Salud, Ciencia y Tecnología. 2025; 5:1615
doi: 10.56294/saludcyt20251615

REVIEW

Power optimization in photovoltaic systems by integrating bio-inspired algorithms in a charge controller: a review

Optimización de la potencia en sistemas fotovoltaico integrando algoritmos bioinspirados en un controlador de carga: una revisión

Luis E. Neira Ropero[1], Aldo Pardo García[1], Francisco Lopez Monsalvo[2], Jorge Luis Diaz Rodriguez[1]

[1]Universidad de Pamplona, Norte de Santander. Pamplona, Colombia.
[2]Universidad del Caribe, Quintana Roo. Cancún, México.

Cite as: Neira Ropero LE, Pardo García A, Lopez Monsalvo F, Diaz Rodriguez JL. Power optimization in photovoltaic systems by integrating bio-inspired algorithms in a charge controller: a review. Salud, Ciencia y Tecnología. 2025; 5:1615. https://doi.org/10.56294/saludcyt20251615

Submitted: 17-09-2024 **Revised:** 01-01-2025 **Accepted:** 03-07-2025 **Published:** 04-07-2025

Editor: Prof. Dr. William Castillo-González

Corresponding author: Luis E. Neira Ropero

ABSTRACT

Photovoltaics is not only presented as a viable response to the global energy crisis, but also as a fundamental tool to mitigate the negative impacts of climate change. However, the efficiency of photovoltaic systems is often compromised by factors such as climate variability, shading, and the intrinsic complexity of solar cells. In this context, the implementation of bio-inspired algorithms in the charge controller stands as an innovative and promising approach to optimize the power generated by solar panels, thus maximizing the overall performance of the system. The convergence between engineering and nature represents a fascinating path towards efficiency in solar energy generation. By incorporating bio-inspired algorithms into the charge controller of a photovoltaic system, we not only advance power optimization, but also open the door to new perspectives for research in renewable energy. Therefore, this research not only contributes to current knowledge in the field of photovoltaics, but also invites us to continue exploring the infinite possibilities offered by the integration of biological principles in engineering for the benefit of a sustainable future. The results obtained not only validated the effectiveness of these approaches in power optimization, but also revealed a significant improvement in the stability and adaptability of the system under changing conditions.

Keywords: Photovoltaic Energy; DC/DC Converter; AI; Genetic Algorithm.

RESUMEN

La energía fotovoltaica no sólo se presenta como una respuesta viable a la crisis energética mundial, sino también como una herramienta fundamental para mitigar los impactos negativos del cambio climático. Sin embargo, la eficiencia de los sistemas fotovoltaicos a menudo se ve comprometida por factores como la variabilidad climática, el sombreado y la complejidad intrínseca de las células solares. En este contexto, la implementación de algoritmos bioinspirados en el controlador de carga se erige como un enfoque innovador y prometedor para optimizar la energía generada por los paneles solares, maximizando así el rendimiento general del sistema. La convergencia entre ingeniería y naturaleza representa un camino fascinante hacia la eficiencia en la generación de energía solar. Al incorporar algoritmos bioinspirados en el controlador de carga de un sistema fotovoltaico, no sólo avanzamos en la optimización de la energía, sino que también abrimos la puerta a nuevas perspectivas para la investigación en energías renovables. Por tanto, esta investigación no sólo contribuye al conocimiento actual en el campo de la fotovoltaica, sino que también nos invita a seguir explorando las infinitas posibilidades que ofrece la integración de principios biológicos en la ingeniería en beneficio de un futuro sostenible. Los resultados obtenidos no solo validaron la efectividad de estos enfoques en la optimización de la potencia, sino que también revelaron una mejora significativa en la estabilidad y adaptabilidad del sistema en condiciones cambiantes.

Palabras clave: Energía Fotovoltaica; Convertidor DC/DC; IA; Algoritmo Genético.

INTRODUCTION

Photovoltaic systems play a crucial role in sustainable energy generation,[1] but energy optimization remains a major challenge to maximize their efficiency.[2] This literature review focuses on the advances of integrating bio-inspired algorithms (figure 1) into the charge controller of photovoltaic systems to improve performance and energy optimization. To perform the selection, a search was initially made in Scopus, then a first analysis was performed using the VOSviwer software (figure 2). Then, the Obsidian software is used to customize certain parameters of the literature (figure 3). By exploring the current challenges in energy optimization within photovoltaic systems, the potential of bio-inspired algorithms to become more efficient every day is examined; these algorithms, which mimic natural processes, offer a novel approach to improve power generation, surpassing traditional methods.[3] Integrating these algorithms into charge controllers not only improves system performance but also presents opportunities for increased efficiency in power generation.

Through detailed investigation of performance evaluation metrics and case studies,[4] this paper also aims to demonstrate the effectiveness of bio-inspired algorithms in optimizing power generation.[5] Furthermore, the paper discusses future prospects and challenges in this field, highlighting potential advancements and contributions to renewable energy technologies,[6,7,8] paving the way to a more sustainable energy future.[7,8,9]

