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Performance Trade-Off Analysis of Grid-Connected PV Systems Between Detailed Switching and Average-Value Models

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Abstract

Grid-connected photovoltaic (PV) systems require accurate modeling and efficient control strategies to ensure reliable operation and optimal power extraction under varying environmental conditions. Achieving a balance between modeling accuracy and computational efficiency remains a major challenge in PV system simulation. This paper evaluates two widely used modeling approaches: the detailed switching model and the average-value model, both implemented in MATLAB/Simulink under identical operating conditions using maximum power point tracking (MPPT). The models are compared in terms of MPPT efficiency, dynamic response, power quality, and simulation time. Results indicate that the detailed switching model provides higher accuracy and better dynamic performance, particularly under rapid irradiance variations, whereas the average-value model significantly reduces simulation time and computational complexity. The study highlights the trade-off between accuracy and efficiency while providing guidance for selecting the most suitable modeling approach according to application requirements.

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Keywords: Photovoltaic Systems, Grid-Connected Systems, Detailed Model, Average Model, Simulation, Maximum Power Point Tracking (MPPT), Performance Evaluation.

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تحليل المقايضة في الأداء لأنظمة الطاقة الشمسية الكهروضوئية المتصلة بالشبكة بين النموذج التفصيلي بالتبديل ونموذج القيم المتوسطة

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الملخص:

تتطلب أنظمة الطاقة الشمسية الكهروضوئية (PV) المتصلة بالشبكة نمذجة دقيقة واستراتيجيات تحكم فعّالة لضمان التشغيل الموثوق والاستخلاص الأمثل للطاقة تحت الظروف البيئية المتغيرة. ولا يزال تحقيق التوازن بين دقة النمذجة والكفاءة الحسابية يمثل تحديًا رئيسيًا في محاكاة أنظمة الطاقة الكهروضوئية. تقيّم هذه الورقة البحثية أسلوبين شائعين للنمذجة، وهما: النموذج التفصيلي القائم على التبديل (Detailed Switching Model) ونموذج القيم المتوسطة (Average–Value Model)، حيث تم تنفيذ كلا النموذجين باستخدام MATLAB/Simulink تحت ظروف تشغيل متماثلة وبالاعتماد على خوارزمية تتبع نقطة القدرة وتمت مقارنة أداء النموذجين من حيث كفاءة (MPPT)، والاستجابة الديناميكية، وجودة القدرة، وزمن المحاكاة. أظهرت النتائج أن النموذج التفصيلي يوفّر دقة وأداءً ديناميكيًا أعلى، خاصةً عند التغيرات السريعة في الإشعاع الشمسي، بينما يساهم نموذج القيم المتوسطة في تقليل زمن المحاكاة والتعقيد الحسابي. وتوضح الدراسة المفاضلة بين الدقة والكفاءة مع تقديم إرشادات لاختيار النموذج الأنسب وفقًا لمتطلبات التطبيق.

وقد تم عرض هذه الورقة العلمية في جلسات المؤتمر الدولي للطاقة المتجددة والنفط والغاز وتغير المناخ "أيريقو" في الفترة 25–27 ابريل 2026م. طرابلس – ليبيا

الكلمات المفتاحية: الأنظمة الكهروضوئية، الأنظمة المتصلة بالشبكة، النموذج التفصيلي، النموذج المتوسط، المحاكاة، تتبع نقطة القدرة العظمى (MPPT)، تقييم الأداء.

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1- Introduction

The global transition toward renewable energy has significantly increased the deployment of photovoltaic (PV) systems due to their abundance, sustainability, and cost-effectiveness [1, 2]. PV energy is generated through the conversion of solar irradiance into electrical power using semiconductor-based materials, making it a key technology in modern distributed generation systems [3]. However, the performance of PV systems is highly dependent on operational conditions, particularly solar irradiance and cell temperature, which directly affect the nonlinear electrical characteristics of PV modules [4]. These variations can lead to significant reductions in energy conversion efficiency under dynamic operating conditions [5].

