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Enhancing Power Generation for Solar-Based Cardiac Pacemakers: A Novel Approach with FOPID and HCMKH-BS2

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Abstract—Biomedical implants, such as implantable cardioverter heart monitors, rely on limited battery life, which necessitates costly replacements and patient discomfort. To address these challenges, a novel solar-based pacemaker model is proposed that is integrated with a fractional-order proportional integral derivative (FOPID) controller and a Hybridized Chaotic multiverse Krill Herd-based Backtracking Search Strategy (HCMKH-BS^2) to enhance power generation for pacemaker operation. Our approach considers the impact of partial shading conditions on solar power. To mitigate these conditions, a FOPID controller with an HCMKH-BS^2 model is developed which also addresses environmental issues through the adoption of a DC-DC converter. The gain parameters of the FOPID controller are determined using the proposed HCMKH-BS^2 algorithm. The proposed technique is implemented to evaluate its performance using various measures in terms of duty cycle, convergence analysis, and power. The performance validation is performed based on the analyses of constant irradiance and changed irradiance. The proposed method achieved a fitness value of 0.01 from the convergence analysis and the duty cycle of 0.48D. These results demonstrate the superiority of our proposed technique over previous methods, highlighting its potential for enhancing the performance of solar-based cardiac pacemakers.

Keywords: cardiac pacemaker, solar, fractional-order proportional integral derivative and DC-DC converter, Krill Herd, backtracking search
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1. INTRODUCTION

Compatible medical devices play a crucial role in modern healthcare innovations, providing support and treatment for patients affected by various real diseases such as disability, diabetes, fibrillation, and bradycardia. The use and application of these clinical devices are integral to medical prescriptions and the delivery of quality medical care [1]. Uninterrupted power supply is essential for the proper functioning of compatible medical devices, including embedded microelectronic clinical gadgets. These devices, such as embedded biosensors based on cardiovascular monitoring, rely on energy sources that can sustain their

NOMENCLATURE

A-PENG	all-in-one piezoelectric nano generator	MaximumIteration	maximum iteration
A^{be}	coefficient	MEMS	micro-electro-mechanical systems
Best_C	best gain parameter	MPPT	maximum power point tracking controller
C	temperature coefficient	N	ideal factor of PV
CIEDs	cardiovascular implantable electronic devices	P	proportional controller
$C_j(T)$	previous speed of Krill	P	target individual population
$C_j(T+1)$	Krill movement	P_{old}	previous generation
COA	chimp optimization algorithm	PER	permuting function
D	derivative controller	PNG	polymer-based nanogenerator
D	population size	PPV-PCBM	active layer-based bulk heterojunction organic solar cell
$E(t)$	error values		
ER_f	speed of Krill's foraging strategy	PSO	particle swarm optimization
$ES_j(T+1)$	Krill's foraging strategy	PV	photovoltaic cell
F_k	constant coefficient	PVDF-TrFE	polyvinylidene fluoride-trifluoroethylene
FOPID	fractional-order proportional integral derivative	$(P_{\text{old}} - P)$	mutation search direction matrix
G	amplitude	q	electron charge
$G(S)$	transfer function's FOPID controller	R	random variable
GWO	Grey Wolf optimization	rnd	random number
HCMKH-BS^2	hybridized chaotic multiverse Krill Herd-based backtracking search strategy	R_S	series resistance
		R_{Sh}	shunt resistance
I	current of PV panel	r_v	module parallel resistance
I	integral controller	T	cell temperature
I_{ph}	electric current of PV	UC_k	upper boundaries
IMPPT	improved maximum power point tracking controller	$U(t)$	control signal
		V	diode thermal voltage
$\text{Iteration}_{\text{Max}}$	iteration at which the optimal gain parameter selection	V_{OC}	open-circuit voltage
		α	coefficient of temperature short circuit current
J	uniform distribution	α_j and C_j^{be}	food attractions
K	Boltzmann's constant	β_j^{target}	targeted node's effectiveness
k	number of parameters	χ_f	weight of inertia of Krill's foraging strategy
LC_k	lower boundaries	κ_m	random value
m	iteration	κ_m	inertial weights with respect to the base station
M	problem dimensions	μW	micro-watt
Max_C	maximum node packet sending speed	:	update operator

operations [2]. Traditional battery replacements for compatible cardiac pacemakers can be costly and cause discomfort for patients, emphasizing the need for alternative power solutions [3].

