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The Influence of Solar Irradiance and Temperature on The Pll-Synchronized Inverter Within Grid-Connected PV Systems

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Abstract

This study assesses the influence of solar irradiance and temperature on aβPLL synchronized inverters by investigating their intricate relationship within grid-connected PV systems. The intermittent nature of the DC side of these systems can significantly impact their performance. However, the extent of this impact remains uncertain when employing the stationary reference frame PLL (aβPLL) algorithm for synchronization with the utility grid. Employing simulation in MATLAB 2020a and a Model Based Design approach in the Simscape toolbox of SIMULINK, we conducted this investigation through two test scenarios: one with constant solar irradiance and varying temperature, and the other with varying solar irradiance and constant temperature. Our results indicate that fluctuations in solar irradiance and temperature have minimal effects on the output parameters of grid-connected PV systems when synchronized with the stationary reference frame PLL (aβPLL) algorithm. This conclusion is supported by the total harmonic distortion values, which all fall within the specified limits of IEEE Standard 929-2000. These findings underscore the potential of aßPLL synchronization as a promising technique, capable of effectively synchronizing grid inverters even in the presence of DC input distortion. This proficiency in grid integration holds promise for enhancing the integration of renewable energy sources into the grid, thereby bolstering power availability for household distribution.

Keywords: Photovoltaic System, Grid-connected inverter, Phase locked loop, Solar irradiance, and Temperature

INTRODUCTION

The significance of Photovoltaic (PV) systems lies in their capacity to harness solar energy, a pivotal aspect in advancing the sustainable development goal of providing access to affordable, reliable, and modern energy. With the global target for 2030 aimed at substantially increasing the share of renewable energy in the global energy mix (Pinar, 2024), the trajectory of PV systems' growth is undeniable. This growth is attributed to their capability to tap into abundant solar energy resources at relatively low installation costs (Kabalc, 2020). However, when integrating PV systems into AC grids using grid-connected inverters (GCIs), adherence

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to standard grid specifications becomes imperative (El Aroudi et al., 2022). Compliance with various grid requirements ensures the safe and dependable operation of PV sources integrated into the utility grid (Ali et al., 2023), with power quality, synchronization, and total harmonic distortion (THD) emerging as paramount parameters (Ali *et al.,* 2022).

The technical challenges associated with synchronizing grid-connected inverters (GCIs) with the utility grid have become a focal point in academic and research circles (Ali et al., 2018). This attention is fueled by the growing adoption of renewable energy sources, particularly solar PV systems, aimed at bolstering grid stability and reliability (Dang et al., 2020). A key challenge in this arena is ensuring seamless synchronization between the fluctuating output of PV systems and the stable utility grid. The phase-locked loop (PLL) method stands out as a commonly employed technique for detecting these components (Ali *et al.,* 2023), serving as an essential algorithm for synchronizing GCIs with the AC grid. Notably, the stationary reference frame PLL (αβPLL) is esteemed for its resilience in synchronization, harmonic filtering capabilities, and stability when deployed in grid-connected PV systems (Monjo et al., 2024a).

Recent research endeavors have particularly focused on comprehending the intricate dynamics among solar irradiance, temperature variations, and grid-connected PV systems (Chumpolrat et al., 2014; Madhukumar et al., 2020). Solar irradiance and temperature fluctuations, inherent to outdoor environments, can significantly impact the performance and efficiency of PV systems (Bhavani et al., 2021; Younas *et al*., 2019). Consequently, investigating the interactions between these environmental factors and the behavior of grid-connected inverters is pivotal for optimizing system design and operation.

This paper presents a comprehensive evaluation of the impact of solar irradiance and temperature on the αβPLL synchronized inverter by scrutinizing the complex interplay among solar irradiance, temperature variations, and grid-connected PV systems

METHOD

This study was conducted using simulation via the Model-Based Design (MBD) approach. In MBD, a system model takes center stage in the development process, guiding activities from requirement development to design, implementation, and testing (Andrews *et al*., 2021; Mina *et al.,* 2016). Figure 1 provides an overview of the Model-Based Design process.

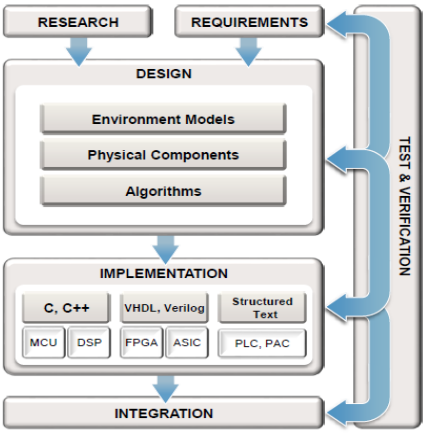


Figure 1: An overview of model-base design (https://www.mathworks.com/solutions/model-based-design.html)

In a grid-connected PV system, the intensity of solar radiation directly influences the short circuit current (Isc) of the PV array, with higher intensities resulting in higher Isc values. Conversely, the temperature of the PV array plays a significant role in determining the open circuit voltage (Voc), with Voc decreasing as temperature increases (Bhavani *et al.,* 2021). The intermittent nature of solar energy prompts an investigation into the effects of solar irradiance and temperature on the αβPLL synchronized inverter within a grid-connected PV system. We conducted this investigation through two test scenarios:

1. Keeping solar irradiance constant while varying temperature.
2. Varying solar irradiance while keeping temperature constant.