To ensure optimal energy harvesting, accurate real-time estimation of solar irradiance and adaptive control strategies are essential [6]. Despite continuous technological advancements, improving the efficiency of PV modules and power electronic converters remains a major challenge. High-performance systems often require advanced semiconductor devices and control algorithms, which increase system complexity and overall cost [7]. To overcome these limitations, Maximum Power Point Tracking (MPPT) techniques have been widely developed and implemented to ensure that PV systems operate at or near their maximum power point under varying operational conditions [8–10]. These techniques have become an essential component of grid-connected PV systems, enabling stable and efficient energy extraction even under rapid changes in irradiance and temperature.

In recent years, extensive research has been conducted on MPPT algorithms, ranging from conventional methods such as Perturb and Observe (P&O) and Incremental Conductance (IncCond) to advanced intelligent techniques, including artificial neural networks (ANN), fuzzy logic control, and metaheuristic optimization methods [11].

A comprehensive review in 2023 demonstrated that intelligent MPPT techniques such as ANN and adaptive neuro-fuzzy inference systems (ANFIS) can achieve higher tracking accuracy compared to conventional approaches, although at the expense of increased computational complexity [12]. In parallel, model-based MPPT and system-level simulation approaches have gained significant attention. Several studies have evaluated MPPT performance under hardware-in-the-loop (HIL) and simulation environments, showing that high tracking efficiencies (above 99%) can be achieved when accurate system parameters are available [12]. However, these methods are sensitive to parameter uncertainties and environmental variations. Another comparative study conducted in 2025 analyzed utility-scale PV systems incorporating DC-DC converters, MPPT controllers, and grid synchronization units under realistic operating conditions, highlighting the trade-offs between conventional MPPT algorithms and their robustness under disturbances [11].

Despite the extensive body of research on PV modeling and MPPT techniques, most existing studies treat detailed switching models and average-value models independently rather than within a unified evaluation framework. Moreover, there is still a lack of systematic studies that compare both modeling approaches under identical operating conditions while considering multiple performance metrics such as dynamic response, power quality, tracking efficiency, and computational cost. This limitation hinders the ability to establish clear guidelines for selecting the most appropriate modeling approach for different applications. Therefore, this paper presents a comprehensive performance evaluation of grid-connected PV systems using both detailed switching and average-value models implemented in MATLAB/Simulink. Both models are subjected to identical irradiance, temperature, and control conditions to ensure a fair and consistent comparison. The performance is assessed using key indicators including MPPT efficiency, transient response, total harmonic distortion (THD), and computational time.

The main contribution of this work lies in developing a unified benchmarking framework that systematically quantifies the trade-off between modeling accuracy and computational efficiency. Unlike previous studies [11, 12], this work provides not only a performance comparison but also practical insights and selection guidelines for choosing the appropriate modeling approach depending on the target application, ranging from detailed converter-level analysis to large-scale grid integration studies.

2- PV (Solar Cell) Modeling

The photovoltaic (PV) cell is the fundamental energy conversion element in a PV system, responsible for converting solar irradiance into electrical energy. Its electrical behavior can be represented by the well-known single-diode model, which provides an accurate balance between model complexity and computational efficiency. As shown in Figure (1), the model consists of a current source I_{ph} representing the photo-

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generated current, a diode D , a series resistance R_s , and a parallel (shunt) resistance R_{sh}.

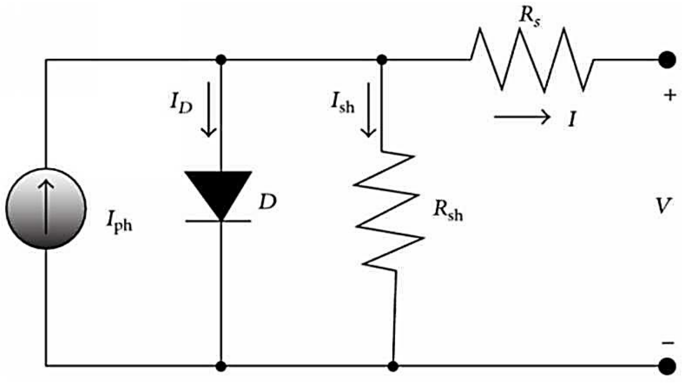

Figure (1): The PV model

The output current of the PV cell can be expressed as:

$$I= I_{ph} – (I_0 (e^{q(v+IRs)/(nkT)} - 1) – ((V+IR_s)/R_{sh}) \qquad (1)$$

where :
I_0 : The diode reverse saturation current.
q: The electron charge
k: Boltzmann's constant,
T: The cell temperature in Kelvin
n: The ideality factor of the diode.