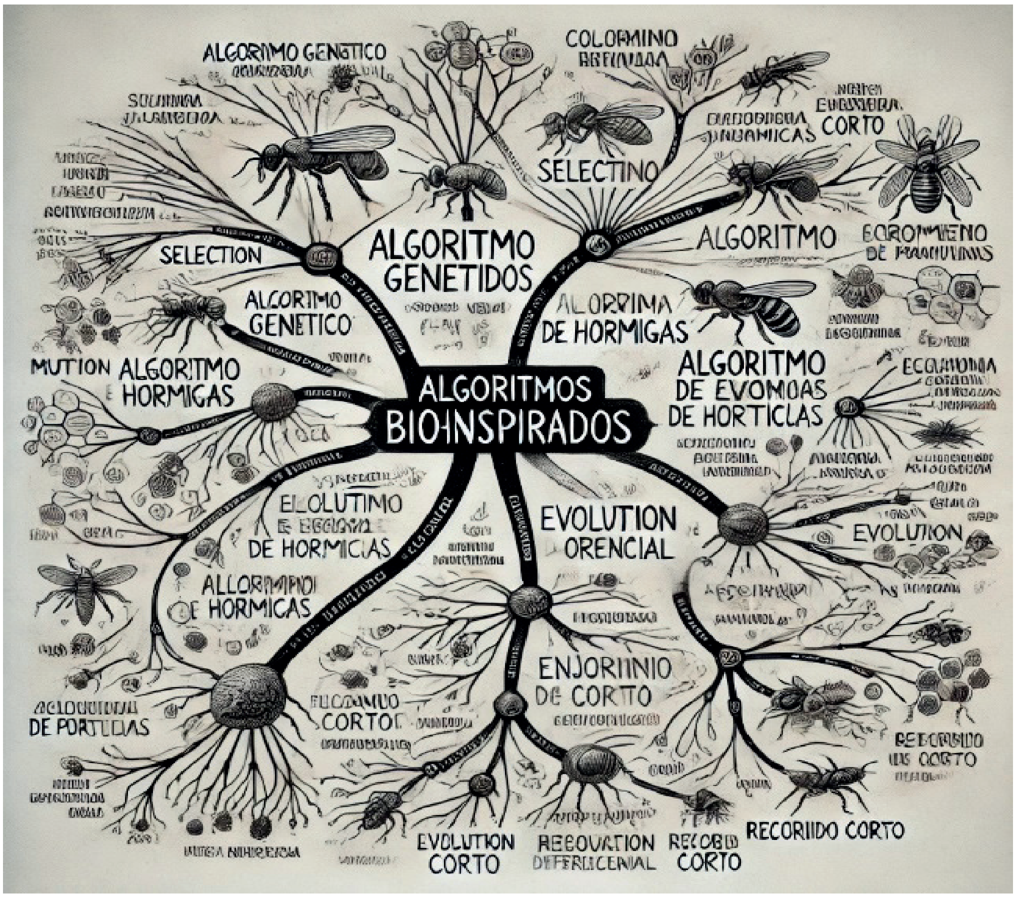

Figure 1. Bio-inspired algorithms

The way genetic algorithms work is based on evolutionary cycles that mimic nature. First, the best-performing individuals are selected from the current population and their genetic material is made available to the next generation. These individuals are combined by a crossover operator that exchanges genes between the two parents to create a new individual. Mutation operators then introduce random mutations into the genes, increasing genetic diversity and preventing the algorithm from falling into suboptimal solutions. This cycle

https://doi.org/10.56294/saludcyt20251615 ISSN: 2796-9711

of selection, crossover, and mutation continues until a convergence criterion is reached, such as a maximum number of generations or a fitness threshold. From this point on, the best individual from the last generation is considered the best solution to the problem.[10,11]

