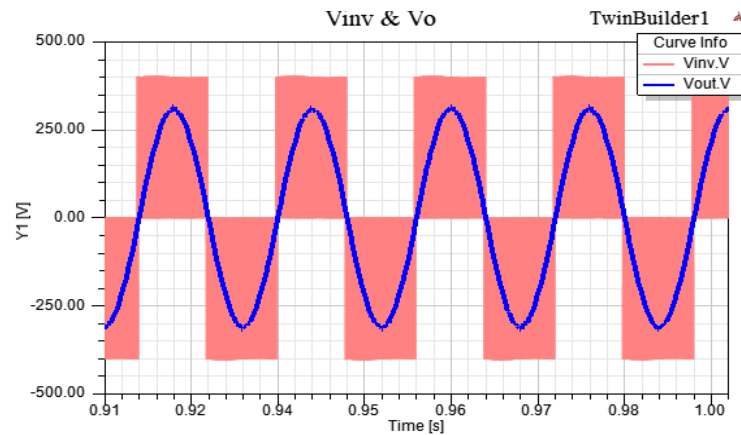


Figure 21. Waveforms of the inverter output voltage (V_{inv}) before the filter and the output voltage (V_o) after the filter.

The signals driving the switching elements in the H-bridge inverter of the simulation circuit are shown in Figure 22. It can be seen that the switching elements on the same arm (S_1 – S_2 and S_3 – S_4) are not conducting at the same time. During the periods when the S_3 – S_4 switches are on, they are driven by PWM signals with a frequency of 40 kHz.

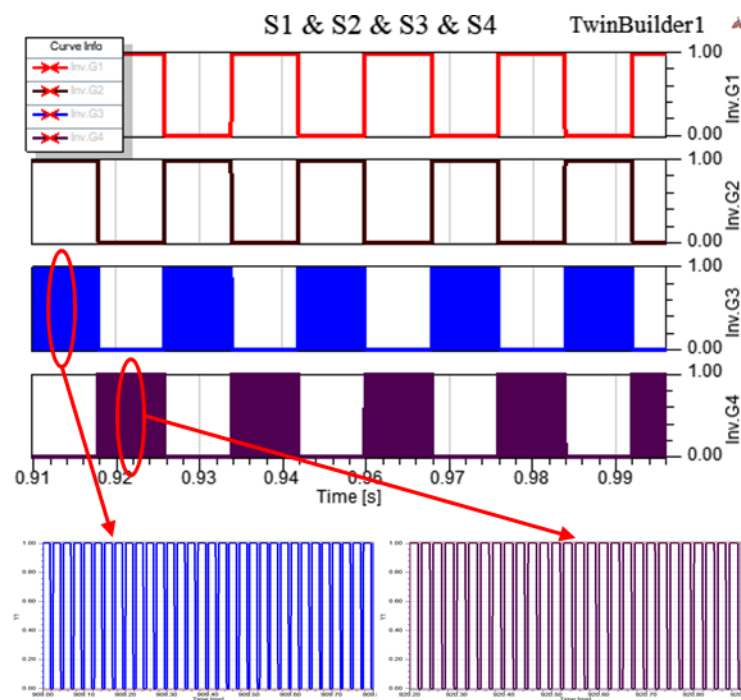


Figure 22. Trigger signals for the inverter's switching elements (S_1 , S_2 , S_3 , S_4).

The waveforms for the grid voltage frequency (f_g), phase (θ) and root mean square (V_{rms}) of the PV system are shown in Figure 23. The root mean square voltage is 220 V and the frequency is 50 Hz.

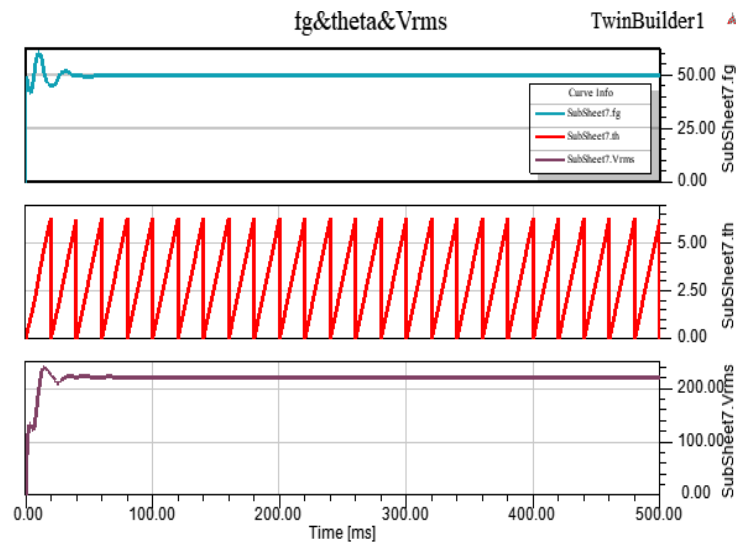


Figure 23. Waveforms of the grid voltage frequency (f_g), phase (θ) and root mean square value (V_{rms}) of the PV system.