The photocurrent I_{ph} depends on both solar irradiance G and temperature T as:

$$Iph = [\ I_{sc\ ,ref} + K_i\ (T - T_{ref})\ ]\ (G/G_{ref}) \qquad (2)$$

where :
$I_{sc\ ,ref}$: The short-circuit current at reference conditions.
K_i: The temperature coefficient of the short-circuit current.
G_{ref}: The standard irradiance .
T_{ref} : The standard temperature.

This model accurately reflects the nonlinear I–V and P–V characteristics of PV modules under varying environmental conditions. In the simulation, multiple PV cells are connected in series and parallel to form a PV array capable of delivering the desired power output. The model parameters are selected based on manufacturer data (e.g., SunPower SPR-305) and verified through MATLAB/Simulink implementation

3- System Configuration

Figure (2) illustrates the overall structure of the grid-connected photovoltaic (PV) system employed in this study. The system comprises four main functional components: the PV array, the DC–DC boost converter, the DC–AC voltage source converter (VSC), and the utility grid. Each stage is equipped with a dedicated control unit designed to enhance system performance and ensure reliable interaction with the grid.

The PV array converts solar irradiance and temperature into electrical energy. The output current and voltage of the array are continuously monitored and sent to the Maximum Power Point Tracking (MPPT) controller. The MPPT algorithm implemented using the Incremental Conductance (IncCond) method in the detailed model and the Perturb and Observe (P&O) method in the average-value model dynamically adjusts the duty cycle of the DC–DC boost converter to maintain operation at the maximum power point under varying irradiance and temperature conditions.

The DC–DC boost converter regulates the PV array's output voltage and steps it up to a suitable level for the inverter stage. It operates at a high switching frequency to achieve fast transient response and DC-link voltage stability.

The DC–AC converter typically a three-phase voltage source converter (VSC) interfaces the DC-link with the AC grid, ensuring proper synchronization, voltage regulation, and current control. The main difference between the detailed and average-value models lies in the representation of the converter switching: the detailed model simulates the actual switching behavior, while the average-value model uses a simplified representation to reduce simulation time while maintaining accuracy.

Finally, the system delivers regulated AC power to the utility grid while meeting grid code requirements regarding voltage quality, power factor, and harmonic distortion. The proposed configuration provides a reliable platform for comparing the performance of detailed and average-value simulation models under identical environmental and operational conditions.

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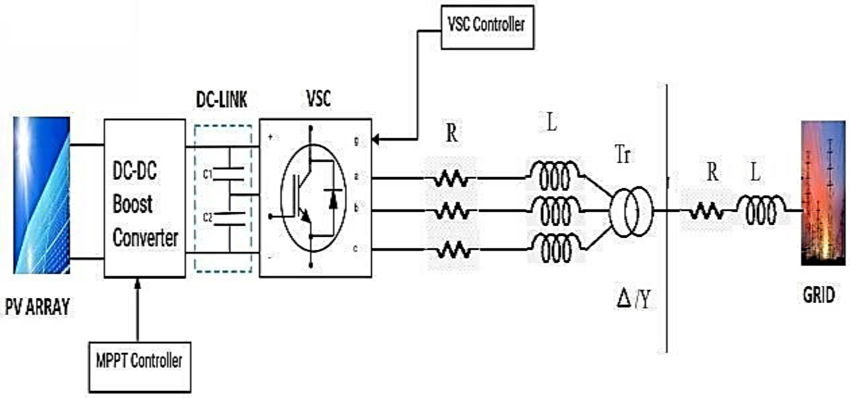

Figure (2): Block diagram of the grid-connected photovoltaic system integrated with MPPT

Each model will be detailed in the following sections. This study employs a simulation-based approach to compare two modeling paradigms of a grid-connected photovoltaic (PV) system: the detailed switching model and the average-value model. Both are implemented in MATLAB/Simulink under identical conditions to ensure a fair comparison. The subsequent sections highlight their differences in switching representation, accuracy, and computational efficiency

A. Detailed Switching Model

The detailed switching model in Figure (3) explicitly represents the switching behavior of power electronic devices.

