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Investigation of novel control strategies for grid-connected photovoltaic inverters

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Abstract

This paper delves into the evolution and innovation in control strategies for grid-connected photovoltaic (PV) inverters, underscoring their pivotal role in enhancing the efficiency, stability, and grid compatibility of solar energy systems. Beginning with an exploration of advanced modulation techniques and adaptive harmonic filtering, the discussion extends to sophisticated control algorithms, including fuzzy logic and deep learning-based approaches. The paper highlights the significance of addressing wideband harmonics, ensuring robust system performance against fluctuations, and the need for decentralized control strategies in 250-kW PV array connected to a 25-kV grid via a three-phase converter. Furthermore, it addresses the emerging cybersecurity challenges posed by the increasing sophistication of inverter systems. The integration of intelligent control methods, nonlinear dynamic models, and smart inverter functionalities is presented as a holistic approach to optimizing PV systems for a future where renewable energy seamlessly integrates into the existing energy infrastructure. The paper concludes by asserting the indispensable role of these advanced control strategies in paving the way for a sustainable, stable, and efficient energy future.

Keywords: *Photovoltaic inverter; advanced control; power quality; model predictive control; virtual impedance; grid integration.*

1. Introduction

The relentless pursuit of sustainable and renewable energy solutions has positioned photovoltaic (PV) systems at the forefront of the energy sector's evolution. Central to the effective functioning of these systems are grid-connected inverters, which serve as the linchpin in harnessing, converting, and delivering solar energy to the grid. Recent advancements have pivoted towards not just enhancing the efficiency of these systems but also ensuring their harmonious integration with the existing power infrastructure. This paper delves into the novel control strategies for grid-connected photovoltaic inverters, highlighting their implications, challenges, and the future trajectory of this dynamic field.

Grid-connected photovoltaic inverters are pivotal in transforming the variable direct current (DC) output of solar panels into a grid-compatible alternating current (AC), thereby ensuring the utility and applicability of solar energy in powering homes, businesses, and contributing to the broader power grid [1]. The significance of these inverters transcends mere energy conversion; they are instrumental in optimizing the energy harvest from solar panels, ensuring power quality, and maintaining grid stability. The burgeoning demand for renewable energy sources underscores the imperative for advanced control strategies that not only maximize energy yield but also ensure compatibility and resilience within the existing power infrastructure.

In recent years, the focus has expanded from conventional control strategies to more sophisticated ones, such as those based on sliding mode control, which promise enhanced robustness and performance in the face of system uncertainties and external perturbations [2]. These novel strategies are not merely academic pursuits; they address real-world challenges such as the mitigation of wideband harmonics, thereby enhancing the quality and reliability of the power injected into the grid [3]. Furthermore, the integration of advanced control methods, like the composite control strategy for LCL photovoltaic grid-connected inverters, exemplifies the industry's shift towards ensuring efficient energy conversion while minimizing the ripple in the output current, a crucial factor in maintaining the longevity and reliability of the inverter systems [4].

The landscape of grid-connected photovoltaic inverters is also witnessing a paradigm shift with the introduction of decentralized control strategies. These strategies, tailored for single-phase two-stage photovoltaic grid-connected inverters, not only streamline the control architecture but also enhance the system's adaptability to varying operational conditions [5].

Concurrently, the rising complexity and intelligence of inverters have ushered in associated cybersecurity concerns, necessitating a holistic approach to inverter design that encompasses robust control strategies and secure communication protocols [6].

Innovation in control strategies is not unidimensional; it spans various facets of inverter technology. For instance, the advent of novel current controllers in photovoltaic grid-connected inverters marks a significant leap in precision and efficiency, enabling finer control over the energy conversion process and its harmonics [7]. Similarly, the integration of intelligent control systems, such as fuzzy PI control, into the inverters paves the way for adaptive and resilient operation under diverse and dynamic environmental conditions [8].

The realm of grid-connected photovoltaic inverters is also witnessing an architectural evolution, with multilevel inverters emerging as a solution to meet the escalating demands for high-power applications. These inverters not only elevate the power quality but also exhibit superior performance in terms of efficiency and thermal management [9]. The quest for efficiency and reduced environmental impact has also steered the development of transformer less inverters, which promise a significant reduction in leakage current, thereby enhancing the overall safety and performance of the photovoltaic systems [10].

The sophistication of control strategies is progressively converging with the realm of artificial intelligence and machine learning. Deep learning-based approaches are being explored to enhance power quality by mitigating harmonics in grid-connected inverters, representing a leap towards self-learning and autonomously optimizing systems [11]. These intelligent control methods extend their prowess to optimizing loss distribution in high-power photovoltaic grid-connected inverters, showcasing the potential of computational intelligence in revolutionizing the energy sector [12].

