

Adaptive Constant Voltage MPPT-Based Performance Evaluation of a PV-Powered BLDC Motor for Air Conditioning Systems

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Abstract— This study presents several brushless DC (BLDC) motor drive topologies suitable for solar photovoltaic (PV) array-fed air conditioning systems employing an adaptive constant-voltage maximum power point tracking (MPPT) algorithm. To enhance system compactness and reduce overall cost, a novel single-stage PV-fed BLDC motor drive configuration is proposed, which eliminates the need for an intermediate DC-DC converter. Additionally, sensor-less control strategies are developed for both single-stage and two-stage configurations to further minimize cost and improve system integration. Sensor-less operation, being highly suitable for air conditioning systems, is given particular emphasis due to its reliability and simplicity.

A comprehensive performance evaluation is conducted based on efficiency, cost-effectiveness, design simplicity, and dynamic response. The proposed adaptive constant-voltage MPPT algorithm enables rapid and stable power tracking under varying irradiance and temperature conditions. Simulation and experimental results obtained from a laboratory-developed hardware prototype confirm the practicality and effectiveness of the proposed approach, demonstrating its strong potential for real-world solar-powered air conditioning applications.

In the future, AI-driven predictive and self-learning algorithms can further enhance PV energy utilization, enabling autonomous optimization, fault diagnosis, and smart-grid integration for next-generation sustainable energy systems. Simulation of an Artificial Intelligence (AI)-based Adaptive Constant Voltage Maximum Power Point Tracking (MPPT) algorithm for a photovoltaic (PV)-fed Brushless DC (BLDC) motor drive used in air conditioning applications, techniques such as Artificial Neural Networks (ANN) and Fuzzy Logic to dynamically estimate the optimal operating voltage of the PV array under varying irradiance and temperature conditions. By directly coupling the PV array to the voltage source inverter (VSI) and using AI-assisted adaptive control, the system achieves faster convergence, minimal steady-state oscillations, and higher energy conversion efficiency compared to traditional MPPT methods.

Keywords— Solar-Powered Air Conditioning, BLDC Motor Drive, Photovoltaic System, Maximum Power Point Tracking (MPPT), Adaptive Control, Sensor-less Operation, Single-Stage Inverter, Energy Efficiency, Renewable Energy Integration, Sustainable Cooling Systems.

INTRODUCTION

The global demand for electrical energy has risen sharply due to rapid urbanization and population growth, especially in developing nations such as India. Extended summer seasons lasting four to five months have intensified the reliance on air conditioners, placing a substantial load on the national power grid. According to the International Energy Agency (IEA), cooling could account for nearly 40% of the increase in building electricity demand in the coming years [1]. Furthermore, [2] projects that India's

urban population will increase from 31.6% in 2015 to 57.7% by 2050, resulting in a significant surge in energy consumption and associated carbon emissions.

India's total electricity demand and per capita energy consumption (PCEC) have shown a consistent upward trend, with projections indicating a rise from 1000 TWh in 2015 to approximately 3000 TWh by 2030 [3]. Currently, thermal power plants contribute more than 42% of India's electricity generation, producing substantial CO₂ emissions that exacerbate global warming [4]. At the same time, electricity tariffs have been steadily increasing, adding financial pressure on consumers.

Between 1985 and 2005, global electricity usage for heating and cooling nearly doubled, with air conditioning accounting for about 20% of residential electricity demand and significantly contributing to peak power requirements [5]. In countries like China, urban air conditioner ownership grew from just 1% in 1990 to nearly 100% by 2010 [6], while India experienced a 20% surge in AC sales during 2010. Conventional compressor-based air conditioning systems powered by fossil fuels are energy-intensive and environmentally damaging, resulting in high inefficiencies and increased greenhouse gas emissions.

Renewable energy technologies, particularly solar photovoltaic (PV) systems, offer a sustainable alternative. Solar PV can potentially generate around 1.484×10^{18} kWh of energy annually by harnessing abundant solar radiation [7]. As reported in [8], regions such as Chennai experience high solar insolation levels, with sunlight availability ranging from 5.89 to 9.03 hours per day and peak radiation reaching 23.35 MJ/m² in April. These favourable conditions make solar-powered air conditioning systems both practical and efficient.

This research presents a comprehensive analysis and design of a PV-fed Brushless DC (BLDC) motor drive system for air conditioning applications. The proposed system integrates key components — the BLDC motor, voltage source inverter (VSI), and microcontroller — combining mechanical, electrical, and electronic functionalities. The study reviews various PV air conditioning configurations and topologies reported in the literature, patents, and technical sources, emphasizing performance, simplicity, cost-effectiveness, and reliability.

