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Intelligent control strategy for grid-integrated PV systems with enhanced dynamic performance

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ABSTRACT

With the increasing integration of solar photovoltaic (PV) systems into modern power grids, grid stability and power quality have become a critical challenge due to environmental variability and non-linear load dynamics. To deal with these problems, this research proposes a novel control strategy by incorporating Deep Attention Dilated Residual Convolutional Neural Network (DADRCNN) with Hippopotamus Optimization Algorithm (HOA) to optimally manage energy in a grid-connected photovoltaic system. The key goal of this study is to mitigate power quality issues like harmonic distortions, voltage fluctuations, and load imbalances, thereby improving the power system's overall performance and stability. To achieve this, DADRCNN precisely tracks the maximum power point, while HOA optimizes the converter's duty cycle to ensure effective control. The proposed control technique is simulated in MATLAB and evaluated against existing strategies. Findings demonstrate that the proposed strategy achieves a high accuracy of 99.84 %, the lowest total harmonic distortion of 1.08 %, and a low computation time of 1.05 s, outperforming existing models. In addition, statistical analysis confirms the robustness and reliability of the proposed technique, indicating its practical applicability for PV energy conversion in smart grid environments.

1. Introduction

a) Background

Solar photovoltaic (PV) systems have become integral to modern energy infrastructures, offering sustainable and environmentally friendly power generation [1]. Their incorporation into grid networks improves energy security by diversifying the energy mix and aids in the reduction of greenhouse gas emissions [2]. The evolution of grid-tied photovoltaic systems has led to the development of multi-functional energy conversion systems that extend beyond mere power generation [3]. These systems are designed to perform secondary services such as reactive power compensation, voltage regulation, and harmonic mitigation, improving overall power quality [4-6]. Complex control techniques have been used to maximize the performance of these multifunctional systems. Techniques such as adaptive neuro-fuzzy inference systems have been explored to improve the dynamic response and stability of grid-tied photovoltaic systems [7-10].

Environmental factors such as fluctuating irradiance and temperature introduce further instability in PV output, making consistent power delivery a challenge [11,12]. Furthermore, the integration of photovoltaic systems into the grid requires effective coordination with energy storage technologies to mitigate intermittency and ensure demand-supply balance [13]. The nonlinear nature of PV systems has led to the development of several Maximum Power Point Tracking (MPPT) approaches, like gradual behaviour, perturb and observe (P&O), and fuzzy-based methods [14]. Managing PV power within the grid and addressing associated challenges presents a formidable task. The literature discusses several solar-fed grid-tied configurations intended to improve power quality [15]. The proposed method has used Solar Energy Conversion Systems (SECS) to support the grid in remote areas and during moments of high demand [16]. These issues become more prominent in smaller energy systems, where load behavior is less predictable and more sensitive to disturbances, often resulting in power quality fluctuations and stability concerns [17].

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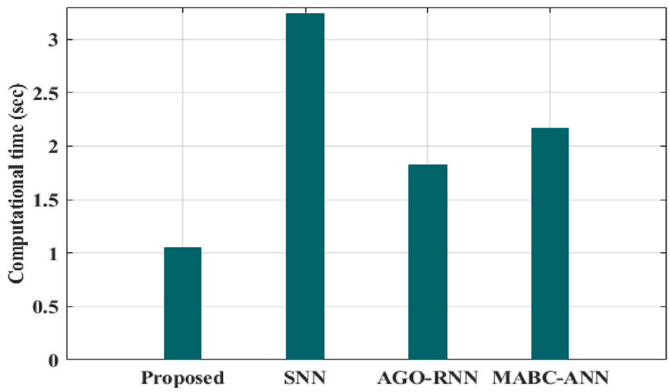

Fig. 10. Comparison of computation time between proposed and existing methods.

Table 3
Comparative analyses between proposed and existing methods.

Methods	Accuracy (%)	THD (%)
Proposed	99.84	1.08
SNN	91.22	4.05
AGO-RNN	94.73	1.89
MABC-ANN	96.01	2.34

Table 4
Statistical comparison between proposed and existing methods.

Methods	Std. Deviation	Mean	Median
Proposed	0.082	1.208	1.173
SNN	0.133	1.362	1.357
AGO-RNN	0.107	1.303	1.296
MABC-ANN	0.096	1.279	1.224

algorithm's robustness but also emphasizes its practical feasibility for deployment in modern distributed energy systems.

Moreover, the proposed method's computational efficiency, demonstrated by its shortest computing time, offers a significant advancement over current methods. This is especially critical for applications in dynamic grid environments where latency can significantly damage response accuracy and system performance. The statistical analysis reinforces this by showing the lowest standard deviation and closer grouping around the mean, indicating higher reliability and consistency. The effective fusion of a bio-inspired optimization method with deep learning-based temporal-spatial feature extraction sets this work apart. This allows for a more intelligent, adaptive, and resilient control strategy that dynamically adjusts to uncertainties, offering significant advancements over rule-based controllers. However, the study does not fully capture the complexities and stochastic variations of real-world grid conditions. Moreover, the strategy was exclusively applied to a PV-based system, which limits its immediate generalizability to hybrid renewable systems involving wind, battery storage, or other distributed energy resources.

5. Conclusion

This research presented a novel control strategy to effectively manage a grid-linked solar photovoltaic system. The proposed strategy is applied to ease power quality issues like harmonic distortions and load imbalances, while also optimizing computational efficiency. The technology guarantees higher energy conversion and increased overall stability of the grid-linked photovoltaic system by precisely tracking the maximum power point with DADRCNN and fine-tuning the duty cycle of the converter using HOA. The proposed control strategy has been excluded in MATLAB and assessed against existing methods. The outcomes indicate that the proposed strategy achieves the fastest computation time of 1.05 s, significantly outperforming SNN, AGO-RNN and MABC-ANN. This highlights its superior computational efficiency, making it well-suited for dynamic grid-tied solar energy applications. Additionally, the proposed method achieves the highest accuracy at 99.84 %, and also attains a low THD of 1.08 % analysed to existing models, indicating superior power quality. Statistical analysis further shows the proposed strategy's reliability, outperforming the existing methods. These findings confirm that the proposed control strategy offers improved performance, establishing it as an effective and robust solution for grid-tied solar energy conversion systems. Future work will focus on extending this control strategy to hybrid renewable energy systems, aiming to further enhance system resilience and energy management. Additionally, implementing the proposed method in real-time hardware setups will provide practical validation.

CRediT authorship contribution statement

Subash Kumar C S: Writing – original draft. **Saravanan R:** Supervision. **Srinivas G:** Supervision. **Murugan A S S:** Supervision.

Ethical approval

There are no human subjects studies in this article that any of the writers have conducted.

Disclosure of interest

Not appropriate.

Code availability

Not appropriate.

Consent to participate:

Not appropriate

Consent for publication:

Not appropriate

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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