Furthermore, harmonic analysis was performed on the grid current to assess its quality. This study was carried out via simulation using the MATLAB/SIMULINK 2020a platform. The grid-connected PV system was tested and validated utilizing the SIMSCAPE TOOLBOX. The two test conditions were evaluated using a 2KVA αβPLL synchronized inverter model integrated with the utility grid, as illustrated in Figure 2.

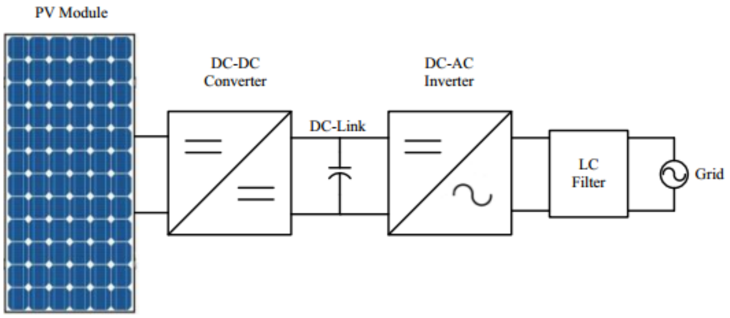


Figure 2: Block diagram of a grid-connected PV system

SIMULATION PROCEDURE

Using the design parameters provided for the grid-connected PV system and the utility grid outlined in Table 1, a circuit model was simulated for the grid-connected PV system integrated with the αβPLL using Simscape Power Systems. This platform was utilized for modeling, simulating, developing control systems, and testing the system-level performance of electrical power systems within MATLAB Version R2020a. Simulation data was logged into the MATLAB workspace for further analysis.

Table 1: Design Parameter of Single Phase Grid-connected Photovoltaic System

S/N	PARAMETER	SYMBOL	VALUE
1	Rated power of the System	P_n	2KW
2	DC Link voltage	V_{dc}	435
3	Grid voltage Amplitude	v_m	$220 \times \sqrt{2}\,V$
4	Nominal Grid frequency	ω_g	100π rad
5	LCL filter		
		L_1 and L_2	20×10^{-4}H
		C	10×10^{-6}F
6	Active power	P_L	$220 \times \frac{10}{\sqrt{2}}\,W$
7	Reactive Power	Q_L	$220 \times \frac{1}{\sqrt{2}}$
8	PV Array		
	Open circuit voltage	V_{oc}	36.3 V
	Short circuit current	I_{sc}	7.84 A
9	Solar Irradiance	I_r	Varied
10	Temperature	T	Varied

The Model-Based Design (MBD) of the grid-connected PV system is depicted in Figure 3. The model underwent two test conditions to assess the impact of solar irradiance and temperature on the αβPLL synchronized inverter within the grid-connected PV system. During the simulation, solar irradiance was initially maintained constant at 1000 W/m² while temperature was varied from 25°C to 50°C. Conversely, in another simulation scenario, temperature was held constant while solar irradiance was varied from 1000 W/m² to 400 W/m².

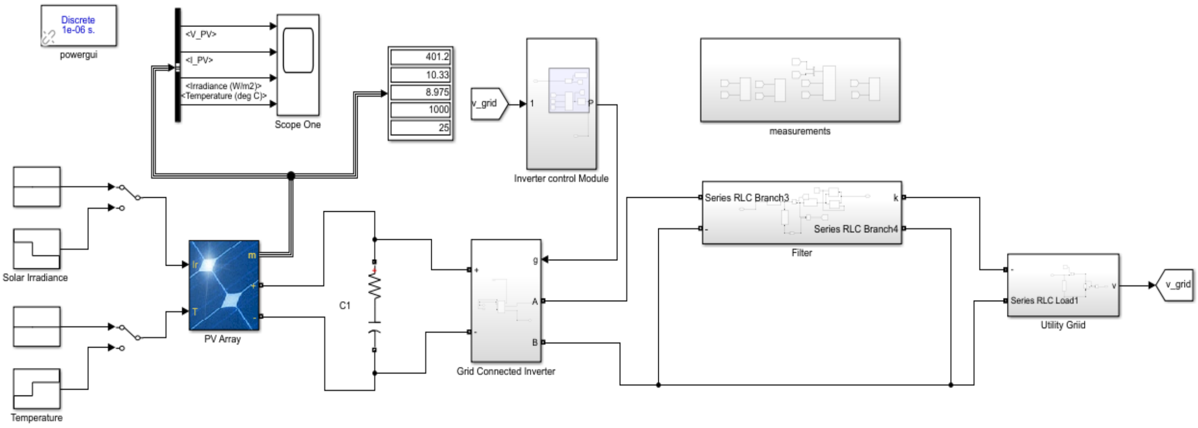


Figure 3: Model based design of the Grid-connected PV system

SIMULATION RESULTS

The PV Array block from the Simscape toolbox of SIMULINK was utilized to implement an array of photovoltaic (PV) modules. The array consisted of 2 parallel strings of modules, each containing 15 series-connected modules per string. This block enables the modeling of preset PV modules sourced from the National Renewable Energy Laboratory (NREL) System Advisor Model within MATLAB. The responses obtained from "Scope One" at the input of the grid-connected PV system under varying solar irradiance and temperature conditions are presented in Figures 4 to 8.