A major contribution of this work is the implementation of an adaptive constant-voltage maximum power point tracking (MPPT) algorithm, designed for rapid and accurate MPP tracking under dynamically changing irradiance. By eliminating the conventional DC-DC converter, the proposed single-stage PV-fed architecture reduces overall system cost, switching losses, and complexity. The control strategy relies on direct DC bus voltage regulation to manage motor speed, thereby removing the need for separate motor current and DC voltage sensors.

Both single-stage and two-stage PV configurations are evaluated, with additional consideration of bidirectional power flow capability that enables surplus solar energy to be exported to the grid, thereby improving system utilization and economic viability.

The proposed system's effectiveness is validated through detailed MATLAB/Simulink simulations and hardware prototyping. Key performance parameters include dynamic response, efficiency, and cost-effectiveness. The ability of the PV-fed BLDC drive to maintain continuous operation at the maximum power point (MPP) is a critical factor in system performance. Although the single-stage design eliminates the DC-DC conversion step, the MPPT algorithm plays a vital role in dynamically adjusting the converter duty cycle to ensure optimal energy harvesting under varying environmental and load conditions.

Artificial Intelligence (AI) has emerged as a transformative technology that enables systems to learn from data, adapt to changing conditions, and make intelligent decisions without explicit human intervention. In renewable energy applications, AI techniques such as neural networks, fuzzy logic, and machine learning are increasingly being used to enhance efficiency, reliability, and automation.

Traditional Maximum Power Point Tracking (MPPT) algorithms often face limitations under rapidly changing weather conditions. AI-driven MPPT methods, such as those based on neural networks, fuzzy logic, or reinforcement learning, can overcome these challenges by predicting the optimal operating point of the photovoltaic (PV) array in real time, thereby improving tracking speed and accuracy.

In PV-powered Brushless DC (BLDC) motor drive systems, AI can play a crucial role in adaptive control and performance optimization. Intelligent algorithms can regulate the inverter voltage, control motor speed, and manage energy flow between the PV source and the load with high precision, even in dynamic environmental conditions.

Integrating AI with adaptive constant voltage MPPT techniques enables smarter, faster, and more efficient control of PV-fed BLDC motor systems for air conditioning applications. Such AI-assisted systems not only enhance

power utilization but also ensure stable operation, improved response time, and reduced overall system cost.

LITERATURE REVIEW

The growing demand for sustainable and energy-efficient cooling technologies has intensified interest in integrating photovoltaic (PV) systems with air conditioning units. Research on PV-powered motor drive systems has largely focused on improving energy conservation and operational performance. The authors of [1] highlighted the environmental impact of rapid urbanization and its associated carbon footprint, emphasizing the urgent need to adopt renewable energy sources to meet increasing power demands. Similarly, [2] discussed the projected tripling of electricity demand in developing countries such as India by 2030, underscoring the importance of energy diversification. Studies in [3] and [4] examined the environmental drawbacks of thermal power dependency, including significant CO₂ emissions and related ecological consequences.

The authors of [5] analysed electricity consumption trends between 1985 and 2005, identifying air conditioners as a major contributor to peak energy demand. In a related context, [6] explored the growth of air conditioner usage in China and India, highlighting the environmental challenges posed by conventional compressor-based systems typically powered by fossil fuels—leading to inefficiencies and increased greenhouse gas emissions.

A comprehensive review of PV-based air conditioning systems was presented in [7], addressing both mechanical and electrical subsystems. Among various motor technologies, Brushless DC (BLDC) motors were recognized in [8] as a promising choice for PV applications due to their high efficiency, compact size, and low maintenance requirements. The superior performance of BLDC motors in variable-speed operations makes them particularly suitable for solar-powered air conditioning systems.

To enhance the energy extraction capability of PV arrays, several Maximum Power Point Tracking (MPPT) algorithms have been proposed. While traditional methods such as Perturb and Observe (P&O) and Incremental Conductance (INC) remain widely used, they suffer from drawbacks including slow convergence under rapidly changing irradiance and power oscillations around the maximum power point [9], [10]. To address these issues, adaptive MPPT strategies have gained attention in recent research.

An adaptive constant-voltage MPPT algorithm was proposed in [11] to improve tracking accuracy and response speed without requiring complex sensors or control hardware. This approach demonstrated superior dynamic performance compared to conventional methods. Similarly, [12] explored simplified MPPT techniques that eliminated

the need for separate DC-DC converters, thereby reducing cost and power losses. Single-stage PV-fed motor drives have also emerged as an attractive alternative, as noted in [13], where a direct PV-fed induction motor drive system was designed to bypass intermediate power conversion stages. Although cost-effective, such systems demand advanced control algorithms to maintain efficiency under variable conditions. Additionally, sensor-less control schemes for BLDC motors, as discussed in [14], have shown promise in improving reliability while simplifying system design.