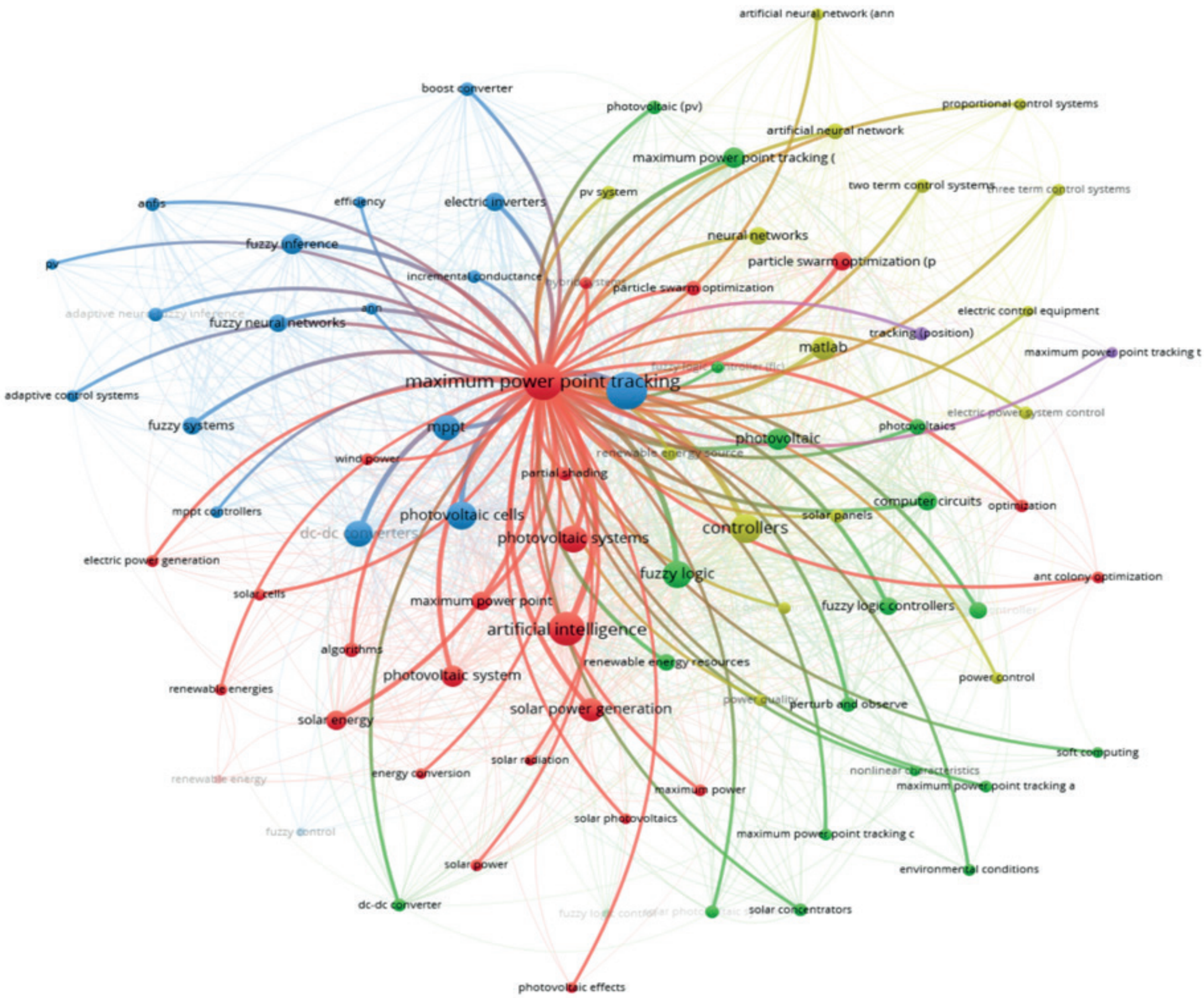

Figure 2. Tracking the maximum power point

Power Optimization in a Photovoltaic System

The optimization of power generation in photovoltaic systems presents a multifaceted challenge that encompasses several technical aspects.[12] Being a critical challenge, the need to improve efficiency and maximize the power delivered to the connected load, thus limiting the optimization process.[13,14] Within these parameters, techniques such as maximum power point tracking (MPPT)[15] and the investigation of optimal power points are essential to improve power generation in photovoltaic systems,[16] but their implementation can be complex, adding to the existing challenges.[13]

The complexity of implementing the MPPT technique is a notable obstacle to achieving optimal power generation,[17] further aggravated by the decrease in the system performance value, which can fall as low as 48,15 % under certain conditions.[13] Furthermore, challenges persist in optimizing power generation due to the dependence of PV systems on environmental conditions such as temperature and solar insolation, which introduce inconsistencies in maximum power point tracking and pose obstacles to efficient energy utilization.[18,19] Selecting appropriate module sizes is another critical challenge to ensure efficient power generation over large area sizes, with modules ranging from several square inches (⟦in⟧^2) to 3500 ⟦in⟧^2 ≈ 2,25 m^2) requiring careful consideration for optimal performance.[20] Also, accurate forecasting is critical to effectively integrate solar power into power grids,[21] but the inherent variability and complexity of PV power generation data present significant challenges in this regard, underscoring the need for advanced predictive models to address these optimization challenges.[22,23]