●PV Array: A 100-kW solar array is modeled as a nonlinear current source dependent on irradiance and temperature. The I–V characteristics are implemented to accurately reflect solar cell physics.

●DC-DC Converter: A unidirectional boost converter operating at a switching frequency of 5 kHz is employed. The duty cycle is regulated by an Incremental Conductance (IncCond) MPPT algorithm with an integral regulator to ensure fast and accurate maximum power extraction.

●VSC Inverter: A three-phase three-level Voltage Source Converter (VSC) interfaces the DC link to the AC grid. The VSC operates under sinusoidal PWM (SPWM) modulation, generating switching harmonics that contribute to total harmonic distortion (THD) in the grid current.

●Grid Connection: The system connects to a 25 kV distribution feeder, which in turn is linked to a 120 kV transmission equivalent. A 260 V/25 kV coupling transformer provides voltage matching, while a 10 kVAR filter capacitor bank mitigates harmonics.

●Discretization: The electrical system is simulated at a time step of 1 µs, and control systems at 100 µs.

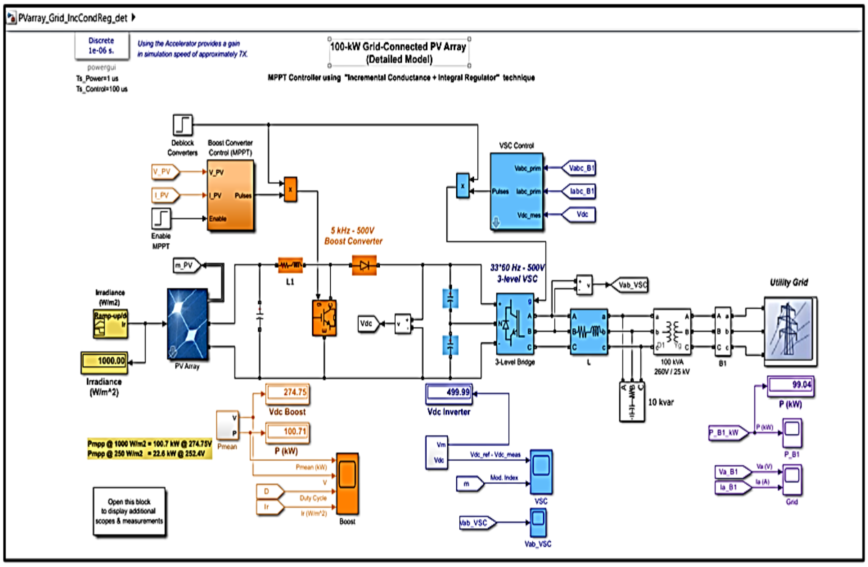

Figure (3): Block diagram of the detailed switching model.

B.Average-Value Model

The average-value model in Figure (4) abstracts the switching operation by replacing converters with averaged mathematical representations, enabling larger time steps and reduced computational effort.

●PV Arrays: Two PV arrays rated at 100 kW each are connected in parallel to provide a combined output.

●Average Boost Converter: Instead of discrete switching, the boost converter is modeled as a controlled DC voltage source, governed by the duty cycle. The Perturb and Observe (P&O) MPPT algorithm is implemented due to its simplicity and robustness.

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- Average VSC Inverter: The inverter is modeled as a controlled three-phase voltage source synchronized with the grid. Harmonics are not represented, making this model suitable for large-scale and long-term studies.

- Grid Connection: Similar to the detailed model, the average system is connected via a coupling transformer. A 20 kVAR filter capacitor is included, although harmonics are inherently absent in this approach.