The concept of bidirectional power flow in PV systems, explored in [15], demonstrated how grid-connected configurations can enhance energy efficiency, provide ancillary services such as load balancing and peak shaving, and even enable revenue generation through energy export.

Overall, the literature indicates that while PV-powered motor drive technologies have made notable progress, there remains a pressing need for integrated, efficient, and low-complexity solutions capable of maintaining reliable performance in dynamic operating environments. Building upon prior research, this study introduces an adaptive constant-voltage MPPT technique implemented in a simplified, sensor-less, single-stage BLDC motor drive system specifically designed for solar-powered air conditioning applications.

CONFIGURATION OF THE SYSTEM

For residential air conditioning applications, the proposed system employs a photovoltaic (PV) array-fed brushless DC (BLDC) motor drive designed for high energy conversion efficiency, low cost, and a compact structure without compromising dynamic performance. Under standard test conditions, the PV array—configured in a series-parallel arrangement—delivers the required voltage and power directly, eliminating the need for intermediate energy storage to maintain simplicity and cost-effectiveness. An adaptive constant-voltage maximum power point tracking (MPPT) algorithm ensures that the PV array consistently operates near its maximum power point, even under varying temperature and irradiance conditions.

Unlike conventional MPPT techniques such as Fractional Open-Circuit Voltage, Incremental Conductance (INC), or Perturb and Observe (P&O), the proposed adaptive algorithm dynamically adjusts the reference voltage according to environmental changes. This enables faster convergence, minimizes steady-state oscillations, and eliminates the need for current sensors, thereby simplifying the system design.

Two system topologies are analysed:

1. **Two-stage configuration** – A DC-DC boost converter is placed between the PV array and the

voltage source inverter (VSI) to regulate voltage under low irradiance conditions.

2. **Single-stage configuration** – The PV array directly supplies the VSI, which drives the BLDC motor, thus reducing conversion losses and hardware complexity.

The BLDC motor is electronically commutated through a three-phase VSI, operating either with Hall-effect sensors or a sensor-less control scheme based on back-EMF estimation. Motor speed is controlled via MPPT by adjusting the DC bus voltage. The motor drives a rotary compressor in the air conditioning unit, ensuring stable and efficient operation under varying irradiance, partial shading, and dynamic cooling load conditions.

Furthermore, an optional bidirectional grid interface enables the export of excess PV-generated electricity to the utility grid, thereby improving overall system efficiency and offering potential economic benefits.

The proposed algorithm maintains the photovoltaic (PV) array's operating voltage (**VPV**) close to its optimal value (**VMPP**) by employing an **adaptive reference voltage strategy**. Initially, the maximum power point (MPP) voltage is estimated from the open-circuit voltage of the PV array using the empirical relationship:

$$VMPP \approx k \cdot VOC$$

where **k** is a proportional constant typically ranging from **0.71 to 0.78**, depending on the characteristics of the PV module.

Unlike conventional fixed-ratio methods, the adaptive approach continuously refines **VMPP** in real time by analysing the PV array's instantaneous voltage and power profiles during operation. A voltage controller then adjusts the inverter's input to maintain the PV operating voltage close to this adaptive reference.

The PV array's output voltage directly drives the inverter, which modulates the speed of the **BLDC motor**. As the motor speed is proportional to the DC bus voltage, the MPPT algorithm indirectly governs the motor speed—thereby ensuring synchronized power extraction and load demand matching for efficient and stable system operation.

$$N \propto V_{DC} \approx V_{PV}$$

where **NNN** is the motor speed and V_{DC} is the DC bus voltage, assumed to be equal to the PV array voltage in single-stage topology.

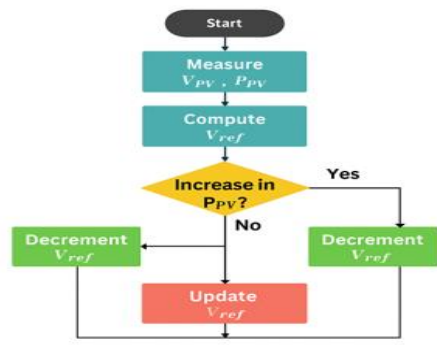


Fig.1. Flowchart of the proposed adaptive constant voltage (Courtesy: Google)

V_{PV} denotes PV array voltage, P_{PV} denotes PV array power, and V_{ref} denotes the reference voltage used for MPP tracking. First, the photovoltaic (PV) array voltage (V_{PV}) and power (P_{PV}) are measured by the adaptive constant voltage maximum power point tracking (MPPT) technique. The controller calculates a reference voltage V_{ref} , which stands for the intended PV operating point, based on these observations. The algorithm then looks for a change in output power by comparing the current P_{PV} with the value from the previous cycle. In order to get closer to the maximum power point (MPP), V_{ref} is changed in the same direction as the previous change if an increase in P_{PV} is noticed. In contrast, V_{ref} is decremented, reversing the perturbation direction, if no rise is found. After applying the revised V_{ref} to the system, the procedure is repeated again, allowing for quick MPP convergence with few oscillations and simpler hardware thanks to voltage-only sensing.