Solar energy presents an attractive option for providing sustainable power to medical implants. The utilization of solar-based energy storage can benefit embedded micro-electronic clinical devices, particularly cardiac biosensors [4]. The ability to harness solar energy within the human body opens up possibilities for regulating specific locations and monitoring cardiovascular conditions [5]. Given the persistent prevalence and impact of heart disease worldwide, embedded heart pacemakers have become essential tools for monitoring and maintaining the cardiac health of patients [6]. Despite advancements in battery technology for embedded cardiac pacemakers, the average patient still requires battery replacement every eight to ten years. This necessitates the development of alternative power solutions to ensure uninterrupted operation [7]. The integration of solar power into pacemaker systems offers a promising approach for extending battery life and reducing the need for frequent replacements [8].

Numerous types of research were analyzed to enhance the power supply for solar pacemakers and some of the algorithms were mostly used for designing effective models. The Butterfly Optimization Algorithm-based Proportional Integral Derivative (BOA-PID) model was utilized to track the linear and nonlinear trajectories of the devices. To enhance the performance of trajectory tracking, the robot-manipulator controller is selected but it requires a different controller for simultaneous enhancement [9]. The Bat-Inspired Algorithm-based Model Predictive Control (BIA-MPC) model was illustrated for longitudinal control by overcoming the issues of parameter uncertainties, gust disturbances, and environment variations. The stability of the system was considered as a major problem under disturbance and perturbation of the system [10].

The robust Kalman filter (KF) was established for the position estimation by tracking constant velocity [11]. To reduce the high computational burden, the Hybrid Discrete Time Laguerre function-based MPC (Hybrid DTLF-MPC) was designed that provide effectiveness while analyzing different scenarios [12]. The inconsistency problem arose due to the huge number of evaluations.

To address the challenges associated with power supply for solar pacemakers, this article proposes a novel Hybridized Chaotic Multiverse Krill Herd-based Backtracking Search Strategy (HCMKH-BS^2) and Fractional-Order PID (FOPID)-based solar pacemaker. The combination of these techniques aims to optimize power generation, improve battery life, and enhance the overall performance of the pacemaker system [13]. This study focuses on developing a biocompatible pacemaker design while considering factors such as partial shading conditions and the utilization of DC converters to regulate and balance voltage generated by the photovoltaic array [14]. Through the integration of advanced control strategies and optimization algorithms, the proposed approach aims to overcome limitations and improve the functionality of solar-based cardiac pacemakers.

The primary contributions are,

- ***HCMKH-BS^2:*** The article introduces a novel optimization algorithm, HCMKH-BS2, which combines the principles of the HCMKH and BS^2. This hybridized approach enhances the efficiency and effectiveness of the optimization process for power generation in the solar pacemaker system.
- ***FOPID Controller***: The article incorporates the FOPID controller into the solar pacemaker system. The FOPID controller is a fractional-order control strategy that provides improved performance and robustness compared to traditional PID controllers. By utilizing FOPID control, the article aims to enhance the power management and regulation capabilities of the solar pacemaker.
- ***Handling Partial Shading Conditions***: The proposed approach addresses the challenges posed by partial shading conditions on solar power generation. This article mitigates impacts on the partial shading and optimizes power output under varying environmental conditions. This ensures the reliable and continuous operation of the solar pacemaker system.
- ***Performance Evaluation and Comparison***: The article evaluates the performance of the proposed HCMKH-BS2- and FOPID-based solar pacemaker system. Performance measures, such as duty cycle, convergence analysis, and power output, are utilized to assess the effectiveness of the system.
- ***Advancement in Biocompatible Pacemaker Design***: The proposed solar pacemaker system, incorporating HCMKH-BS2 and FOPID control, contributes to the advancement of biocompatible pacemaker design. By utilizing solar energy and optimizing power generation, the system aims to extend battery life, reduce the need for frequent battery replacements, and enhance the overall performance and functionality of cardiac pacemakers.

Overall, the article presents a comprehensive approach that combines optimization algorithms, control strategies, and power management techniques to address the challenges associated with solar-based cardiac pacemakers. The proposed contributions contribute to improving the sustainability, efficiency, and reliability of these medical devices.

The article organization of this research is as follows: Section 2 presents a literature survey for previous cardiac pacemaker technologies, highlighting their merits and demerits. Section 3 offers a detailed explanation and implementation of the proposed technique. The experimental result of this current work by using different graphical representations is presented in Section 4. At last, Section 5 concludes the article with future directions.