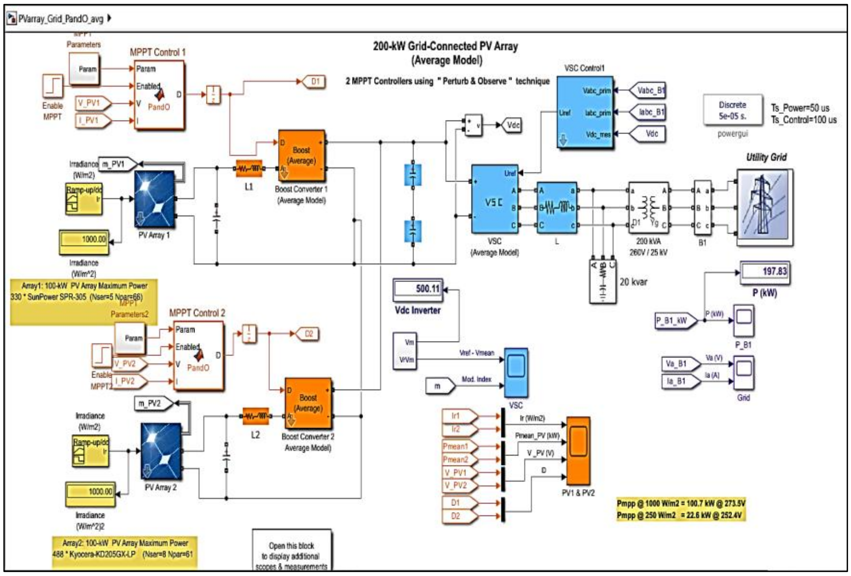

Figure (4): Block diagram of the average-value model.

4- **Control Strategy Implementation**

The control strategies focus primarily on Maximum Power Point Tracking (MPPT). The detailed model employs the Incremental Conductance with Integral Regulator method, which is more accurate under rapidly changing irradiance. Meanwhile, the average model uses the Perturb and Observe (P&O) method, offering simplicity and robustness but with slower convergence during fast irradiance variations.

In addition, the VSC controller ensures grid synchronization and unity power factor operation in both models.

A. Incremental Conductance (IncCond) method

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The Incremental Conductance (IncCond) method is one of the most effective techniques for Maximum Power Point Tracking (MPPT) in solar energy systems. This method works by comparing the instantaneous conductance (I/V) with the incremental conductance (ΔI/ΔV) to determine the direction of voltage change that increases the power. When these conductance are equal, the system reaches the Maximum Power Point (MPP) [13].

To improve the system's response and reduce errors caused by rapid environmental changes, an Integral Regulator is often added to the IncCond method. The integral controller corrects accumulated deviations in voltage or current, enhancing MPP tracking accuracy and improving system stability.

The steps of this method, including the integral regulator, are illustrated in the flowchart, as shown in Figure (5)

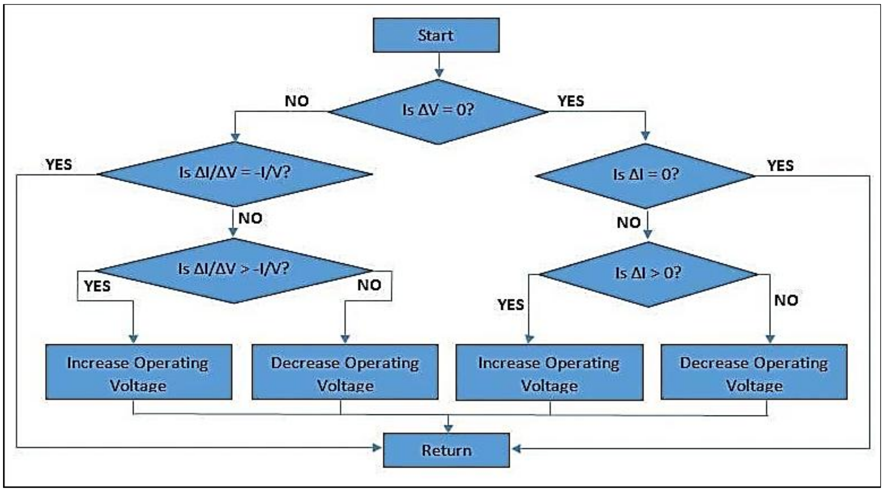

Figure (5): The Flowchart of the Incremental Conductance (IncCond) method.