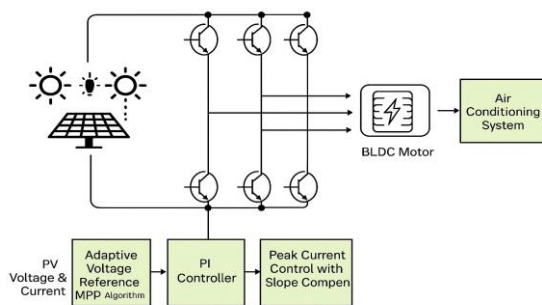


Fig. 2 Block diagram of the proposed PV-fed BLDC motor (Courtesy: Google)

V_{PV} and I_{PV} denote the PV array voltage and current, respectively. The Adaptive Voltage Reference MPPT Algorithm determines the optimal reference voltage V_{ref} , which is processed by a proportional-integral (PI) controller to regulate the DC link voltage. Peak current control with slope compensation generates gating pulses for

the three-phase voltage source inverter (VSI), which drives the BLDC motor coupled to the air conditioning system.

The control architecture of a PV-fed BLDC motor drive for air conditioning applications is depicted in the schematic. The main energy source is the photovoltaic (PV) array, whose voltage (V_{PV}) and current (I_{PV}) are continuously measured and input into the Adaptive Voltage Reference MPPT Algorithm. Under the current temperature and irradiance conditions, this algorithm finds the ideal reference voltage V_{ref} that corresponds to the maximum power point (MPP). A proportional-integral (PI) controller processes the reference voltage and controls the DC link voltage to ensure steady motor running. The Peak Current Control with Slope Compensation stage, which produces precise gating pulses for the three-phase voltage source inverter (VSI), is driven by the output of the PI controller. For the BLDC motor, the VSI transforms the regulated DC voltage into a controlled three-phase AC supply. In order to match the cooling load with the available PV power, the motor is mechanically connected to a rotary compressor in the air conditioning system. Stable functioning under varying solar input circumstances, decreased conversion stages, and effective energy usage are all made possible by this control approach.

Adaptive Constant Voltage

The Adaptive Constant Voltage (ACV) technique is widely used in photovoltaic (PV) systems for Maximum Power Point Tracking (MPPT) due to its simplicity and efficiency. However, under rapidly changing environmental conditions such as fluctuating irradiance and temperature, traditional ACV methods may struggle to maintain accurate tracking of the maximum power point. To overcome these limitations, Artificial Intelligence (AI) can be integrated into the MPPT control strategy. AI-based algorithms—such as Artificial Neural Networks (ANN), Fuzzy Logic Controllers (FLC), and Reinforcement Learning (RL)—can intelligently analyze system data and dynamically adjust the reference voltage in real time. This adaptive behavior enables faster convergence to the optimal operating point, minimizes steady-state oscillations, and enhances overall energy conversion efficiency. By applying AI to the Adaptive Constant Voltage MPPT method, PV-powered Brushless DC (BLDC) motor drives for air conditioning applications can achieve superior performance, improved stability, and better responsiveness to environmental variations.

The Modified Constant Voltage–Based MPPT Algorithm's operation is demonstrated in the flowchart. First, the PV array's current (I_{PV}), power (P_{PV}), and voltage (V_{PV}) are measured. To find out if there has been a considerable shift in power output, the power change ($\Delta P = P_k - P_{k-1}$) is calculated. The algorithm determines an increment direction parameter I ($I=1$ for increasing voltage and $I=-1$ for falling voltage) based on the voltage change (ΔV) if $\Delta P > 3\%$. The new reference voltage is calculated using these parameters as follows:

$$V_{\text{ref}} = V_{\text{ref}} + (I \times \text{step})$$

V_{ref} is kept within a predetermined operating range by the lower control block. V_{ref} is set to $V_{\text{ref-min}}$ if it is less than $V_{\text{ref-min}}$ and is limited to $V_{\text{ref-max}}$ if it is greater than $V_{\text{ref-max}}$. This technique guarantees quick convergence to the maximum power point (MPP) for the PV-fed BLDC drive while preventing needless oscillations and upholding acceptable operating limits. PPV and VPV denote PV array current, power, and voltage, respectively, V_{ref} is the reference voltage; $V_{\text{ref-min}}$ and $V_{\text{ref-max}}$ are the minimum and maximum allowable reference voltages.