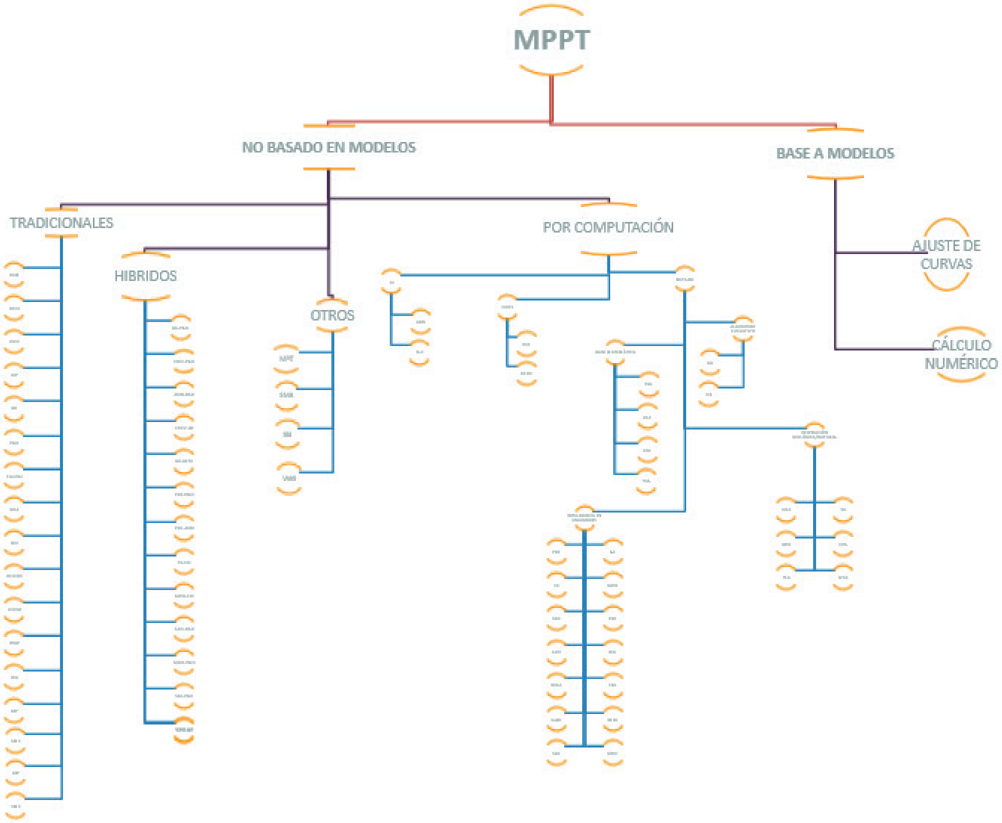

Figure 3. MPPT taxonomy

This is why these types of algorithms have become promising tools to improve energy optimization in photovoltaic systems, offering unique solutions based on natural processes. Researchers have explored several bioinspired algorithms, such as the ant colony algorithm(24,25) and the artificial immune system algorithm, to improve energy optimization in photovoltaic systems, showing innovative approaches to improve system efficiency.(26) In particular, these algorithms have been used to address challenges such as managing mismatches between demand and production and determining the optimal capacity of energy sources such as photovoltaic panels, batteries, wind turbines and diesel generators or in hybrid systems.(26) Likewise, bioinspired algorithms have shown potential to optimize the size of inverters and the tilt angles of solar panels, thus contributing to the overall energy optimization of these systems. Leveraging algorithms such as the NSGA-II genetic algorithm,(27) researchers have even demonstrated the ability of moderately sized PV systems that cover a substantial portion of a home's electricity demand, leading to an annual reduction in greenhouse gas emissions per home.

The integration of these algorithms with charge controllers offers countless benefits that can revolutionize energy optimization strategies. For example, the hybrid control technique NFGA, which fuses ANFIS and GA, has been shown to effectively track real reference curves within a PV system, demonstrating its efficiency and accuracy in operation. Parameters within the Gaussian membership function of ANFIS can also be optimized, leading to improved performance and error reduction compared to non-optimized techniques. Furthermore, the introduction of a new control strategy based on neural network techniques is promising in the synthesis of control laws for electronic power converters, indicating the innovative potential of bio-inspired algorithms in this field. The bio-inspired hybrid algorithm not only offers enhanced optimization capabilities for the charge controller but also optimizes the duty cycle, a critical outcome of a PV grid, further underlining the advantages of integrating these algorithms into such systems.(28)

Bio-inspired algorithms for energy optimization

Bio-inspired algorithms, such as the grasshopper optimization algorithm (AOS)(29,30) and the bacterial foraging algorithm (BFO),(31) mimic natural processes to optimize energy generation by mimicking behaviors observed in natural phenomena, in the first case, mimicking a swarm of grasshoppers, while in the second case, BFO is inspired by the social behavior of Escherichia coli (E. coli) when foraging.(32)

Differential evolution,(33,34) invasive weed optimization, Cuckoo search algorithm,(36,37) Firefly algorithm (FA),(38,39) and Krill herd algorithm.(40,41) These algorithms are designed to achieve optimal demand allocation in a power system while respecting constraints that the system may have. Significant advances using these types of algorithms; specifically, small population-based particle swarm optimization (SPPSO) and bacterial foraging algorithm have been instrumental in identifying multiple optimal configurations of photovoltaic power systems (PSS), demonstrating their effectiveness in improving system performance and efficiency.[42] Also, algorithms such as Cuckoo search algorithm (CSA), Firefly algorithm (FA), and Krill herd algorithm (KHA) have been instrumental in addressing key optimization challenges in power system operations, particularly in optimal energy allocation to improve system efficiency and performance.[43] Likewise, incorporating bio-inspired algorithms such as Bayesian Optimization (BO)[44] for univariate forecasting of wind power time series has proven beneficial in optimizing hyperparameters and improving wind power forecasts by leveraging lagged data and input variables.[45] These bio-inspired optimization techniques offer a promising avenue to address the challenges associated with optimizing power generation in PV systems, paving the way for increased efficiency and better power delivery to connected loads.

Integration of Bio-inspired Algorithms into Charge Controllers

In another related area, bio-inspired computational intelligence techniques have proven to be crucial for improving the charging efficiency of plug-in electric vehicles (PEV). Significant research has already been conducted on the use of bio-inspired techniques for PEV charging optimization, demonstrating the potential of these methods.[50] The future of PEV charging optimization lies in innovative techniques such as Cuckoo Search (CSA), Artificial Fish Swarm Algorithm (AFSA),[51] Artificial Bee Colony (ABC),[52] Chaotic Slime Mold Algorithm (CSMA),[53] which are discussed as potential optimization strategies in the field. Photovoltaic systems can not only improve the efficiency of power generation, but can also lead to a reduction of CO2 emissions and contribute to promoting sustainable transport. This integration of advanced nature-derived optimization techniques into charge controllers represents a progressive step towards achieving optimal power generation and utilization in photovoltaic systems.

Recent advances in bio-inspired computing have opened avenues for controller optimization in the realm of power systems, offering a wide range of approaches to improve power generation efficiency through intelligent algorithms and system integration.[54] Researchers have successfully demonstrated the efficacy of integrating bio-inspired controllers into simulated systems, showcasing the simplicity and robustness of such approaches in optimizing the performance of these systems.[55] This integration not only presents an opportunity to refine power optimization in photovoltaic systems, but also offers a path to address challenges related to system reliability in renewable energy frameworks.[56]

Evaluating the performance of photovoltaic systems with bio-inspired algorithms

One of these methods, the P&O (Perturb and Observe) metaheuristic MPPT has the advantage of working close to the MPP despite a slight oscillation, but also performs under static conditions (STC) better than under variable conditions, demonstrating its robustness in evaluating system efficiency; the Incremental Conductance (IC) algorithm is accurate and fast in tracking the MPP compared to P&O and successfully reduces oscillation under various changing conditions, so it can be concluded that the IC algorithm performs better than the P&O algorithm and traditional techniques;[57,58] likewise, the Firefly algorithm, known for its efficiency and speed, demonstrated faster tracking of the maximum power point compared to traditional methods such as the (P&O) algorithm. The efficient MPPT-FA method[59] showed superior traceability, improving the measurement of the performance of a photovoltaic system.[60] An essential aspect when evaluating the performance of this type of installations is to maximize energy extraction and identify the parameters of the photovoltaic cells accurately and reliably.[61] With the GBAS algorithm,[62] the optimization efficiency is increased to determine unknown parameters of different photovoltaic models, outperforming other metaheuristic algorithms in terms of accuracy and stability. These algorithms aim to guide the photovoltaic system to operate closer to the point of maximum global power, reducing the steady-state error and improving the overall performance.[63,64,65]