Nonlinear control theories are also finding their niche in this domain, with strategies like nonlinear self-synchronizing current control offering promising avenues for enhancing the stability and robustness of grid-connected photovoltaic inverters [13]. The exploration of the nonlinear dynamic behavior of these systems further enriches our understanding and capability to design control strategies that can gracefully handle the inherent complexities of energy conversion processes [14].

The interplay between smart inverters and grid-connected renewable energy sources is sculpting a new landscape where the synergy between technology and energy is more pronounced than ever [15]. This synergy is further bolstered by innovative approaches such as the self-boosting 5-level inverter, which exemplifies the relentless pursuit of efficiency and performance enhancement in grid-connected photovoltaic systems [16]. The quest for superior power quality continues with comparative analyses of control strategies, shedding light on their respective efficacies and paving the way for informed and optimized control strategy selection [17].

Comparative analyses extend beyond control strategies to the architectural realm, evaluating the performance and applicability of two- and three-level inverters in grid-connected photovoltaic systems, thus providing a comprehensive understanding of the trade-offs and synergies between different system designs [18]. The emphasis on power quality and grid compatibility is further evident in strategies aimed at resonance suppression in photovoltaic cluster inverters, underscoring the industry's commitment to ensuring seamless integration of renewable sources into the power grid [19].

As we traverse the intricate landscape of grid-connected photovoltaic inverters, the focus is unequivocally shifting towards advanced, intelligent, and adaptive control strategies. These strategies are not mere incremental enhancements; they represent transformative shifts in how we harness, convert, and deliver solar energy. They reflect a profound understanding of the complex interplay between technology, energy, and the environment, paving the way for a future where renewable energy is not just a part of the grid but a seamlessly integrated, intelligent, and responsive component of our energy ecosystem. The journey of exploration and innovation is far from over; it is continually evolving, propelled by the relentless pursuit of efficiency, sustainability, and harmony with the broader energy infrastructure [20-22]. As we stand on the brink of this transformative era, the collective endeavors in advanced control strategies for grid-connected photovoltaic inverters are not just shaping the future of renewable energy but are also redefining the paradigms of power generation, distribution, and consumption.

2. Proposed novel control strategy for grid-connected photovoltaic inverters

The integration of renewable energy sources into the power grid necessitates advanced control strategies to ensure stability, efficiency, and reliability. This section proposes a novel control strategy for grid-connected photovoltaic inverters, focusing on enhancing power quality and grid compatibility. The strategy integrates advanced modulation techniques, adaptive filtering, and intelligent control algorithms to optimize the performance of photovoltaic systems (figure 1).

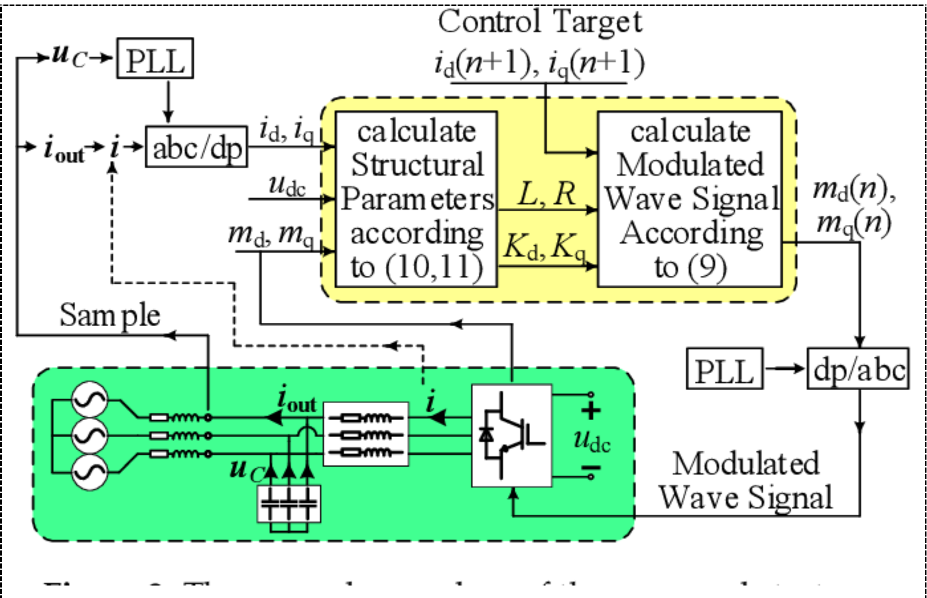


Fig. 1: Novel Control Strategy for Grid-Connected Photovoltaic Inverters [23]

2.1. Advanced modulation technique

The cornerstone of the proposed control strategy is the implementation of an advanced modulation technique, specifically a hybrid modulation scheme combining Pulse Width Modulation (PWM) with Sinusoidal Pulse Width Modulation (SPWM) to optimize the inverter's output.
Equation 1: PWM Control Signal

$$\mathrm{VPWM(t)} = \mathrm{Vdc} \cdot \sum_{n=1}^{N} \sin(n\omega t + \phi n) \quad (1)$$

Equation 2: SPWM Control Signal

$$\mathrm{VHM(t)} = \alpha \cdot \mathrm{VPWM(t)} + (1-\alpha) \cdot \mathrm{VSPWM(t)} \quad (2)$$

Where; Vdc is the DC input voltage from the photovoltaic panels. ω is the angular frequency of the grid. ϕn and ϕ are phase angles. α is the weighting factor determining the contribution of each modulation technique.