2. RELATED WORKS

In this section, the focus is on reviewing various designs and control techniques for implantable cardiac pacemakers. Several studies conducted by different researchers are summarized to provide an overview of the advancements in this field.

Haeberlin *et al.* [15] introduced a novel approach by developing a battery-free pacemaker that utilizes a solar panel to directly convert transdermal light into electricity. Traditional pacemakers rely on battery packs, which have limited storage power and require frequent and uncomfortable replacements. The researchers demonstrated the feasibility of using solar energy harvested from within the skin to power pacemakers. They conducted experiments by implanting solar-powered pacemakers in pigs and successfully operated them in total darkness for an extended period, simulating challenging conditions.

Expanding on the concept of solar-powered pacemakers, Haeberlin *et al.* [16] explored the idea of pacing without the need for batteries. They investigated the potential of transdermal solar energy to provide sufficient power for pacemakers. The study involved calculating the harvestable power from a subcutaneously implanted solar panel and assessing its performance under different lighting conditions. The researchers determined that a 1 cm2 solar panel could potentially collect 2500 W of energy from sunlight and evaluated its efficacy in powering the pacemaker system.

Tholl *et al.* [17] introduced a subdermal solar energy harvesting model to reduce the frequency of battery replacements in devices like pacemakers. The subcutaneous solar panel's output power depends on various factors such as implant placement, skin characteristics, and photovoltaic traits. The researchers used Monte Carlo simulations to estimate the maximum power generated by dermal photovoltaic modules during midday direct sunlight in geographical mid-latitudes. This analysis considered the implantation details and dimensions of the solar array to determine the potential power generation.

Wangatia *et al.* [18] focused on the use of solar cells to power biomedical electronics. They highlighted the critical role of medical electrical equipment in healthcare and the challenges associated with powering such devices. The review highlighted recent studies that have explored the integration of solar panels to power and charge biomedical devices. The advancements in photovoltaic technology have made solar panels a promising solution for meeting the power requirements of these devices.

Dong *et al.* [19] discussed various techniques such as triboelectric designs, piezoelectric-based sensing, and cardiac energy harvesting. They emphasized the importance of developing self-sufficient energy production systems to enhance the lifespan and efficiency of cardiovascular medical implants and other surgically implanted biomedical devices. The researchers highlighted the potential of utilizing the heart's natural energy as an organic charger for powering these devices.

Mahmud *et al.* [20] conducted a study on the application of Micro-Electro-Mechanical Systems (MEMS) and microfluidics technology in the design of energy harvesting devices. The objective of their research was to develop a consistent, portable, and stable power supply for self-powering devices. In their work, they focused on using electromagnetic energy harvesters to charge self-powered pacemakers by harnessing the movement of the heart.

Foster *et al.* [21] demonstrated a circadian photoentrainment study and analyzed the responses of the cardiac system in both mice and humans. The unique aspect of this research was its focus on the human circadian system's sensitivity compared to other studies that used bright white artificial light. However, in this particular article, the stimulus duration was not varied consistently.

Tholl *et al.* [17] presented a study on subdermal solar energy harvesting for the purpose of implanting self-powered cardiac pacemakers. The subdermal solar module's output was predicted in terms of factors such as solar cell properties, optical properties, and implantation depth. However, the lifetime of the subdermal solar harvester was found to be very low.

Zhang *et al.* [22] developed a self-powered pacemaker utilizing an All-in-one Piezoelectric Nano Generator (A-PENG) for biomechanical energy harvesting. This innovative approach involved extracting energy from the conduction system pacing, which takes advantage of the valid myocardium and cardiac pulsation. The experimental results demonstrated enhanced output performance. However, it should be noted that this approach required lengthy procedures and carried a high risk associated with repeated surgeries.

In a different study, Co *et al.* [23] proposed a modern pacemaker design to address limitations such as finite battery life, blood stream infections leading to cardiac structure damage, pacemaker malfunction, and implantation issues associated with traditional pacemakers. Their solution involved the development of a bio-pacemaker, which aimed to overcome these challenges. However, in this particular article, the suitability of multichamber pacing in avoiding the need for transvenous leads was not addressed.