In the quest to optimize power generation in photovoltaic systems, they have emerged as promising tools. These algorithms are evaluated based on several metrics to determine their effectiveness in improving power generation. One such metric is the maximum relative error, where the Differential Evolution (DE) algorithm using the 1D5P model[66] exhibited a minimum error of 0,4 % under conditions close to the reference, demonstrating its accuracy in optimization tasks. In contrast, the Genetic Algorithm (GA) with the 2D7P model[67] demonstrated a maximum relative error of 9,59 % under conditions far from the reference, highlighting its limitations in power generation optimization. When comparing the performance of different algorithms, the Particle Swarm Optimization (PSO) algorithm outperformed the GA algorithm, especially in scenarios with significant temperature and irradiance variations. Furthermore, the efficiency of these algorithms was evaluated by comparing the results with data from a Canadian module manufacturer under various irradiation and temperature conditions, ensuring their applicability in real-world environments. By using metrics such as relative errors and parameters extracted from models under various conditions, researchers have been able to evaluate the performance of bio-inspired algorithms and refine their optimization strategies to improve power generation in photovoltaic systems.[68,69]

Considering the above, bio-inspired algorithms have shown great promise and potential for improved performance. In particular, the PSO 1D5P and DE 1D5P schemes have emerged as pioneers, showing favorable results in parameter extraction and module simulation with exceptional accuracy. These algorithms have not only proven to be robust and accurate, but have also demonstrated efficiency by requiring minimal processing time and without additional external data besides the technical information provided in the PV module datasheet. This distinguished ability to leverage bio-inspired algorithms without the need for supplementary external inputs distinguishes this approach, underlining its autonomy and self-sufficiency in optimizing photovoltaic systems. By leveraging the inherent strengths of natural processes, these bio-inspired algorithms have the potential to revolutionize energy optimization in photovoltaic systems, offering innovative solutions to address challenges related to system reliability and size optimization in renewable energy applications.[69,70,71]

Future prospects and challenges

These investigations hold great promise for future advancements in renewable energy technology. Inspired by biological processes, such as the behavior of one or some of the algorithms named above; as well as the possibility of making hybrid systems, these algorithms can optimize the efficiency and performance of photovoltaic systems. One of the key areas where bio-inspired algorithms can have a significant impact is in optimizing the orientation and tracking of solar panels to maximize sunlight absorption. These algorithms can enable PV systems to adapt and respond to changing environmental conditions, ensuring optimal power generation around the clock. Furthermore, bio-inspired algorithms have the potential to improve the fault detection and self-repair capabilities of PV systems, enhancing their overall reliability and longevity. By mimicking the resilience and adaptability found in nature, these algorithms can help overcome technical challenges and pave the way for more efficient and sustainable solar energy solutions. As research in this field progresses, the future integration of bio-inspired algorithms into PV systems is poised to revolutionize the renewable energy sector and accelerate the transition to a greener and more sustainable energy landscape.

CONCLUSIONS

These algorithms can optimize charging efficiency in real time thanks to their ability to dynamically adapt to environmental fluctuations such as changes in solar radiation and temperature.

Unlike traditional methods, which rely on predefined environments, bio-inspired algorithms can search for global solutions, resulting in better management and conversion of solar energy and higher usage efficiency.

Another important advantage is the robustness and flexibility of bio-inspired algorithms.

The distributed nature and ability to explore multiple solutions make the charge controller more resilient by making it more resistant to failures and unforeseen situations, thus increasing the reliability of the charge controller.

These algorithms are highly scalable and can adapt to different sizes of PV systems, from small to large-scale PV systems, and maintain high efficiency in each case.

Their ability to continuously learn based on historical data and current conditions provides better performance than traditional methods that rely on static parameters and manual adjustments.

The future integration of adaptive photovoltaic materials, inspired by biological mechanisms, could improve energy conversion by changing their properties in response to environmental stimuli.

These advances, combined with artificial intelligence, will lead to photovoltaic systems that not only adapt automatically, but also learn and improve their performance over time. The creation of smart microgrids and autonomous sensor networks equipped with bio-inspired algorithms will enable more efficient control and management, ensuring the stability and efficiency of photovoltaic installations in complex and dynamic energy environments.

REFERENCES

1. Lefore N, Closas A, Schmitter P. Solar for all: A framework to deliver inclusive and environmentally sustainable solar irrigation for smallholder agriculture. Energy Policy. 2021;154.

2. Halassa E, Mazouz L, Seghiour A, Chouder A, Silvestre S. Revolutionizing Photovoltaic Systems: An Innovative Approach to Maximum Power Point Tracking Using Enhanced Dandelion Optimizer in Partial Shading Conditions. Energies (Basel). 2023;16(9).

3. Dhal KG, Das A, Ray S, Gálvez J, Das S. Nature-Inspired Optimization Algorithms and Their Application in Multi-Thresholding Image Segmentation. Arch Comput Methods Eng. 2020;27(3).

4. Lasso Cardona LA, Rincón Reyes E, Estrada Holguín GD. Introducción a la evaluación de capacidades: una revisión teórica. Rev Colomb Tecnol Avanz. 2023;2(36).