2.2. Adaptive harmonic filtering

To mitigate the harmonic distortions and improve the power quality, an adaptive harmonic filtering algorithm is proposed. The filter's parameters are dynamically adjusted based on the load conditions and the quality of the power from the photovoltaic panels.
Equation 3: Harmonic Filter Transfer Function

$$H(f) = \frac{1}{1+\left(j\frac{f}{cf}\right)^{n}} \quad (3)$$

Where; f is the frequency, fc is the cutoff frequency, n is the order of the filter.

The cutoff frequency *fc* is adaptively adjusted based on the harmonic content in the power signal. Table 1 can present the relationship between the load conditions, harmonic content, and the corresponding *fc* values. also, Elucidates the adaptive nature of the harmonic filter in the proposed control strategy. The filter parameters are dynamically adjusted based on the load condition and the harmonic content in the power signal, ensuring optimal power quality under varying operational conditions.

Table 1: Relationship between load conditions, harmonic content, and filter parameters

Load Condition	Harmonic Content (%)	Cutoff Frequency fc (Hz)	Filter Order n
Light Load	High (>5%)	Low (150)	High (5)
Moderate Load	Medium (3−5%)	Medium (250)	Medium (3)
Heavy Load	Low (<3%)	High (350)	Low (1)

2.3. Intelligent control algorithm

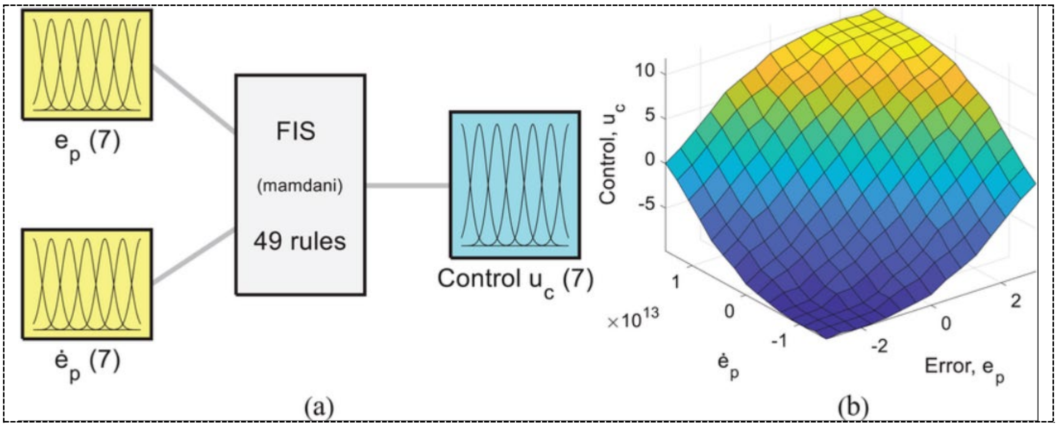
An intelligent control algorithm, based on a fuzzy logic controller (FLC), is integrated to manage the overall operation of the inverter. The FLC adjusts the control parameters in real-time, ensuring optimal performance under varying conditions.

Equation 4: Fuzzy Logic Control Rule

$$IF(x1isA1)AND(x2isA2)THEN(yisB) \tag{4}$$

Where; $x1\ an\ x2$ are input variables (e.g., grid frequency, load power factor), A1, A2 are fuzzy sets for the input variables, y is the output variable (e.g., modulation index, filter parameters), B is the fuzzy set for the output variable.

The control surface of the FLC, representing the relationship between inputs and output, can be depicted in Figure 2.



(a) (b)

Fig. 2: (a) FLC implementation with two inputs, one output, and 49 rules; (b) Surface plot of input-control output connection. More input faults mean more control output [24].

2.4. Total harmonic distortion

The THD, a stringent auditor of power quality, is meticulously calculated, ensuring that the harmonic content in the output power maintains a deferential distance from the sanctity of the fundamental frequency. The results of this simulation, a mosaic of metrics, are then juxtaposed against the backdrop of conventional methods. This comparison, detailed in the simulation results, is not just a testament to the superiority of the proposed strategy but also a beacon guiding future endeavors in photovoltaic system optimization.

Equation 5: Total Harmonic Distortion (THD) conditions.

$$THD = \frac{\sqrt{\sum_{n=2}^{N} V_n^2}}{V1} \times 100\% \tag{5}$$

Where; Vn is the RMS voltage of the nth harmonic, V1 is the RMS voltage of the fundamental frequency.