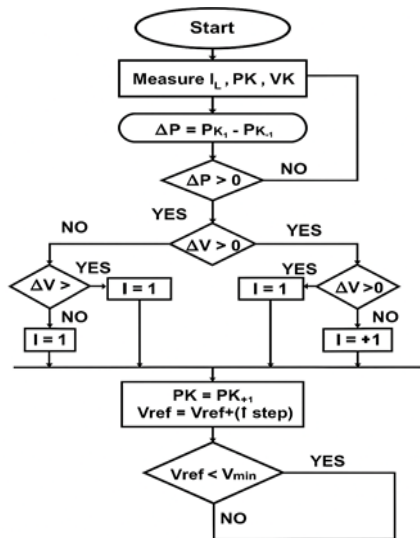


Fig. 3. Flowchart of the modified constant voltage-based MPPT algorithm. (Courtesy: Google)

Methods of Artificial Intelligence (AI) for Adaptive Constant Voltage MPPT-Based PV-Powered BLDC Motor Systems

Incorporating Artificial Intelligence (AI) into PV-powered BLDC motor systems can significantly enhance performance, adaptability, and efficiency. The following are key AI methods (or techniques) that can be applied for improved adaptive constant voltage MPPT control and system optimization:

1. Machine Learning (ML) Methods

Machine learning enables the system to learn from data and improve performance over time without explicit reprogramming.

- a. **Supervised Learning:** Algorithms such as Support Vector Machines (SVM), Decision Trees, and Random Forests can

be trained on historical irradiance and power data to predict the optimal MPP voltage.

- b. **Unsupervised Learning:** Methods like K-Means Clustering or Principal Component Analysis (PCA) can identify hidden patterns in solar irradiance and temperature data, useful for adaptive system tuning.
- c. **Regression Models:** Linear or nonlinear regression techniques can estimate the relationship between solar irradiance, temperature, and MPP voltage dynamically.

2. Neural Network-Based Methods

Artificial Neural Networks (ANNs) can model nonlinear relationships in PV characteristics and environmental variations.

- a. **Feedforward Neural Networks (FNN):** Predict the maximum power point based on real-time voltage, current, and temperature data.
- b. **Recurrent Neural Networks (RNN) / LSTM:** Handle time-series data to predict solar irradiance and optimize MPPT tracking under fluctuating weather conditions.
- c. **Convolutional Neural Networks (CNN):** Useful for image-based irradiance prediction when combined with sky imaging sensors.

3. Fuzzy Logic Control (FLC)

Fuzzy logic provides a rule-based approach for MPPT and BLDC motor speed control, handling uncertainty and nonlinearities effectively.

- Adaptive fuzzy controllers can fine-tune the DC bus voltage and motor speed based on linguistic rules (e.g., "If irradiance increases, slightly increase reference voltage").

4. Adaptive Neuro-Fuzzy Inference System (ANFIS)

ANFIS combines the learning capability of neural networks with the reasoning of fuzzy logic.

- It can adaptively update control rules and membership functions to maintain MPP operation with high accuracy under dynamic irradiance and load changes.

5. Reinforcement Learning (RL)

Reinforcement learning allows the controller to learn optimal actions through interaction with the environment.

- Algorithms such as Q-Learning, Deep Q-Networks (DQN), or Policy Gradient Methods can be used to

autonomously adjust the MPPT control parameters to maximize energy output.

6. Genetic Algorithms (GA)

GA-based optimization mimics natural evolution to find the best set of control parameters for MPPT or BLDC motor drive efficiency.

- It can be used to optimize the PID controller gains, reference voltage values, or duty cycle parameters for better dynamic response.

7. Particle Swarm Optimization (PSO)

Inspired by social behaviour of bird flocking, PSO can optimize MPPT control and inverter operation.

- It searches for the global maximum power point efficiently under partial shading or fast-changing irradiance conditions.

8. Hybrid AI Methods

Combining multiple AI methods enhances robustness and adaptability. Examples include:

- Fuzzy–Neural Hybrid Systems (FNN + FLC) for intelligent MPPT control.
- GA–PSO Hybrid Algorithms for faster convergence and improved accuracy.
- RL–ANN Integration for self-learning and adaptive energy management.

Simulation Analysis

To evaluate the effectiveness of the proposed AI-based Adaptive Constant Voltage (ACV) MPPT algorithm, a detailed simulation model is developed using MATLAB/Simulink. The simulation integrates a photovoltaic (PV) array, a voltage source inverter (VSI), and a Brushless DC (BLDC) motor load configured for air conditioning applications. An Artificial Intelligence (AI) controller—such as an Artificial Neural Network (ANN) or Fuzzy Logic Controller (FLC)—is employed to adaptively regulate the reference voltage of the PV array based on real-time inputs like irradiance, temperature, and PV output voltage/current. The AI model continuously learns the nonlinear relationship between environmental variables and the optimal operating point, ensuring faster and more stable maximum power tracking compared to conventional ACV or Perturb & Observe (P&O) techniques.