The THD ratios for the output voltage and current obtained from the simulation of the PV system are shown in Figure 24. As can be seen, the THD ratio for both voltage and current is a very low value of 0.8%. These values are below the standards specified by the IEEE for voltage and current harmonics (IEEE Std 519-2022, 2022). Consequently, it is concluded that the designed LCL filter exhibits high performance.

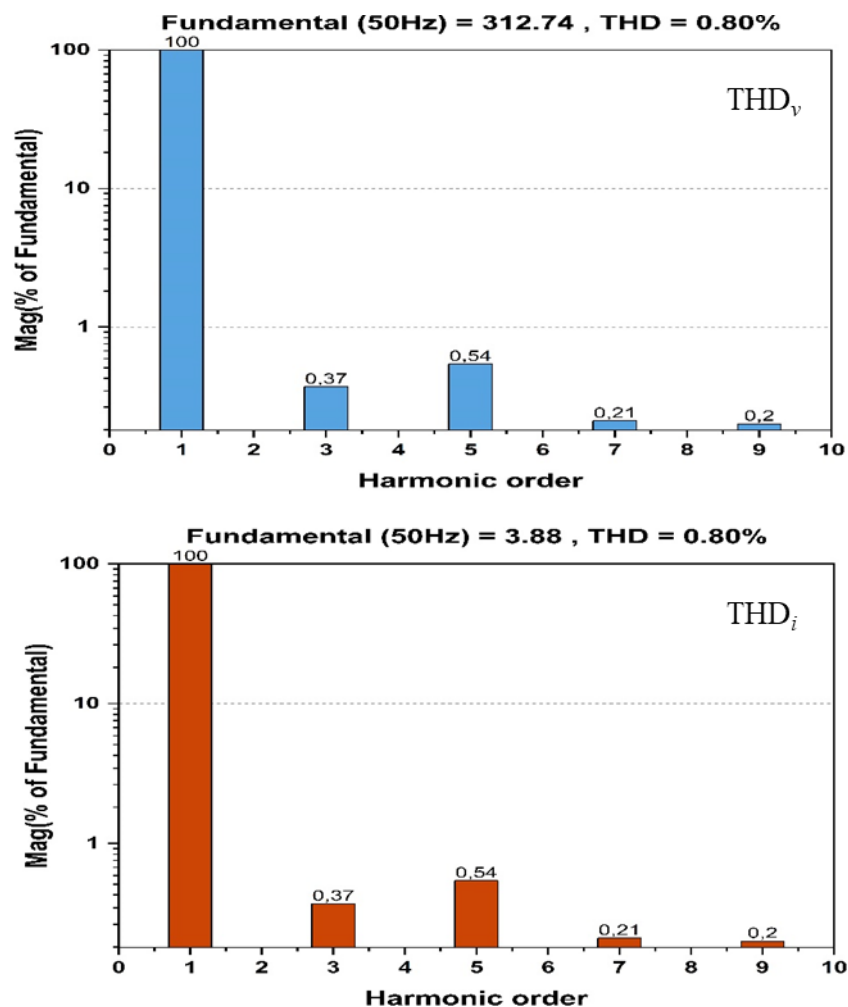


Figure 24. THD ratio of the output voltage and current of the simulation circuit.

4. Conclusions

The proposed grid-connected photovoltaic system was analyzed in the ANSYS Twin Builder environment under various irradiance and temperature conditions. The results obtained demonstrate that the system performs successfully in terms of stable operation and high power quality. Upon examining the behavior of the PV panels, it was observed that power and current increased with rising irradiance, whilst the voltage remained largely constant; this finding is consistent with the literature.

Using a high-efficiency DC-DC converter, a stable DC bus voltage of 400 V was achieved from an input voltage of approximately 110 V. The achievement of high voltage gain even at low duty cycles demonstrates the effectiveness of the proposed topology. On the inverter side, phase alignment with the grid was achieved through PLL-based control, and it was observed that the output current was in phase with the grid voltage.

The results of the harmonic analysis confirm the effectiveness of the LCL filter. The fact that the total harmonic distortion ratio is approximately 0.8% for both voltage and current indicates that the system complies with IEEE standards.

Overall, the proposed framework offers a more comprehensive approach compared to existing literature by integrating power electronics, control and multi-domain modelling, and provides significant contributions to both academic research and practical applications.

This study is simulation-based, and the future hardware-level validation of the system emerges as a key requirement. Furthermore, the implementation of more advanced control methods in place of the PI-based control structure holds the potential to enhance system performance, particularly under dynamic operating conditions. To make the model more realistic, it is recommended that multi-domain effects such as thermal effects, switching losses and electromagnetic interference be taken into account. Furthermore, the evaluation of the system in a hybrid configuration with energy storage units and a more comprehensive analysis of grid interactions are considered important areas of research for future studies.

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