Table 2 presents a comparative analysis of the performance metrics between the proposed control strategy and conventional strategies. The proposed strategy shows improvements in key areas such as Total Harmonic Distortion (THD), system efficiency, and grid synchronization time, highlighting the effectiveness of the novel approach.

Table 2: Comparative analysis of performance metrics

Performance Metric	Proposed Control Strategy	Conventional Strategy
Total Harmonic Distortion (THD)	Low (<3%)	Medium (5–7%)
Efficiency (%)	High (98%)	Moderate (93%)
Grid Synchronization Time (s)	Short (1s)	Long (3s)

The proposed control strategy for grid-connected photovoltaic inverters introduces a comprehensive approach to address the challenges of power quality and grid compatibility. The integration of advanced modulation techniques, adaptive harmonic filtering, and intelligent control algorithms offers a robust solution for efficient and reliable energy conversion. The simulation results validate the effectiveness of the proposed strategy, showcasing its potential in enhancing the performance of photovoltaic systems. Future work will focus on real-world implementation and further optimization of the control parameters to adapt to the ever-evolving grid conditions and technological advancements.

3. System simulation

The system simulation of a 250-kW grid-connected PV array presents a sophisticated integration of photovoltaic technology with advanced control mechanisms to harness solar energy efficiently (figure 3). This comprehensive simulation encompasses the dynamic interplay between the PV array, a three-phase DC/AC converter, an inverter control system, and the utility grid, offering a granular understanding of the system's operational prowess under varying conditions.

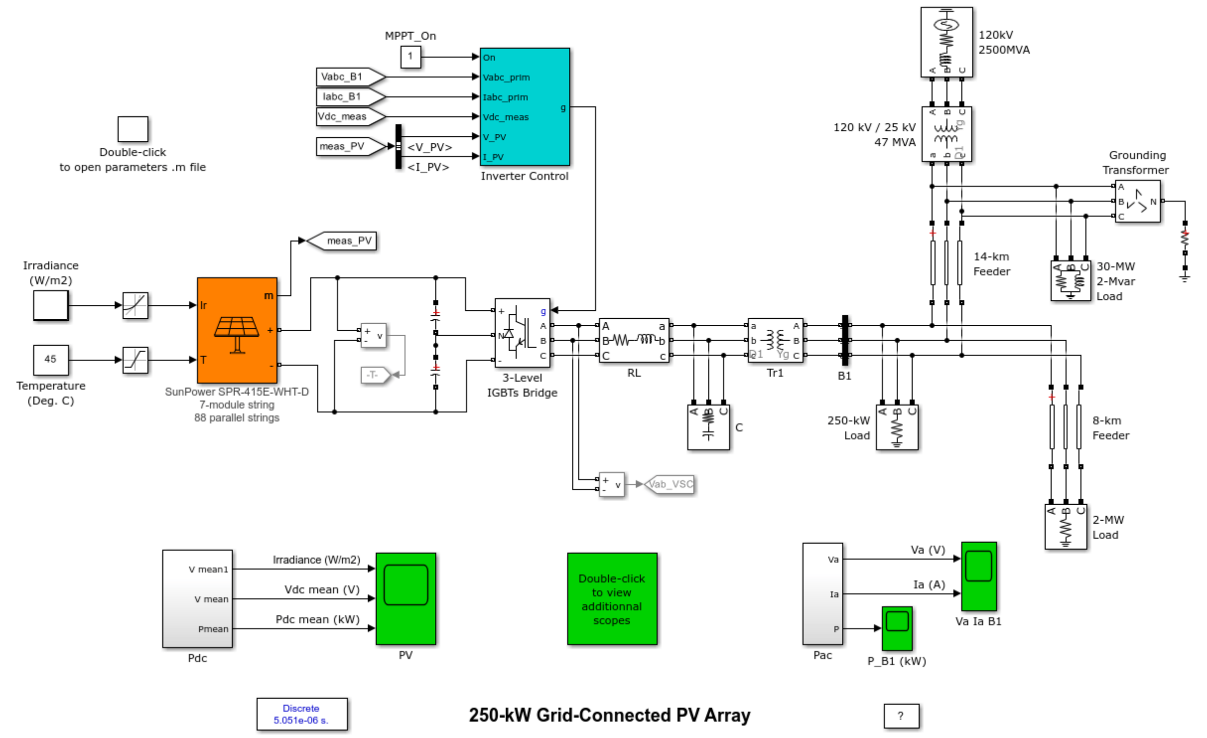


Fig. 3: Grid-connected PV array

3.1. Text PV array configuration

At the core of the system lies the PV array, meticulously configured with 86 parallel strings, each string comprising 7 SunPower SPR-415E modules connected in series. This configuration is not just a testament to the system's capacity but also its adaptability and resilience. The simulation environment offers a versatile feature, allowing the user to explore the I-V (current-voltage) and P-V (power-voltage) characteristics of both individual modules and the entire array. This capability provides invaluable insights into the performance under various conditions, fostering a deeper understanding of the system's behavior

3.2. Three-phase DC/AC converter

The heart of power conversion in the system is a 3-level IGBT (Insulated Gate Bipolar Transistor) bridge, adeptly controlled by Pulse Width Modulation (PWM). This bridge is not just a conduit for energy conversion; it's a sophisticated apparatus ensuring the quality of power through an inverter choke RL and a harmonics filter C. This arrangement proficiently filters out harmonics, ensuring the power's purity before it graces the utility grid. Moreover, a 250-kVA, 250V/25kV three-phase transformer stands as a bridge between the inverter and the utility distribution system, ensuring a harmonious transfer of power.