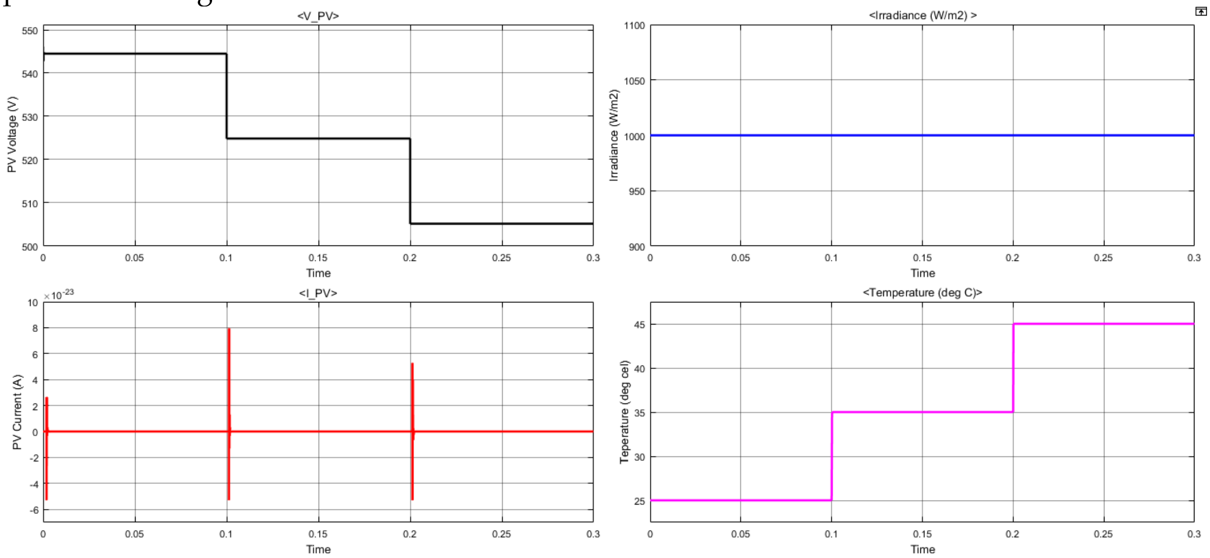


Figure 4: Response of input voltage and the temperature when the irradiance was kept constant

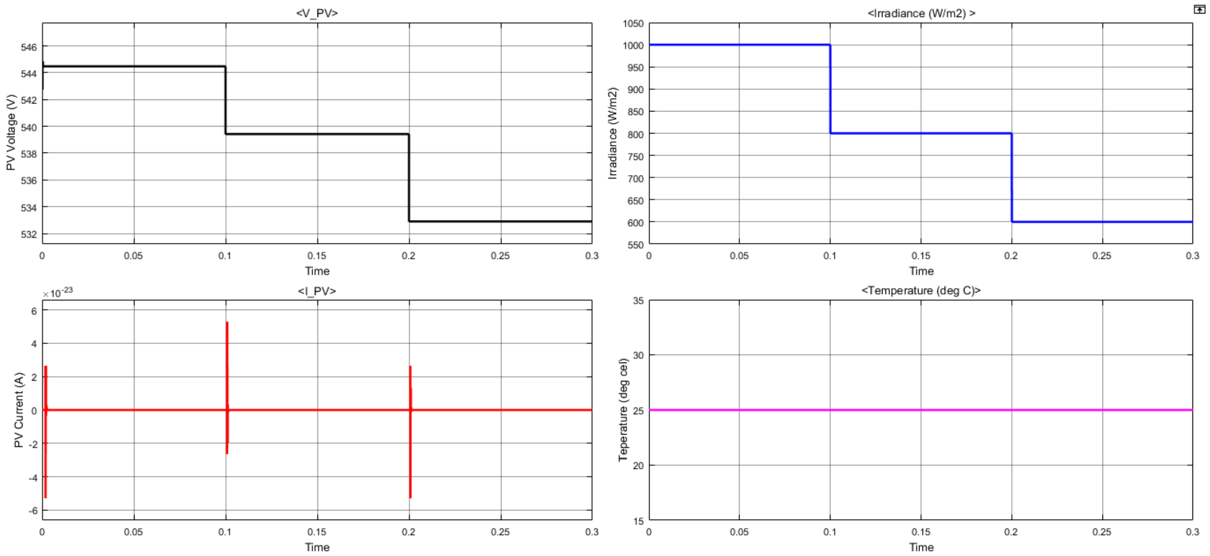


Figure 5: Response of input voltage and the irradiance when the temperature was kept constant