5. Shehab M, Abu-Hashem MA, Shambour MKY, Alsalibi AI, Alomari OA, Gupta JND, et al. A Comprehensive Review of Bat Inspired Algorithm: Variants, Applications, and Hybridization. Arch Comput Methods Eng. 2023;30.

6. Hijjawi U, Lakshminarayana S, Xu T, Piero Malfense Fierro G, Rahman M. A review of automated solar photovoltaic defect detection systems: Approaches, challenges, and future orientations. Sol Energy. 2023;266.

7. Mellit A, Kalogirou SA. MPPT-based artificial intelligence techniques for photovoltaic systems and its implementation into field programmable gate array chips: Review of current status and future perspectives. Energy. 2014;70.

8. Li X, Wang X, Ma Y, Deng W, Wu Y, Li J, et al. Recent progress in functional two-dimensional photovoltaic photodetectors and related emerging applications. J Mater Chem A. 2023;11.

9. Giri NC, Mohanty RC. Agrivoltaic system: Experimental analysis for enhancing land productivity and revenue of farmers. Energy Sustain Dev. 2022;70.

10. Lambora A, Gupta K, Chopra K. Genetic Algorithm- A Literature Review. En: Proc Int Conf Mach Learn Big Data Cloud Parallel Comput COMITCon. 2019.

11. Pérez García D, García Reina F, Hernández Eduardo D. Reducing electrical energy losses by distribution using a novel measurement and control technology for decision making. Colomb J Adv Technol. 2019;2(34):144-50.

12. Chudinzow D, Nagel S, Güsewell J, Eltrop L. Vertical bifacial photovoltaics – A complementary technology for the European electricity supply? Appl Energy. 2020;264.

13. Ishaque K, Salam Z. A deterministic particle swarm optimization maximum power point tracker for photovoltaic system under partial shading condition. IEEE Trans Ind Electron. 2013;60(8).

14. Srinivas P, Swapna P. Maximum Power Point Tracking Algorithm for Advanced Photovoltaic Systems. Int J Recent Innov Trends Comput Commun. 2022;10(9).

15. Katche ML, Makokha AB, Zachary SO, Adaramola MS. A Comprehensive Review of Maximum Power Point Tracking (MPPT) Techniques Used in Solar PV Systems. Energies. 2023;16.

16. Elbarbary ZMS, Alranini MA. Review of maximum power point tracking algorithms of PV system. Front Eng Built Environ. 2021;1(1).

17. Shukir SS. Half-Cut Cell Solar Panels to Reduce the Effect of High Temperature and Shadow on the Productivity of Solar Panels. J Altern Renew Energy Sources. 2022;3(7).

18. Issaadi W, Issaadi S, Khireddine A. Comparative study of photovoltaic system optimization techniques: Contribution to the improvement and development of new approaches. Renew Sustain Energy Rev. 2018;82.

19. Bhallamudi R, Kumarasamy S, Sundarabalan CK. Effect of dust and shadow on performance of solar photovoltaic modules: Experimental analysis. Energy Eng. 2021;118(6).

20. Balbis Morejón M, García Reina F, Cabello Eras JJ, Sousa Santos V. Energy characterization of the operation of an air conditioning equipment in a given location. Rev Colomb Tecnol Avanz. 2019;2(34):71-6.

21. Kahwash F, Barakat B, Maheri A. Coupled thermo-electrical dispatch strategy with AI forecasting for optimal sizing of grid-connected hybrid renewable energy systems. Energy Convers Manag. 2023;293.

22. Hanif MF, Naveed MS, Metwaly M, Si J, Liu X, Mi J. Advancing solar energy forecasting with modified ANN and light GBM learning algorithms. AIMS Energy. 2024;12(2).

23. Mumbere KS, Sasaki Y, Zoka Y, Yorino N, Bedawy A, Krifa C, et al. Day-Ahead Optimal Resilient Energy Management for Grid-Connected Prosumer Microgrids. En: IEEE PES Innov Smart Grid Technol Conf Eur. 2023.

https://doi.org/10.56294/saludcyt20251615 ISSN: 2796-9711

24. Chao KH, Rizal MN. A hybrid MPPT controller based on the genetic algorithm and ant colony optimization for photovoltaic systems under partially shaded conditions. Energies (Basel). 2021;14(10).

25. Pan M, Li C, Gao R, Huang Y, You H, Gu T, et al. Photovoltaic power forecasting based on a support vector machine with improved ant colony optimization. J Clean Prod. 2020;277.

26. Medina-Barahona CJ, Mora GA, Calvache-Pabón C, Salazar-Castro JA, Mora-Paz HA, Mayorca-Torres D. Creation-oriented IoT architecture proposal of prototypes for application on platforms educational and research. Colomb J Adv Technol. 2022;1(39):118–25.

27. Vukadinović A, Radosavljević J, Đorđević A, Protić M, Petrović N. Multi-objective optimization of energy performance for a detached residential building with a sunspace using the NSGA-II genetic algorithm. Sol Energy. 2021;224.

28. Dabra V, Paliwal KK, Sharma P, Kumar N. Optimization of photovoltaic power system: a comparative study. Prot Control Mod Power Syst. 2017;2(1).

29. Yan Z, Li Y, Eslami M. Maximizing micro-grid energy output with modified chaos grasshopper algorithms. Heliyon. 2024;10(1).

30. Veza I, Karaoglan AD, Ileri E, Kaulani SA, Tamaldin N, Latiff ZA, et al. Grasshopper optimization algorithm for diesel engine fuelled with ethanol-biodiesel-diesel blends. Case Stud Therm Eng. 2022;31.