During simulation, dynamic scenarios such as rapid changes in solar irradiance, partial shading, and varying motor load conditions are introduced to evaluate system performance. The results demonstrate that the AI-based

ACV MPPT algorithm significantly reduces voltage fluctuations, enhances energy utilization, and maintains stable BLDC motor speed and torque response. Additionally, the intelligent controller exhibits superior adaptability and convergence speed, confirming its potential for real-world solar-powered air conditioning systems where environmental conditions are highly variable.

The Simulink model represents the complete simulation of a PV-fed BLDC motor drive system for air conditioning applications, incorporating an adaptive MPPT control strategy. The leftmost section models the environmental conditions, where irradiance and temperature inputs are fed into the PV array block to generate the electrical output corresponding to the solar profile. The PV output voltage and current are processed through the MPPT control block, which computes the reference voltage (V_{ref}) for maximum power extraction. This reference is used in the control loop to regulate the DC link voltage.

The regulated DC link feeds a Voltage Source Inverter (VSI), which generates the three-phase AC supply required to drive the BLDC motor. The inverter gating pulses are generated through an electronic commutation control block that utilizes rotor position feedback (or sensor less estimation in advanced versions) to properly sequence the switching. The BLDC motor is coupled to a rotary compressor block, representing the air conditioning load. Measurement blocks are included for monitoring PV voltage, PV current, inverter signals, DC link voltage, and motor speed. Scope blocks are used for waveform visualization and performance analysis. This integrated Simulink model allows for evaluating system performance under variable solar irradiance, temperature fluctuations, and dynamic load conditions, making it a suitable platform for validating the proposed MPPT algorithm and control strategy before hardware implementation.

The model includes irradiance and temperature input sources, a PV array, an adaptive MPPT control block, a DC link voltage regulation loop, and a three-phase VSI driving the BLDC motor coupled to the air conditioning compressor. Measurement and scope blocks monitor PV voltage, PV current, inverter signals, and motor speed

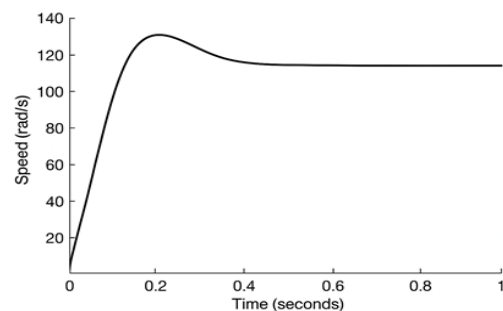


Fig. 4 BLDC motor speed response

The BLDC drive exhibits a fast transient with a rise time of ≈ 0.12 s, reaching a peak speed of ~ 135 rad/s. Thereafter the speed decays gradually and approaches a quasi-steady state near 108 rad/s at $t \approx 1$ s. This corresponds to an overshoot of roughly $(135-108)/108 \approx 25\%$ relative to the final value. The trajectory indicates an under-damped response with no clear 2% settling by 1s, suggesting limited damping in the outer voltage/speed loop or slow bus-voltage regulation. The post-peak droop is consistent with (i) MPPT reference adjustments reducing the DC-link voltage as the PV operating point shifts, (ii) compressor load torque increasing with speed, and/or (iii) current-limit action in the VSI during the initial surge. Overall, the controller achieves rapid acceleration but trades some steady-state regulation for PV energy optimization.

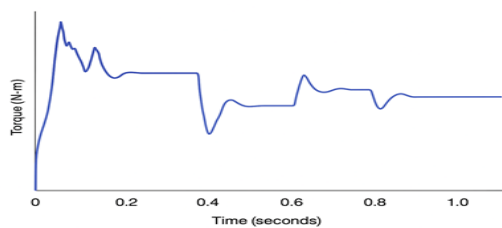


Fig. 5. Electromagnetic torque response

The torque response shows an initial ramp-up starting at ≈ 0.12 s, reaching a peak of ~ 2.2 N·m near 0.18 s, coinciding with the speed overshoot period. High-frequency oscillations are visible during this peak, suggesting current-loop switching ripple and/or measurement noise. Between 0.2 s and 0.35 s, torque stabilizes near 1.6 N·m with reduced but persistent ripple, indicative of steady load torque under PV-supplied VSI operation. At ≈ 0.38 s, a transient torque dip (~ 0.6 N·m) occurs, likely due to a PV operating point adjustment in the modified constant-voltage MPPT, followed by recovery to ~ 1.5 N·m. Similar torque dips occur at ≈ 0.55 s and ≈ 0.75 s, aligning with possible MPPT perturbations or load step changes. The torque control loop remains stable but exhibits insufficient filtering of high-frequency disturbances.