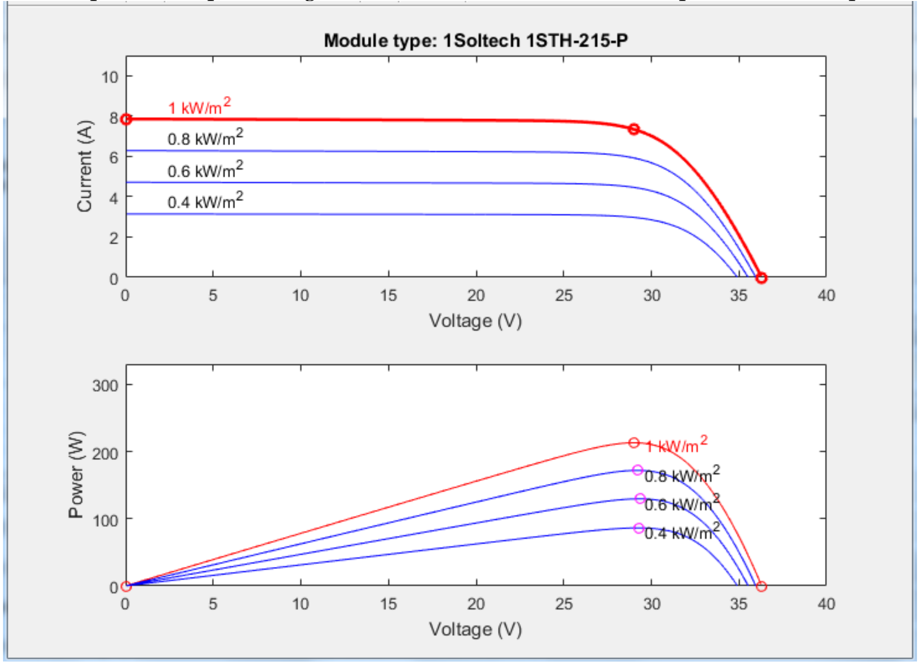


Figure 6: Variation of PV array power and current with voltage when temperature is constant

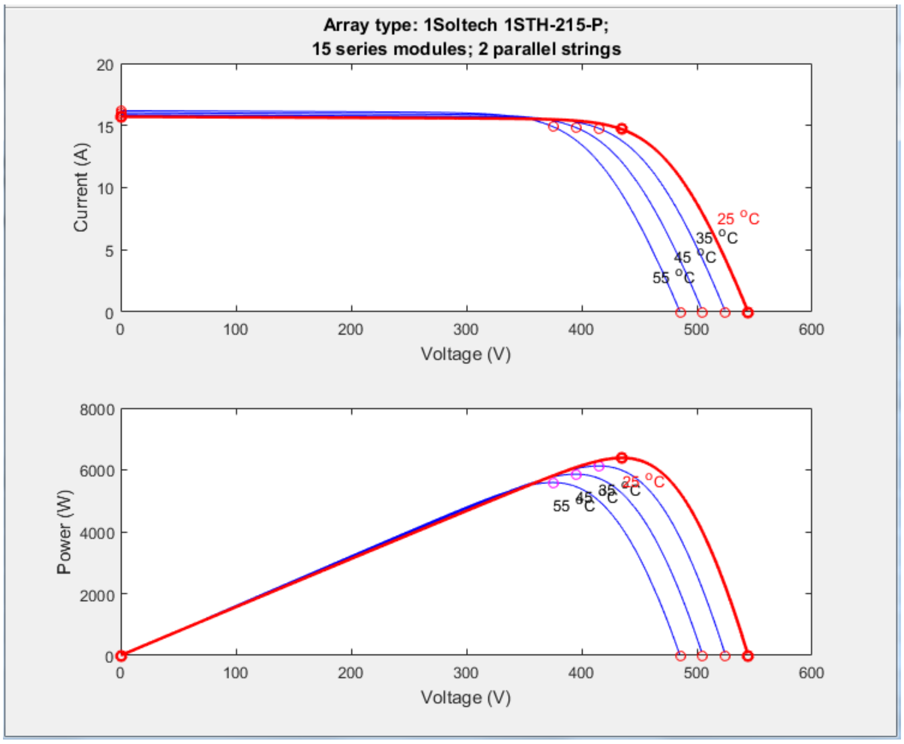


Figure 7: Variation of PV array power and current with voltage when irradiance is constant

The responses for evaluation of the impact of solar irradiance and temperature on the αβPLL synchronized inverter for the two test conditions were presented as follows.