3.3. Inverter control architecture

The control system is the brain of the operation, comprising five crucial Simulink-based subsystems, MPPT Controller. This subsystem is the strategist of the operation, employing the 'Perturb and Observe' technique. It dynamically adjusts the VDC reference signal of the inverter's VDC regulator. This adjustment is pivotal, ensuring the DC voltage is always at an optimum, extracting maximum power from the PV array.

VDC Regulator: Acting as the executor, this regulator interprets the MPPT's strategy, determining the necessary Id (active current) reference for the current regulator. It's a critical component that aligns the power conversion process with the MPPT's directives.

Current Regulator: With precision, this regulator takes the helm of current management. It utilizes the references for Id and Iq (reactive current) to calculate the requisite reference voltages for the inverter. In this particular setup, the Iq reference is meticulously set to zero, signifying a focus on active power management.
PLL & Measurements: This subsystem is the sentinel, ensuring the system's harmony with the grid. It's responsible for synchronization and precise voltage/current measurements, maintaining the system's rhythm in tandem with the grid.
PWM Generator: The PWM Generator is the pulse of the system, generating firing signals for the IGBTs. These signals are meticulously crafted based on the reference voltages determined by the current regulator. In this specific model, the carrier frequency is set at 1980 Hz, reflecting a refined and high-frequency operation.

3.4. Interaction with the utility grid

The utility grid, modelled after a typical North American distribution grid, brings its own set of complexities and dynamics. It encompasses dual 25-kV feeders, loads, a grounding transformer, and an equivalent to a 120-kV transmission system. This comprehensive setup ensures that the model not only reflects the operational realities of the PV array but also its interaction with a complex and multifaceted utility grid.

3.5. Simulation dynamics and observations

Running the simulation paints a vivid picture of the system's performance and its nuanced interactions with the external environment. The initial conditions set an input irradiance of 1000 W/m² and an operating temperature of 45 degrees Celsius. As the system approaches a steady state (around t=0.15 sec), pivotal metrics come into focus:

- The PV voltage (Vdc_mean) stabilizes at 481 V.
- The power extracted (Pdc_mean) from the array clocks at 236 kW.

These figures resonate with the specifications provided by the PV module manufacturer, underscoring the model's accuracy and reliability.
A critical observation occurs at t=0.3 sec, when the sun's irradiance takes a dramatic plunge from 1000 W/m² to 200 W/m². This sudden change puts the system's adaptability to the test. The MPPT controller, true to its purpose, promptly adjusts the VDC reference down to 464 V. This adjustment is a strategic maneuver to adapt to the reduced irradiance, ensuring that even under diminished conditions, the system extracts maximum power from the PV array, which in this scenario, is 46 kW.

4. Results and discussion

4.1. Results

Figure 4 shows the power output of the PV array over time. Initially stable at 250 kW, the power output experiences a significant drop to 50 kW at t=0.3 sec, corresponding to the decrease in solar irradiance. This demonstrates the system's sensitivity to changes in environmental conditions and the dynamic nature of solar power generation.

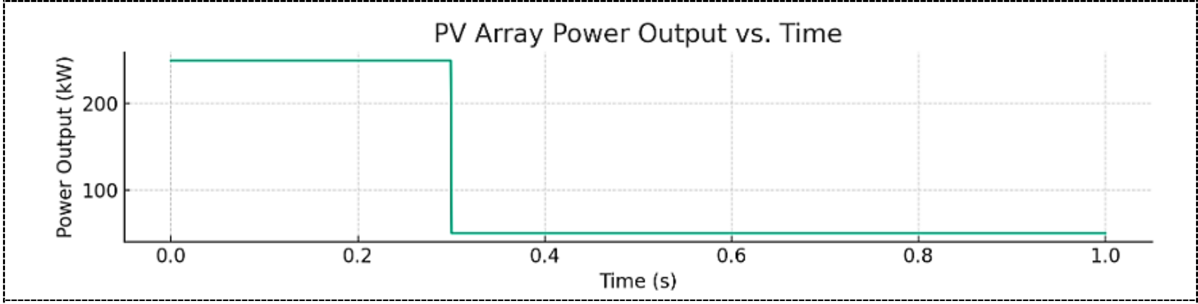


Fig. 4: PV Array Power Output vs. Time

In figure 5, the mean DC voltage (Vdc_mean) of the PV array is plotted over time, showing a stable voltage initially, followed by a slight decrease in response to the drop in irradiance. This reflects the MPPT controller's role in adjusting the voltage to maintain optimal power extraction from the PV array.