31. Zhang Y, Lv Y. Research on electrical load distribution using an improved bacterial foraging algorithm. Front Energy Res. 2023;11.

32. Carrillo Gómez JK, Duran Acevedo CM, Garcia Rico RO. Bacterial discrimination of drinking water through of an electronic nose and a volatiles extraction equipment. Rev Colomb Tecnol Avanz. 2019;1(33).

33. Fang HW, Feng YZ, Li GP. Optimization of wave energy converter arrays by an improved differential evolution algorithm. Energies (Basel). 2018;11(12).

34. Gumede SB, Saha AK. Optimizing recloser settings in an active distribution system using the differential evolution algorithm. Energies (Basel). 2022;15(22).

35. Rahmani Y, Shahvari Y, Kia F. Application of invasive weed optimization algorithm for optimizing the reloading pattern of a VVER-1000 reactor (in transient cycles). Nucl Eng Des. 2021;376.

36. Abdulaziz S, Attlam G, Zaki G, Nabil E. Cuckoo search algorithm and particle swarm optimization based maximum power point tracking techniques. Indones J Electr Eng Comput Sci. 2022;26(2).

37. Huang X, Xie Z, Huang X. Fault location of distribution network base on improved cuckoo search algorithm. IEEE Access. 2020;8.

38. Anshory I, Jamaaluddin J, Wisaksono A, Sulistiyowati I, Hindarto, Rintyarna BS, et al. Optimization DC-DC boost converter of BLDC motor drive by solar panel using PID and firefly algorithm. Results Eng. 2024;21.

39. Khizer M, Liaquat S, Zia MF, Kanukollu S, Al-Durra A, Muyeen SM. Selective harmonic elimination in a multilevel inverter using multi-criteria search enhanced firefly algorithm. IEEE Access. 2023;11.

40. Abdollahi A, Ghadimi AA, Miveh MR, Mohammadi F, Jurado F. Optimal power flow incorporating FACTS devices and stochastic wind power generation using krill herd algorithm. Electronics (Switzerland). 2020;9(6).

41. Niu P, Chen K, Ma Y, Li X, Liu A, Li G. Model turbine heat rate by fast learning network with tuning based on ameliorated krill herd algorithm. Knowl Based Syst. 2017;118.

42. Das TK, Venayagamoorthy GK, Aliyu UO. Bio-inspired algorithms for the design of multiple optimal power system stabilizers: SPPSO and BFA. IEEE Trans Ind Appl. 2008;44(5).

43. Sudhakar AVV, Karri C. Bio Inspired Algorithms in Power System Operation: A Review. En: Proc Int Conf Recent Trends Electr Electron Comput Technol ICRTEECT. 2017.

44. Sultana N, Hossain SMZ, Almuhaini S, Düştegör D. Bayesian optimization algorithm-based statistical and machine learning approaches for forecasting short-term electricity demand. Energies (Basel). 2022;15(9).

45. Karim FK, Khafaga DS, Eid MM, Towfek SK, Alkahtani HK. A novel bio-inspired optimization algorithm design for wind power engineering applications time-series forecasting. Biomimetics. 2023;8(3).

46. Hilali A, Mardoude Y, Essahlaoui A, Rahali A, Ouanjli N El. Migration to solar water pump system: Environmental and economic benefits and their optimization using genetic algorithm based MPPT. Energy Rep. 2022;8.

47. Guenounou O, Belkaid A, Colak I, Dahhou B, Chabour F. Optimization of fuzzy logic controller based maximum power point tracking using hierarchical genetic algorithms. En: 9th Int Conf Smart Grid icSmartGrid. 2021.

48. Ghavifekr AA. Application of heuristic techniques and evolutionary algorithms in microgrids optimization problems. En: Power Systems. 2021.

49. Yadav K, Kumar B, Guerrero JM, Lashab A. A hybrid genetic algorithm and grey wolf optimizer technique for faster global peak detection in PV system under partial shading. Sustain Comput Inform Syst. 2022;35.

50. Rahman I, Mohamad-Saleh J. Plug-in electric vehicle charging optimization using bio-inspired computational intelligence methods. En: Stud Syst Decis Control. 2018.

51. Rahman I, Mohamad-Saleh J. Plug-in electric vehicle charging optimization using bio-inspired computational intelligence methods. En: Amini MH, Boroojeni KG, Iyengar SS, Pardalos PM, Blaabjerg F, Madni AM, editores. Sustainable Interdependent Networks: From Theory to Application. Cham: Springer Int Publ; 2018. p. 135-47.

52. Boonraksa T, Boonraksa P, Marungsri B. Optimal capacitor location and sizing for reducing the power loss on the power distribution systems due to the dynamic load of the electric buses charging system using the artificial bee colony algorithm. J Electr Eng Technol. 2021;16(4).

53. Dhawale D, Kamboj VK, Anand P. An optimal solution to unit commitment problem of realistic integrated power system involving wind and electric vehicles using chaotic slime mould optimizer. J Electr Syst Inf Technol. 2023;10(1).

54. Roni MHK, Rana MS, Pota HR, Hasan MM, Hussain MS. Recent trends in bio-inspired meta-heuristic optimization techniques in control applications for electrical systems: a review. Int J Dyn Control. 2022;10.

55. Ni J, Wu L, Fan X, Yang SX. Bioinspired intelligent algorithm and its applications for mobile robot control: A survey. Comput Intell Neurosci. 2016;2016.