Responses of αβPLL Synchronized Inverter When the Solar Irradiance Was Kept Constant and The Temperature Was Varied

The response performance of αβPLL synchronized grid-connected inverter at the output between the inverter and the utility grid when the solar irradiance is kept constant at 1000W/m^2 and the temperature is varied from 25^{o}C to 55^{o}C are presented in figure 8 to 11

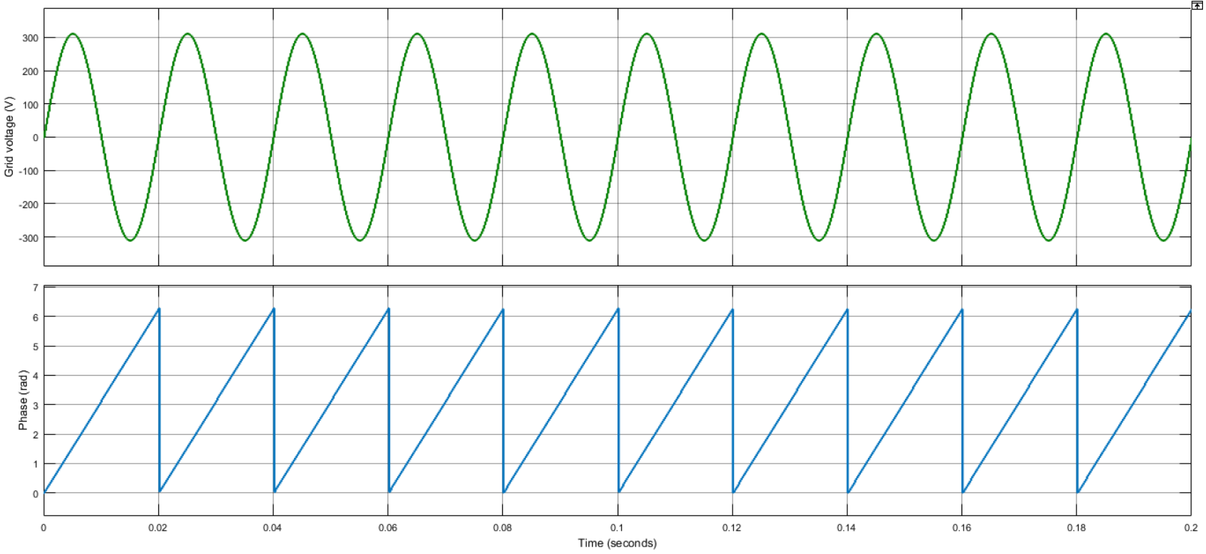


Figure 8: Grid voltage waveform and phase angle detected by the αβPLL (Test case 1)

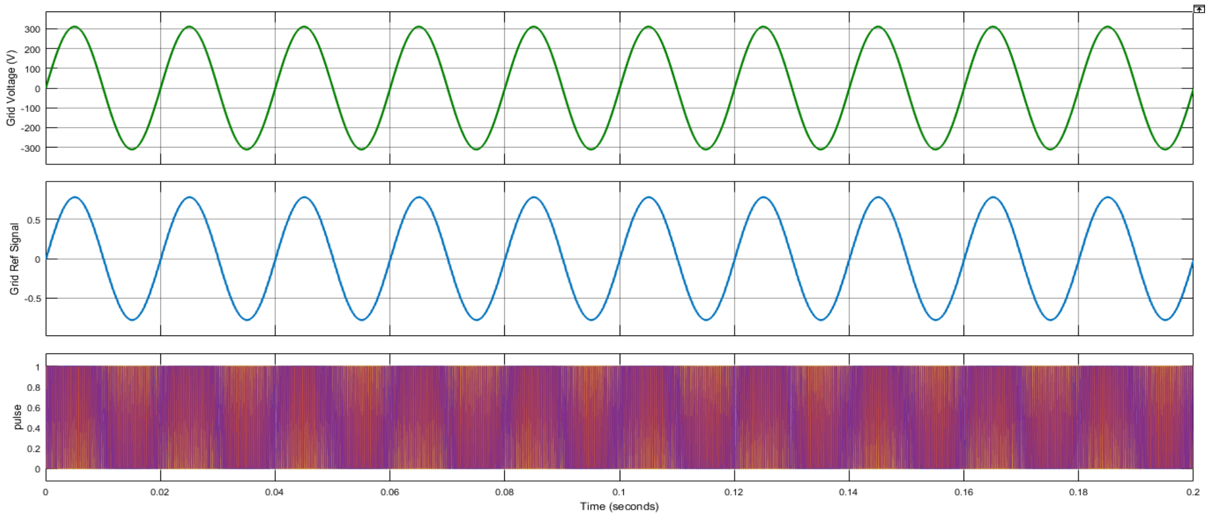


Figure 9: The grid voltage, the reference signal, and the pulses generated to drive the gate of the inverter (test case 1).