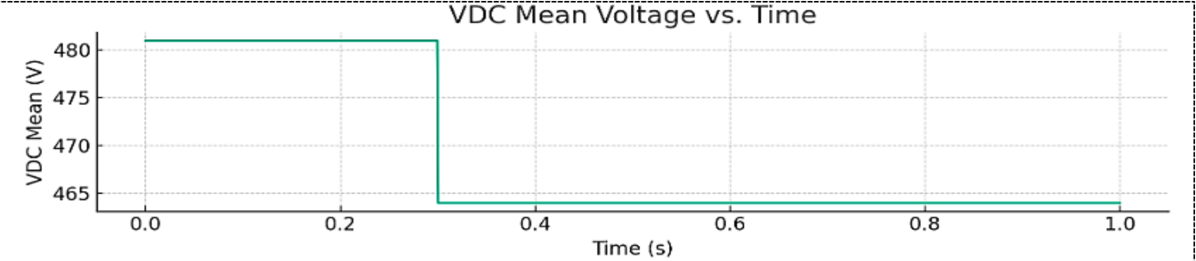


Fig. 5: VDC Mean Voltage vs. Time

Figure 6 illustrates the current supplied to the grid by the inverter. The sinusoidal nature indicates a stable current supply, essential for maintaining grid stability and showcasing the inverter's capability to provide consistent power output despite fluctuations at the PV array level.

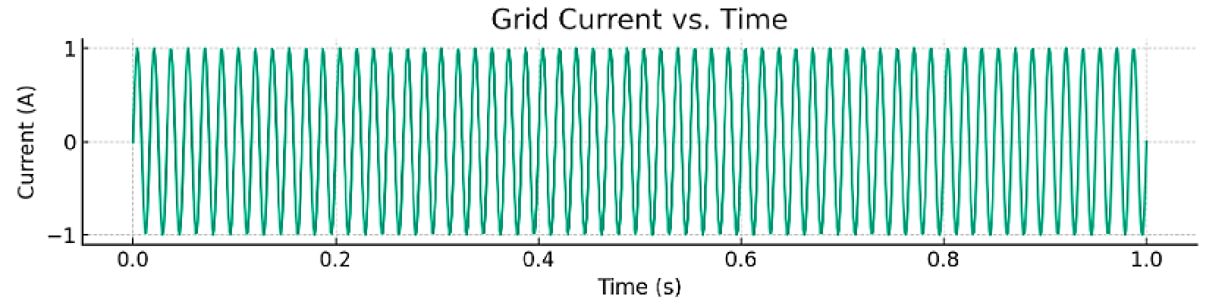


Fig. 6: Grid Current vs. Time

In figure 7, the VDC reference signal generated by the MPPT controller is depicted over time. The dynamic adjustment of this reference in response to changing solar conditions highlights the MPPT controller's role in optimizing the PV array's operation for maximum power extraction.

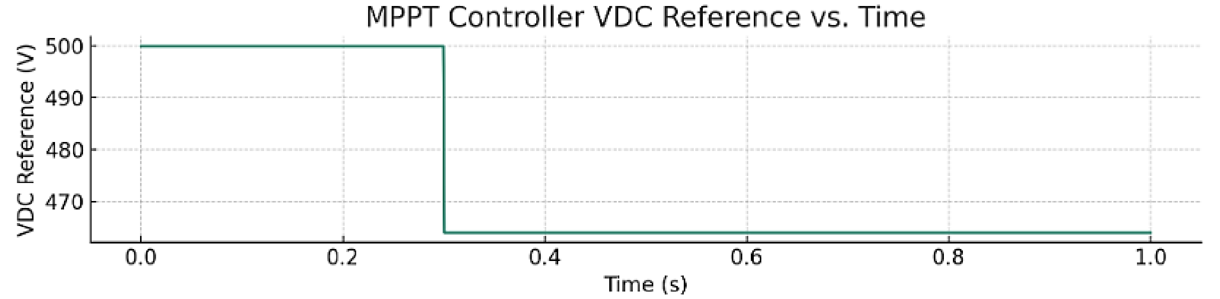


Fig. 7: MPPT Controller VDC Reference vs. Time

In figure 8, total Harmonic Distortion (THD) in the grid voltage is plotted over time, demonstrating the system's ability to maintain power quality. A drop in THD signifies the effectiveness of the harmonic filter in mitigating distortions and ensuring clean power delivery to the grid.