B. The Perturb and Observe (P&O) method

The Perturb and Observe (P&O) method is one of the most widely used techniques for Maximum Power Point Tracking (MPPT) in solar energy systems. This method works by periodically perturbing the operating voltage and observing the resulting change in power. If the power increases, the voltage adjustment continues in the same direction; if the power decreases, the direction is reversed. The P&O method is simple

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and easy to implement, but it may cause small oscillations around the maximum power point under steady-state conditions[13] .
The steps of the Perturb and Observe (P&O) method are illustrated in the flowchart, as shown in Figure (6):

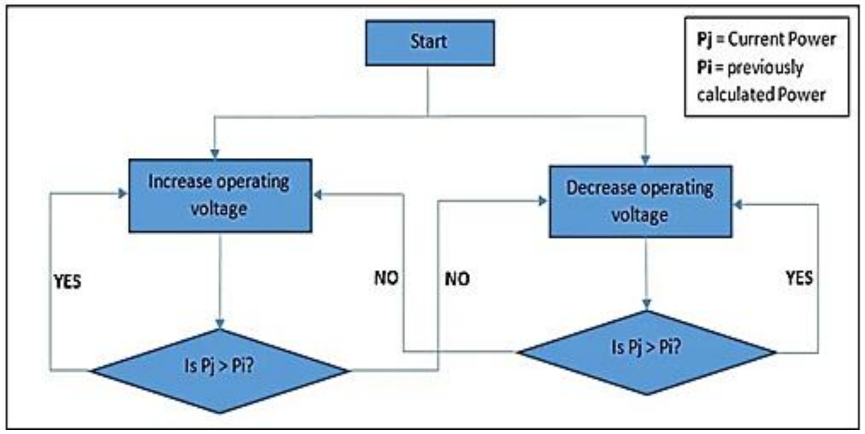

Figure (6) : Flowchart of the Perturb and Observe (P&O) method

I. Simulation result and Discussion

Both the detailed switching model and the average-value model of the grid-connected photovoltaic (PV) system were implemented in MATLAB/Simulink R2020 under identical environmental and operating conditions. To ensure a consistent comparison, both models were tested under the same irradiance and temperature conditions. The simulation period was set to 1 second, with irradiance varying from 1000 W/m² to 600 W/m² and temperature maintained at 25°C to evaluate the dynamic tracking capability of each MPPT controller. The detailed model employed a small simulation step size of 1 µs to accurately capture switching effects, while the average-value model used a larger step size of 50 µs, significantly reducing computational requirements.

- Performance Evaluation and Comparative Analysis

The results presented in this section provide a detailed comparison between the detailed switching and average-value modeling approaches. Each figure and table highlights a specific performance aspect, enabling quantitative and qualitative assessment of both models.

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1- MPPT Efficiency and Power Output

The Incremental Conductance (IncCond) algorithm used in the detailed model demonstrated superior accuracy during rapid irradiance fluctuations, maintaining stable operation around the Maximum Power Point (MPP). The Perturb and Observe (P&O) algorithm in the average model showed slightly slower convergence, with small oscillations around the MPP under steady-state conditions. The tracking efficiencies were found to be 99.3% for the detailed model and 98.9% for the average-value model, confirming the higher precision of the IncCond-based approach.

2- Dynamic Response

Under step changes in irradiance, the detailed model exhibited a faster transient recovery (settling time ≈ 0.06 s) compared to the average-value model (settling time ≈ 0.12 s). The use of an integral regulator in the IncCond controller contributed to improved dynamic behavior, minimizing overshoot and steady-state error.

3- Computational Efficiency

Simulation runtime was a key differentiator between the two modeling techniques. The detailed switching model, with a simulation step size of 1 µs, required approximately 8.2 seconds to complete one second of real-time simulation. The average-value model, using a step size of 100 µs, achieved the same duration in 1.0 second a reduction of nearly 87% in computation time. This makes the average-value model significantly more practical for system-level or optimization studies.