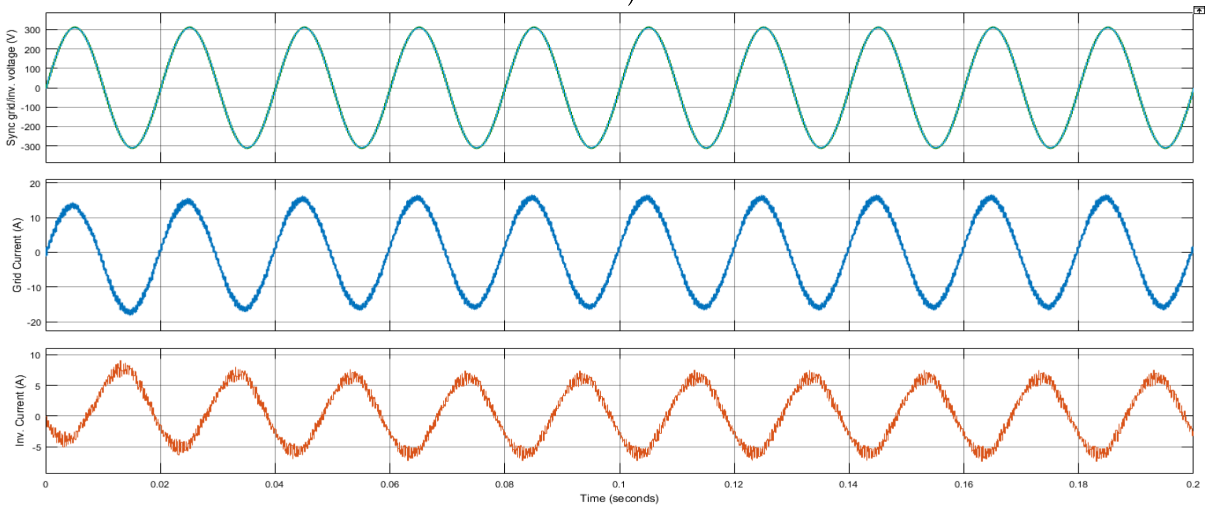
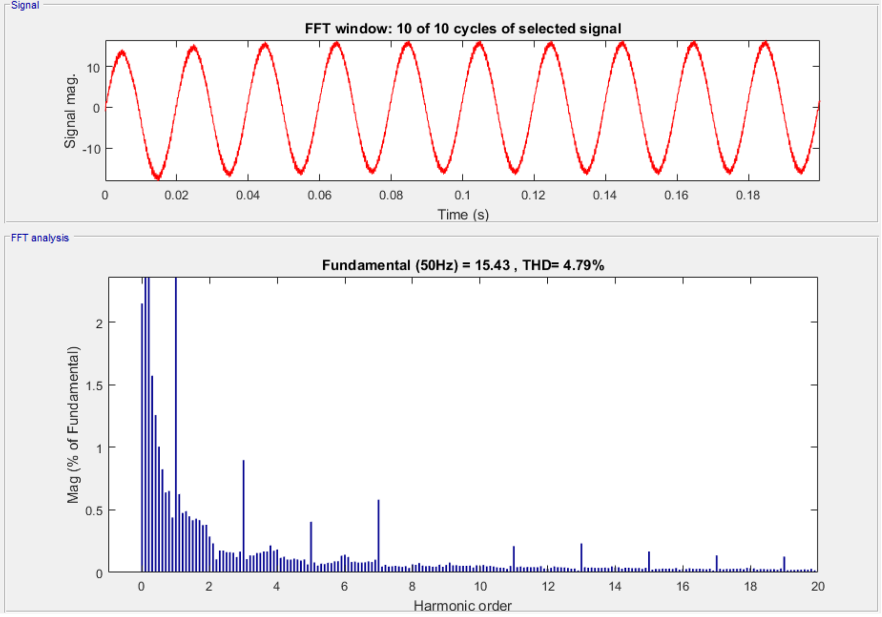


Figure 10: Synchronized grid and inverter voltage together with the grid and inverter current (Test case 1)



FFT window: 10 of 10 cycles of selected signal

Fundamental (50Hz) = 15.43 , THD= 4.79%

Figure 11: Harmonic analysis of the grid current (Test case 1)

Responses of αβPLL Synchronized Inverter When Temperature Was Kept Constant and Solar Irradiance Was Varied

The response performance of αβPLL synchronized grid-connected inverter at the output between the inverter and the utility grid when the temperature was kept constant at 25°C and the solar irradiance is varied from 1000W/m² to 400 w/m² are presented in figure 12 to 15