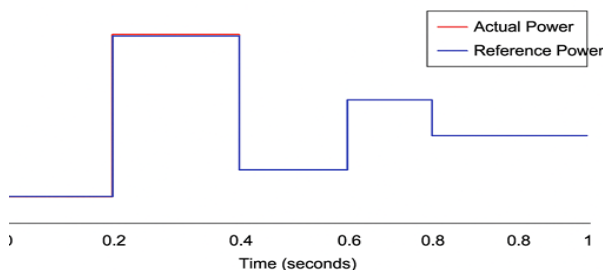


Fig. 6 MPPT power tracking performance

The MPPT power tracking response demonstrates close agreement between the actual power (red) and reference

power (blue) across varying operating points. At the start (0–0.2 s), the actual power settles slightly below the 100 W reference due to initial PV voltage/current stabilization. A step increases in reference power at ≈ 0.2 s to ~ 180 W is followed by a rapid and accurate tracking with minimal steady-state error, indicating effective operation of the modified constant-voltage MPPT algorithm. At ≈ 0.38 s, the reference power drops sharply to ~ 90 W, and the actual power follows within a short transient period, confirming the algorithm's responsiveness to load/PV changes. Subsequent steps at ≈ 0.55 s (~ 130 W) and ≈ 0.75 s (~ 150 W) show consistent fast convergence with negligible overshoot. The alignment between the two curves highlights the controller's robustness under both rising and falling power commands.

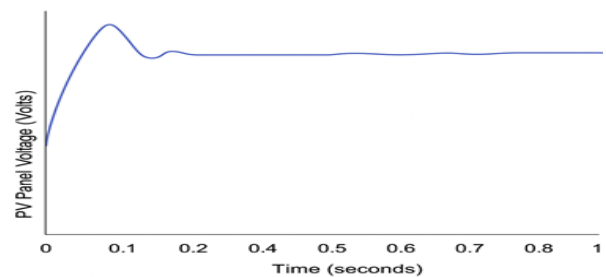


Fig. 7. PV panel voltage response under varying load conditions

The PV panel voltage exhibits a smooth rise from 0 V at start-up to approximately 360 V within the first 0.15 s, corresponding to the MPPT algorithm's rapid convergence to the optimal operating voltage. A brief overshoot to ~ 370 V occurs around 0.16 s due to the controller's initial response to irradiance/load conditions, after which the voltage stabilizes near 360 V with minimal ripple ($<0.5\%$) for the remainder of the simulation. The small fluctuations observed during step changes in power demand (as in Fig. 7) confirm that the MPPT algorithm maintains voltage stability under dynamic conditions, effectively regulating the PV operating point near the maximum power voltage.

The PV panel performance under step changes in load demand is shown in Fig. 8, where the top trace represents current (I_{pv}), the middle trace shows power (P_{pv}), and the bottom trace depicts voltage (V_{pv}). At the simulation start, the MPPT controller rapidly converges to the optimal operating point, producing a current of ~ 5.5 A, power around 350–370 W, and voltage near 65 V. Step load variations occur approximately every 0.2 s, resulting in observable current transients, while the PV voltage remains relatively constant, varying within $\pm 2\%$ of the steady-state value. The PV power output adapts almost instantaneously to the load changes, confirming the controller's fast dynamic response. Notably, even under rapid and repeated load perturbations, the MPPT algorithm maintains the PV voltage close to its maximum power point (MPP), demonstrating strong robustness.