Table (1) Summary of Results

Model Type	MPPT Algorithm	MPPT Efficiency (%)	Settling Time (s)	THD (%)	Simulation Time (s)
Detailed Switching Model	**IncCond + Integral**	**99.3**	**0.06**	**3.1**	**8.2**
Average-Value Model	**P&O**	**98.9**	**0.12**	**—**	**1.0**

These results confirm that the detailed model is preferable for studies requiring accurate harmonic representation and converter-level analysis, while the average-value model is better suited for control design, long-term stability analysis, and grid integration studies**.**

4- Simulation Scopes

Figures 7 and 8 show the detailed switching model and the average-value model, respectively.

While the waveforms in the detailed model exhibit ripples and fast oscillations and the average-value model appears smooth and stable, the performance differences between the two models are summarized in Table (2) for a clear comparison.

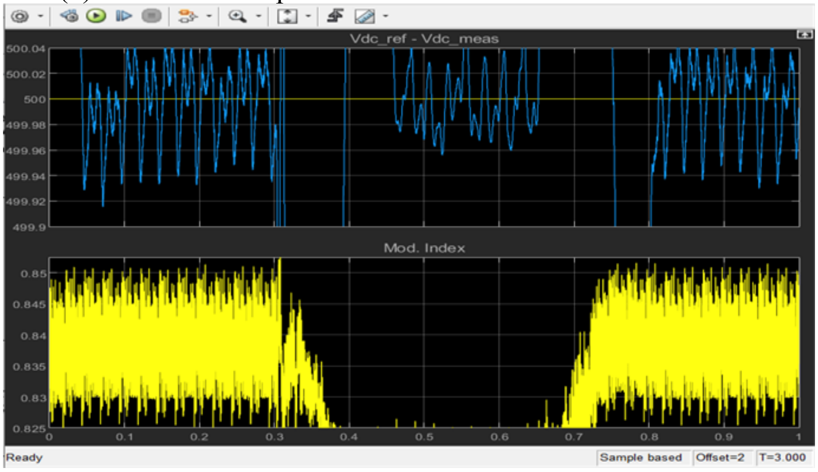

Figure (7): The detailed switching model

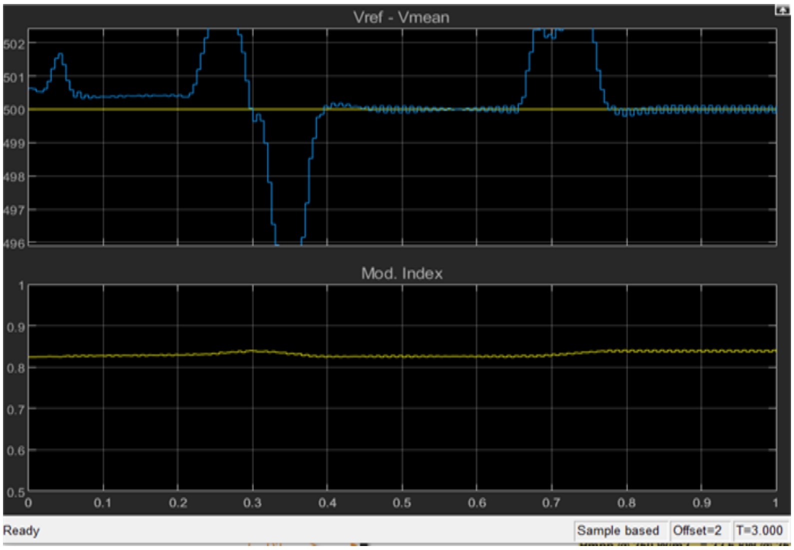

Figure (8): The average-value model

Table (2) Comparison Between the Two Modeling Approaches

Aspect	Detailed Switching Model	Average-Value Model
Voltage ripple	High due to PWM switching	Very low ripple
Noise level	Significant	Minimal
Modulation index	Large, fast oscillations	Smooth and stable
Simulation speed	Slow	Fast
Suitable for	Harmonic & switching studies	Control design & dynamics

Figure (9) illustrates the Detailed Switching Model, while Figure (10) depicts the Average-Value Model. The key performance differences between the two models, including waveform oscillations, ripple, and computational efficiency, are summarized in Table (2). As shown, the detailed switching model exhibits high-frequency ripples in PV voltage, power, and duty cycle, providing a more accurate representation of converter dynamics. In contrast, the average-value model produces smooth and stable waveforms, offering faster and more efficient system-level simulation while still accurately tracking irradiance variations.