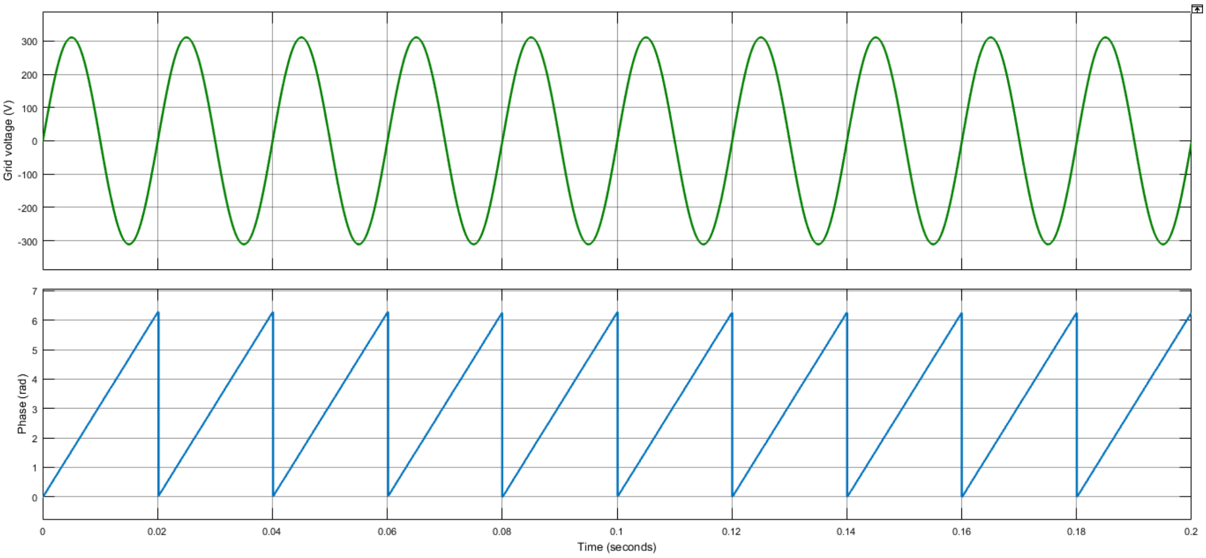


Figure 12: Grid voltage waveform and phase angle detected by the αβPLL (Test case 2)

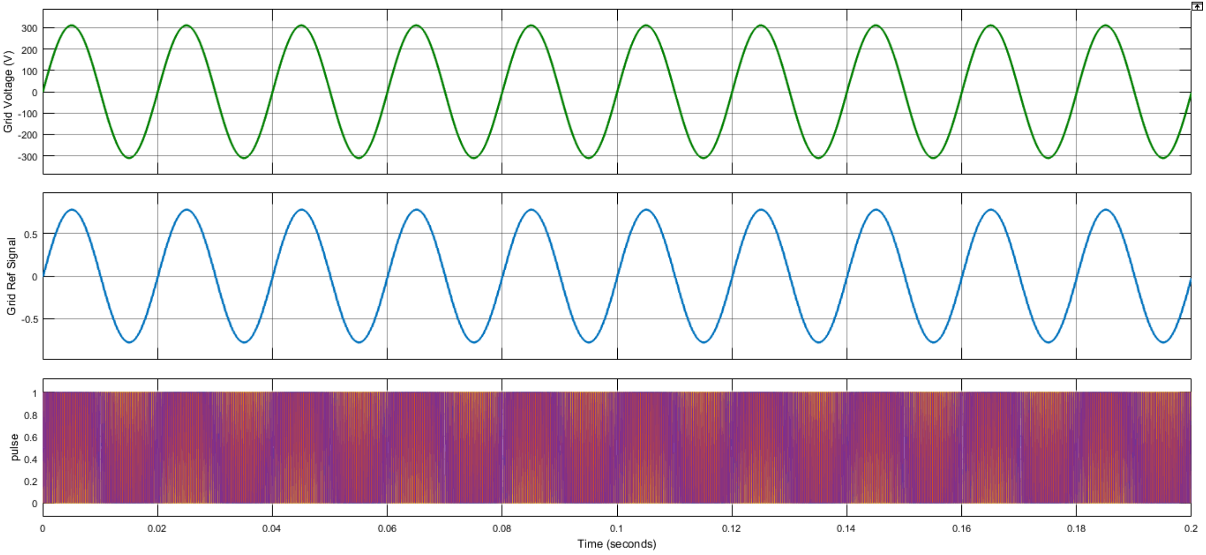


Figure 13: The grid voltage, the reference signal, and the pulses generated to drive the gate of the inverter (test case 2).

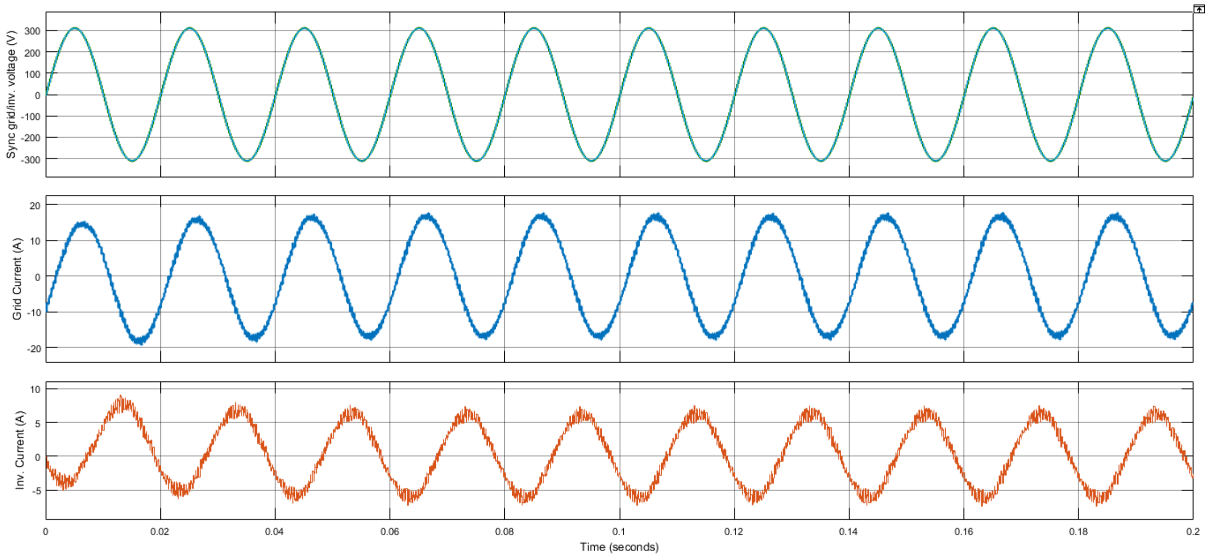


Figure 14: Synchronized grid and inverter voltage together with the grid and inverter current (Test case 2)