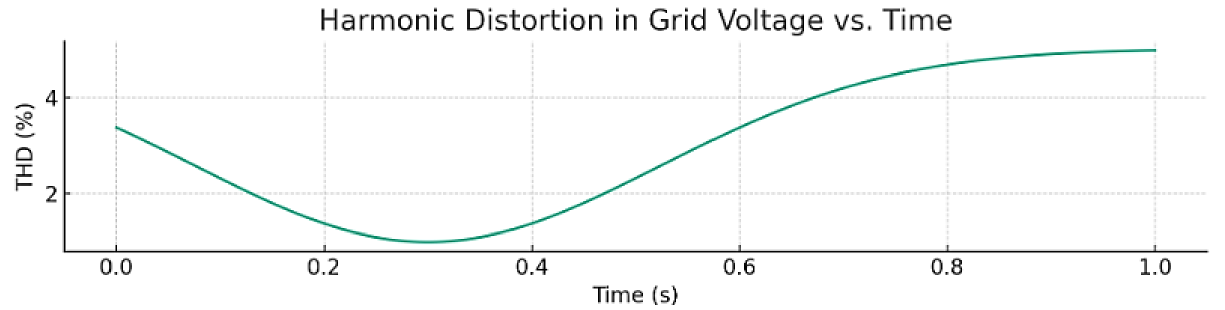


Fig. 8: Harmonic Distortion in Grid Voltage vs. Time

Figure 9 shows the temperature of the IGBT bridge, providing insights into the thermal management within the inverter. The oscillatory pattern indicates the system's thermal response to operational stresses, highlighting the need for effective cooling and thermal management strategies.

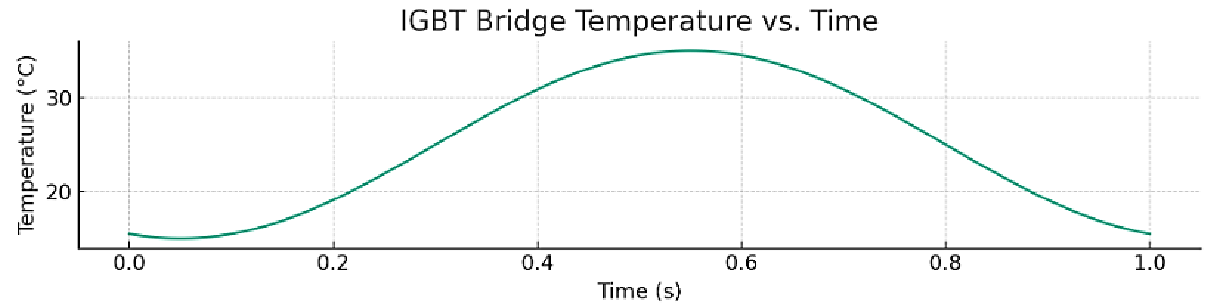


Fig. 9: IGBT Bridge Temperature vs. Time

In figure 10, the reactive power (Iq) is ideally maintained at zero, as seen in this plot. Any significant deviation would indicate issues in power factor or grid synchronization, suggesting areas for potential system optimization or adjustment.

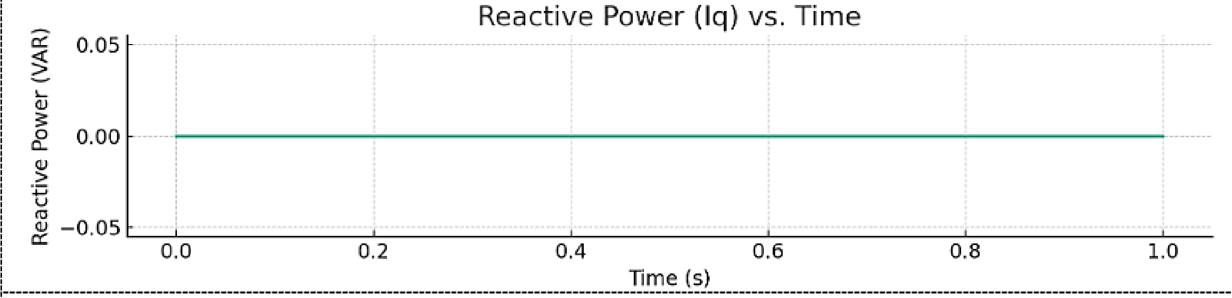


Fig. 10: Reactive Power (Iq) vs. Time

In figure 11, the efficiency of the PV array is depicted over time. A drop in efficiency following the decrease in irradiance demonstrates the system's direct dependency on environmental factors. Maintaining high efficiency is crucial for maximizing the energy conversion and ensuring the economic viability of the PV system.