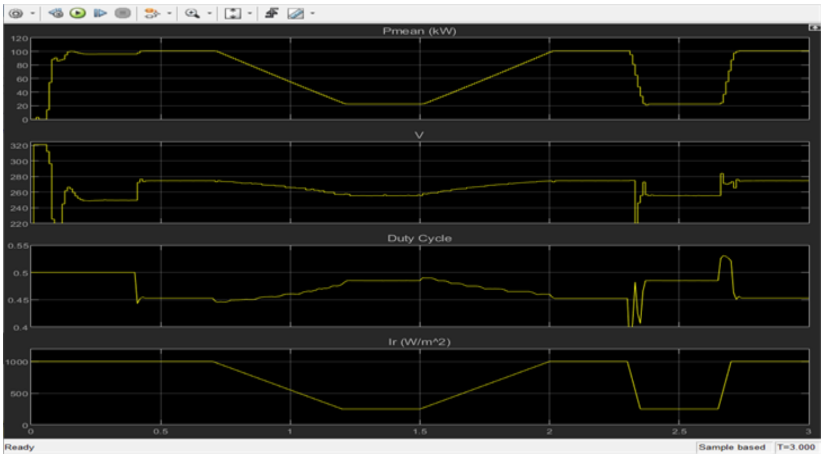

Figure (9): The Detailed Switching Model performance

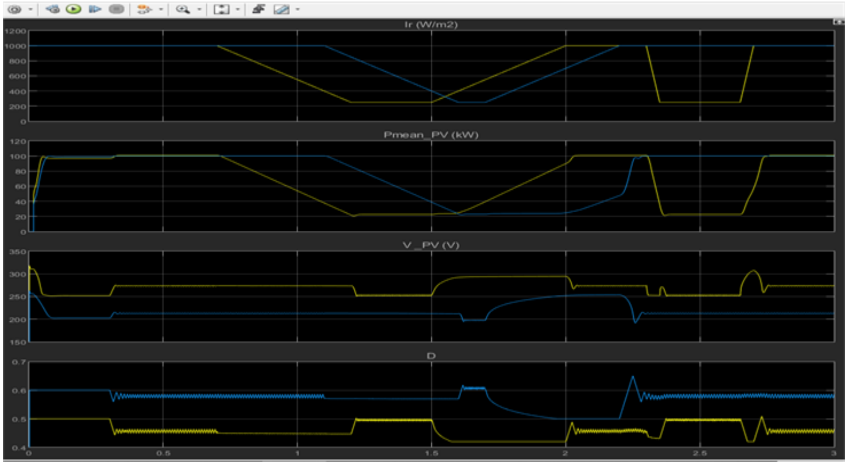

Figure (10): The average-value model performance

Conclusion

This paper presented a comprehensive comparative analysis of detailed switching and average-value models for grid-connected photovoltaic systems with MPPT control. The results confirm that the detailed switching model offers higher modeling fidelity, improved dynamic response, and accurate representation of switching effects and harmonics, making it suitable for power quality assessment and converter-level studies. In contrast, the average-value model provides a computationally efficient alternative with significantly reduced simulation time while maintaining acceptable accuracy, making it more appropriate for large-scale system analysis, control design, and optimization studies. The findings clearly demonstrate that the choice of modeling approach depends on the specific application requirements, particularly the trade-off between accuracy and computational efficiency. Future work will focus on enhancing the proposed framework by incorporating intelligent MPPT techniques such as artificial neural networks, developing hybrid modeling approaches, and validating the models using real-time or hardware-in-the-loop simulations to further improve practical applicability.

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