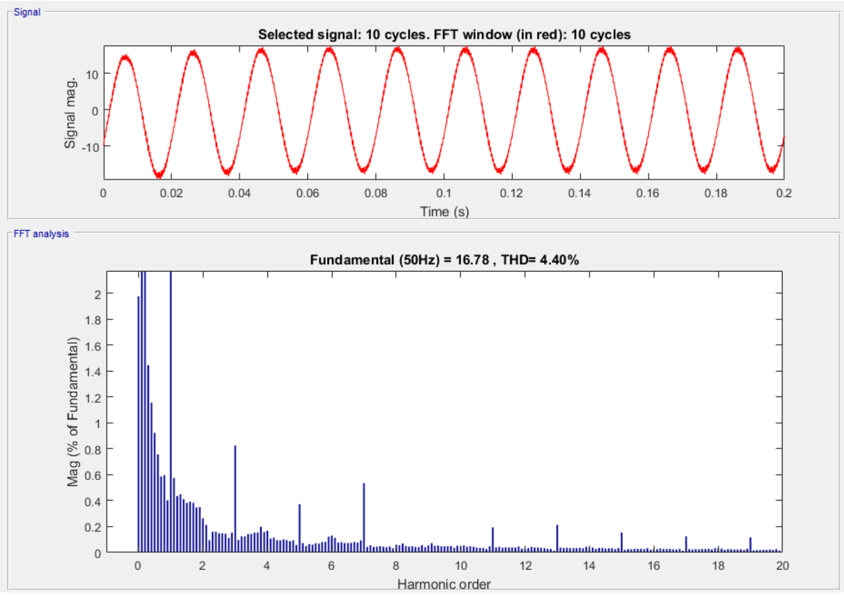


Figure 15: Harmonic analysis of the grid current (Test case 2)

DISCUSSION

The results obtained from varying solar irradiance and temperature in the DC link input of the grid-connected PV system are depicted in Figures 4 and 5. Figure 4 illustrates the scenario where irradiance remained constant while temperature varied. It is observed that the DC link voltage decreases with increasing temperature, while the variation in current remains imperceptible. Conversely, when the temperature was held constant and irradiance varied, it was noted that the current at the system's input increased with rising irradiance, while the variation in DC link voltage was negligible. Figures 6 and 7 show the variation of PV array power and current with voltage when temperature and irradiance are constant, respectively. Both figures indicate a decrease in overall power input due to a decrease in current and voltage resulting from reduced irradiance and increased temperature. These findings highlight the intermittency of the DC input of the system, prompting the evaluation of the impact of solar irradiance and temperature on the αβPLL synchronized inverter under two test conditions.

Analyzing the response performance of the αβPLL synchronized grid-connected inverter between the inverter and the utility grid under test case 1, where solar irradiance remained constant at 1000 W/m2 and the temperature varied from 25°C to 55°C, Figure 8 shows a perfectly triangular detected phase. This results in an estimated grid voltage with imperceptible variation, leading to a perfectly periodic reference signal used to generate pulses for driving the inverter gate via PWM, as depicted in Figure 9. Figure 10 demonstrates the perfectly synchronized grid and inverter voltage, with an initial synchronization time of 20ms. However, the grid current exhibits slight disturbances with harmonics. Harmonic analysis, as shown in Figure 11, indicates a total harmonic distortion of 4.79%, within the specified limits of IEEE Standard 929-2000.

Similar results were obtained for test case 2, where the temperature was kept constant at 25°C and solar irradiance varied from 1000 W/m^2 to 400 W/m^2, as presented in Figures 12 to 15. However, the distortion from harmonics in the grid current is lower compared to that in test case 1. Harmonic analysis in Figure 15 indicates a THD of 4.4%, also within the specified limits of IEEE Standard 929-2000. Overall, the results indicate that variations in solar irradiance and temperature have minimal significance on the output parameters of the grid-connected PV system when synchronized with the stationary reference frame PLL (αβPLL) algorithm.

CONCLUSION

In conclusion, our study reveals that fluctuations in solar irradiance and temperature minimally affect the output parameters of grid-connected PV systems when synchronized with the αβPLL algorithm. Through rigorous investigation and simulation, we observed consistent performance of the αβPLL synchronized inverters under varying environmental conditions. The total harmonic distortion values, falling within IEEE Standard 929-2000 limits, further affirm the robustness of αβPLL synchronization in mitigating DC input distortion. These findings underscore the promising potential of αβPLL synchronization as an effective technique for integrating renewable energy sources into the grid, ultimately enhancing power availability for household distribution.

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