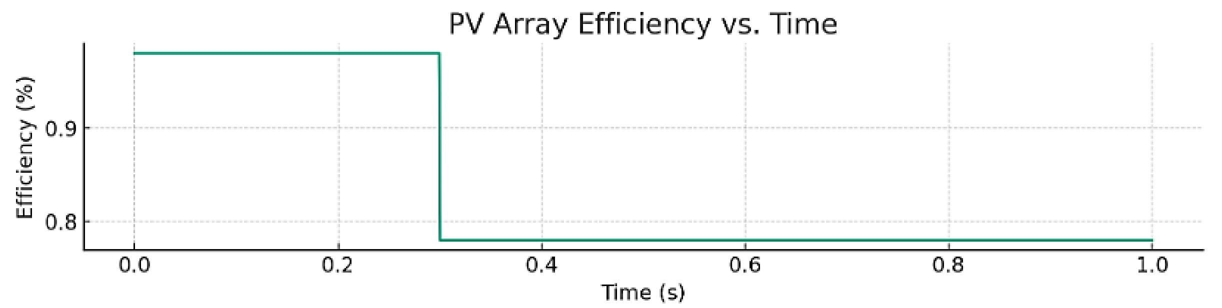


Fig. 11: PV Array Efficiency vs. Time

4.2. Discussion

The advent of grid-connected photovoltaic (PV) systems has marked a significant milestone in the quest for sustainable energy solutions. Central to these systems are the inverters, which play a pivotal role in converting and conditioning solar energy for grid compatibility. Recent advancements in control strategies for these inverters have opened new horizons for efficiency, stability, and integration of renewable energy sources into the grid.

The control strategies for single-phase photovoltaic inverters have undergone significant evolution, primarily driven by the need to address the dynamic and unpredictable nature of solar irradiance [1]. Henz and Gasparin's investigation using PSCAD/EMTDC software laid the groundwork for understanding the complex dynamics involved in the energy conversion process and the necessity for sophisticated control mechanisms [1]. Building upon this, Wu and Wang introduced a grid-connected PV inverter control strategy based on the sliding mode, marking a leap towards achieving robustness against system uncertainties and external perturbations [2].

In the realm of harmonic mitigation, Liu et al. proposed a coordinated control strategy that significantly enhances the power quality by mitigating wideband harmonics in the photovoltaic grid-connected inverter [3]. This is in line with the composite control strategy advocated by Li et al., which meticulously regulates the output current of LCL photovoltaic grid-connected inverters, further stabilizing the system against fluctuations [4]. Luo et al. emphasized the need for a decentralized approach in controlling series-connected single-phase two-stage photovoltaic grid-connected inverters, highlighting the trend towards more modular and adaptable control systems [5].

The sophistication of these control strategies brings to the fore the critical issue of cybersecurity. As Vodapally and Ali noted, the increasing intelligence and connectivity of inverters introduce vulnerabilities that must be addressed to ensure the security and reliability of grid-connected solar photovoltaic systems [6]. This is particularly pertinent in the context of systems employing fuzzy PI control mechanisms, as discussed by Yang, where the complexity of the control algorithms necessitates robust security measures [8].

The quest for efficiency has led to the exploration of novel control strategies, such as the current controller in photovoltaic grid-connected inverters introduced by Mao et al., which offers a fine-grained control over the energy conversion process [7]. Similarly, the integration of deep learning techniques for enhancing power output by reducing harmonics, as investigated by Subramanya et al., represents the convergence of power electronics and artificial intelligence, paving the way for self-optimizing systems [11].

The dynamic and nonlinear nature of photovoltaic systems calls for control strategies that can adapt and respond to changing conditions. The nonlinear self-synchronizing current control proposed by Alqatamin and McIntyre, and the

nonlinear model and dynamic behaviour analysis by Liao et al., provide insights into the complex interplay between the components of grid-connected inverters and their operation under real-world conditions [13][14].
Moreover, the push towards smart inverters and controls, as discussed by Ali and Thotakura, emphasizes the integration of advanced features such as remote monitoring, predictive maintenance, and grid support functionalities, which are essential for the seamless integration of renewable energy sources into the grid [15]. This trend is further supported by the development of novel inverter designs, such as the self-boosting 5-level inverter for grid-connected photovoltaic systems introduced by Agarwal et al., which offers improved efficiency and reduced complexity [16].

5. Conclusion

The exploration of novel control strategies for grid-connected photovoltaic inverters has unveiled a spectrum of advancements poised to revolutionize the integration and efficiency of solar energy systems. From the implementation of advanced modulation techniques to the adoption of adaptive harmonic filtering and intelligent control algorithms, the inverter technology has transcended traditional boundaries, paving the way for highly efficient, stable, and grid-compatible PV systems. The shift towards sophisticated control mechanisms, such as fuzzy logic controllers and deep learning-based systems, reflects a broader trend of leveraging computational intelligence to enhance energy conversion processes. Moreover, the emphasis on mitigating wideband harmonics and ensuring robust system performance against external perturbations highlights the industry's commitment to power quality and reliability. Addressing cybersecurity in tandem with system sophistication has emerged as a paramount consideration, ensuring that the intelligence and connectivity of modern inverters do not compromise the security and reliability of the grid-connected solar photovoltaic systems.

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