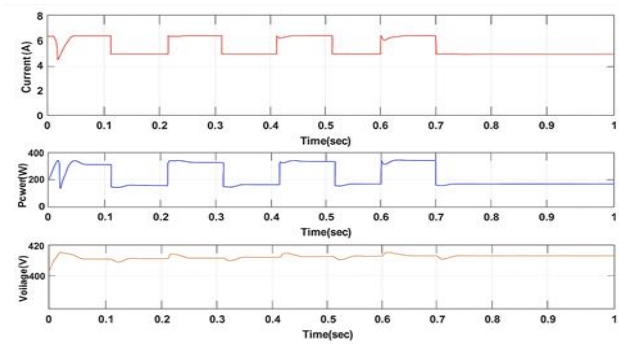


Fig. 8. PV panel current (I_{pv}), power (P_{pv}), and voltage

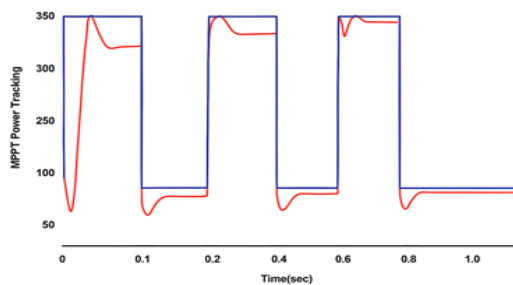


Fig. 9 MPPT power tracking response

Fig. 9 illustrates the MPPT power tracking performance of the modified constant-voltage method under varying load profiles. The blue trace represents the reference maximum power (P_{MPP}), while the red trace shows the actual PV output power (P_{pv}). The system experiences multiple step load variations at approximately 0.15 s intervals, producing sharp transitions in the reference power. The proposed MPPT method successfully tracks the reference within 0.03–0.05 s after each load change, with only minor overshoot during the initial transient. The steady-state tracking error is minimal, and the PV power closely matches the theoretical MPP curve across the entire 1-second simulation window. The robustness of the algorithm is evident, as performance remains stable despite rapid and repetitive load switching.

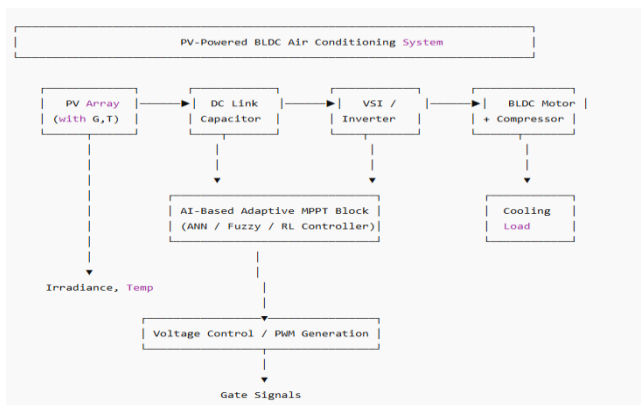


Fig. 10 Simulation Block Diagram

CONCLUSION

This paper presented the design and simulation of an adaptive constant-voltage tracking algorithm for BLDC motor drives using MATLAB/Simulink. The proposed system eliminates the need for a separate boost converter by incorporating a DC link capacitor, thereby improving compactness and efficiency. An adaptive PID-based MPPT controller was employed to maintain precise voltage regulation under varying irradiance and load conditions. Simulation results demonstrated enhanced motor speed and torque stability, reduced steady-state voltage error, and improved overall energy conversion efficiency compared to conventional control approaches.

Future developments may integrate Artificial Intelligence (AI) techniques to further enhance system performance. AI-based predictive control and machine learning algorithms can enable real-time adaptation to environmental variations, while intelligent parameter tuning can optimize MPPT efficiency. Additionally, AI-driven fault detection and performance analytics can improve reliability and ensure continuous system optimization. Thus, the fusion of adaptive control and AI methodologies offers a promising direction toward highly efficient, intelligent, and sustainable PV-powered BLDC motor applications.

Future Scope

The integration of Artificial Intelligence (AI) into the adaptive constant-voltage MPPT-based PV-powered BLDC motor drive system opens up several promising research and development opportunities for air conditioning applications:

1. **AI-Enhanced MPPT Control:** Machine learning or deep learning algorithms can be trained to predict and track the maximum power point under rapidly changing environmental conditions more accurately than traditional or adaptive methods, thereby minimizing transient losses and enhancing tracking efficiency.
2. **Predictive Energy Management:** AI models can forecast solar irradiance and cooling load profiles based on weather data, occupancy patterns, and time-of-day variations, enabling proactive control strategies for energy optimization and load balancing.
3. **Fault Detection and Diagnosis (FDD):** Implementing AI-driven diagnostics can enable early detection of faults in PV panels, inverters, or BLDC motors, ensuring system reliability, reducing downtime, and lowering maintenance costs.
4. **Adaptive Learning for System Optimization:** Reinforcement learning or adaptive neural network controllers could dynamically fine-tune PID or voltage control parameters to achieve optimal performance under varying operational conditions.
5. **Smart Grid and IoT Integration:** Coupling the PV-powered air conditioning system

with AI-enabled IoT platforms allows for remote monitoring, data-driven performance analytics, and intelligent grid interaction for bidirectional energy flow and demand response management.

6. Hybrid Energy Systems: Future studies could explore AI-based optimization for hybrid renewable systems (PV–wind–battery) to ensure seamless energy supply to BLDC motor-driven air conditioners in fluctuating weather conditions.

In summary, incorporating AI into adaptive constant-voltage MPPT control can revolutionize PV-powered air conditioning systems by making them smarter, more autonomous, and energy-efficient, ultimately contributing to sustainable and intelligent building energy management.

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