56. Medina MSG, Aguilar J, Rodriguez-Moreno MD. A bioinspired emergent control for smart grids. IEEE Access. 2023;11.

57. Ahmad M, Numan A, Mahmood D. A comparative study of perturb and observe (P&O) and incremental conductance (INC) PV MPPT techniques at different radiation and temperature conditions. Eng Technol J. 2022;40(2).

58. Saber H, Bendaouad AE, Rahmani L, Radjeai H. A comparative study of the FLC, INC and P&O methods of the MPPT algorithm for a PV system. En: 2022 19th IEEE Int Multi-Conf Syst Signals Devices SSD. 2022.

59. MPPT algorithms (PSO, FA, and MFA) for PV system under partial shading condition, case study: BTS in Algazalia, Baghdad. Int J Smart Grid. 2020.

60. Watanabe RB, Ando Junior OH, Leandro PGM, Salvadori F, Beck MF, Pereira K, et al. Implementation of

the bio-inspired metaheuristic firefly algorithm (FA) applied to maximum power point tracking of photovoltaic systems. Energies (Basel). 2022;15(15).

61. Sun L, Wang J, Tang L. A powerful bio-inspired optimization algorithm based PV cells diode models parameter estimation. Front Energy Res. 2021;9.

62. Sun L, Wang J, Tang L. A powerful bio-inspired optimization algorithm based PV cells diode models parameter estimation. Front Energy Res. 2021;9.

63. Haddou A, Tariba NE, Ikken N, Bouknadel A, Omari HEL, Omari HEL. Comparative study of new MPPT control approaches for a photovoltaic system. Int J Power Electron Drive Syst. 2020;11(1).

64. UU Republik Indonesia, Munawir M, Nasional BS, Susanta G, Jatimnet.com, MajaMojokerto.net, et al. Penentuan alternatif lokasi tempat pembuangan akhir (TPA) sampah di Kabupaten Sidoarjo. Energies (Basel). 2022;15(1).

65. Chellakhi A, El Beid S, Abouelmahjoub Y. An improved adaptable step-size P&O MPPT approach for standalone photovoltaic systems with battery station. Simul Model Pract Theory. 2022;121.

66. Shafi MA, Khan M, Bibi S, Shafi MY, Rabbani N, Ullah H, et al. Effect of parasitic parameters and environmental conditions on I-V and P-V characteristics of 1D5P model solar PV cell using LTSpice-IV. East Eur J Phys. 2022;2022(2).

67. Castro Mejía PJ, Barranzuela Crisant JP, Cisneros Távara MA, Gómez Castillo FF, Manayalle Mera DN, Quintanilla Paico LA, et al. Renewable Energy and the Utilization of Agricultural Waste in Chiclayo. Environmental Research and Ecotoxicity. 2023; 2:53. https://doi.org/10.56294/ere202353

68. Provensi LL, de Souza RM, Grala GH, Bergamasco R, Krummenauer R, Andrade CMG. Modeling and simulation of photovoltaic modules using bio-inspired algorithms. Inventions. 2023;8(5).

69. Ma Y, Yang H, Zhang D, Ni Q. Operation flexibility evaluation and its application to optimal planning of bundled wind-thermal-storage generation system. Electronics (Switzerland). 2019;8(1).

70. Grala GH, Provensi LL, Krummenauer R, da Motta Lima OC, de Alcantara GP, Andrade CMG. Investigation of the use of evolutionary algorithms for modeling and simulation of bifacial photovoltaic modules. Inventions. 2023;8(6).

71. System P, Adaptive U, Dawan P, Sriprapha K, Kittisontirak S, Boonraksa T. Comparison of power output forecasting on the inference systems and particle swarm. Energies. 2020.

72. Dawan P, Sriprapha K, Kittisontirak S, Boonraksa T, Junhuathon N, Titiroongruang W, et al. Comparison of power output forecasting on the photovoltaic system using adaptive neuro-fuzzy inference systems and particle swarm optimization-artificial neural network model. Energies (Basel). 2020;13(2).

FINANCING
None.

CONFLICT OF INTEREST
None.

AUTHORSHIP CONTRIBUTION
Conceptualization: Luis E. Neira Ropero, Aldo Pardo García, Francisco Lopez Monsalve, Jorge Luis Rodriguez.
Data curation: Luis Neira, Aldo Pardo, Francisco Lopez, Jorge Luis Diaz Rodriguez.
Formal analysis: Luis Neira, Aldo Pardo, Francisco Lopez, Jorge Luis Diaz Rodriguez.
Research: Luis Neira, Aldo Pardo, Francisco Lopez, Jorge Luis Diaz Rodriguez.
Methodology: Luis Neira, Aldo Pardo, Francisco Lopez, Jorge Luis Diaz Rodriguez.
Project management: Luis Neira, Aldo Pardo, Francisco Lopez, Jorge Luis Diaz Rodriguez.
Resources: Luis Neira, Aldo Pardo, Francisco Lopez, Jorge Luis Diaz Rodriguez.
Software: Luis Neira, Aldo Pardo, Francisco Lopez, Jorge Luis Diaz Rodriguez.

Supervision: Luis Neira, Aldo Pardo, Francisco Lopez, Jorge Luis Diaz Rodriguez.
Validation: Luis Neira, Aldo Pardo, Francisco Lopez, Jorge Luis Diaz Rodriguez.
Display: Luis Neira, Aldo Pardo, Francisco Lopez, Jorge Luis Diaz Rodriguez.
Drafting - original draft: Luis Neira, Aldo Pardo, Francisco Lopez, Jorge Luis Diaz Rodriguez.
Writing - proofreading and editing: Luis Neira, Aldo Pardo, Francisco Lopez, Jorge Luis Diaz Rodriguez.