Zeng *et al.* [24] conducted research on the development of self-powered cardiovascular implantable electronic devices, specifically pacemakers, along with wearable active sensors. The main objectives of this study were twofold: harvesting sustainable power sources for cardiac pacemakers and monitoring physiological signals using self-powered devices that offer high performance and low power consumption. The field of cardiovascular diagnosis and treatment necessitated mainstream solutions such as wearable medical sensors and self-powered implantable devices.

The Active Layer-based Bulk Heterojunction Organic Solar Cell (PPV-PCBM) was elaborated by Chamola and Mittal [25] for providing power to advanced pacemakers. The research demonstrated that the battery of the pacemaker could be recharged within 6 min, enabling the pacemaker to operate continuously for 24 h without requiring any external illumination. The power was provided to the pacemaker in irradiance situations by generating the organic solar cell.

Moerke *et al.* [26] conducted research on cardiovascular implantable electronic devices (CIEDs) to address the challenges of limited battery life and device failure. Their focus was on designing biological pacemakers that could enhance heart automaticity by transmitting surrogates. However, improvements were needed in energy harvesting devices to ensure long-term stability, efficient power delivery, and effective energy storage.

Azimi *et al.* [27] presented a study on the development of cardiac energy harvesters using a polyvinylidene fluoride-trifluoroethylene (PVDF-TrFE)-based film. The electricity was generated from the cardiac motions by using biocompatible and flexible piezoelectric polymer-based nanogenerator (PNG) for power battery-free heart pacemakers. However, the research highlighted the need for extended testing periods to validate the feasibility of these devices for actual medical applications.

In a different perspective, Deng *et al.* [28] developed CIEDs from historical viewpoints to enhance power supplies and therapeutic capabilities. The focus of their work was on pacemakers, which provide periodic electrical stimulation to maintain a normal heartbeat in cases of failed intrinsic cardiac conduction integrity. However, this article emphasized the need for investigating biocompatible fiber batteries to ensure long-term reliability of the devices.

Overall, these related works provide insights into different approaches for powering cardiac pacemakers, including solar-based energy harvesting and alternative energy sources such as piezoelectricity and tribo electricity. These studies aim to improve the lifespan, efficiency, and reliability of implantable cardiac pacemakers while reducing the need for frequent battery replacements.

2.1. Motivation and Research Gap

The motivation for the proposed research stems from the limitations and challenges associated with current battery-powered cardiac pacemakers. While traditional pacemakers have been effective in managing heart rhythm abnormalities, they are limited by the finite lifespan of their batteries. Patients often require battery replacements every 8 to 10 years, leading to discomfort, high costs, and potential risks associated with surgical procedures.

To address these issues, the motivation behind the research is to develop a biocompatible pacemaker that can harness solar energy for power generation, thereby reducing or eliminating the need for frequent battery replacements. By incorporating solar-based energy harvesting, the proposed research aims to extend the lifespan of cardiac pacemakers and improve the overall functionality and reliability of these devices.

Furthermore, the research seeks to optimize the power management and regulation capabilities of the solar pacemaker system. Under varying environmental conditions, the effectiveness of the power generation is enhanced by integrating FOPID controller and HCMKH-BS2 algorithm.

The research gap lies in the need for an advanced and sustainable solution for cardiac pacemakers that overcomes the limitations of battery-powered systems. While some studies have explored solar energy harvesting and alternative energy sources for pacemakers, novel optimization algorithms, and control schemes are required to maximize power generation, ensure reliable operation under challenging environmental conditions, and improve overall performance.

The proposed research addresses this research gap by introducing the novel HCMKH-BS^2 algorithm and integrating it with the FOPID controller to optimize power generation in a solar pacemaker system. The research aims to fill the gap by evaluating the performance of the proposed system and comparing it with existing optimization techniques. Additionally, the research contributes a comprehensive analysis under partial shading conditions on power generation and developing strategies to mitigate these effects.

In summary, the motivation behind the research is to develop a sustainable and efficient solution for cardiac pacemakers by harnessing solar energy and optimizing power generation through advanced control strategies. The research gap lies in the need for novel optimization algorithms and comprehensive analysis of partial shading effects, which the proposed research aims to address.

3. SYSTEM MODEL

The system model comprises several components, including the Maximum Power Point Tracking (MPPT) controller, a skin equivalent circuit (SEC) model, a boost converter, and a photovoltaic (PV) cell. The system model aims to offer the required power to the implantable cardiac pacemaker. Figure 1 illustrates the structure of proposed system. The complete embedded setup is positioned close to the focal point function of infrared radiation, which is generated by a laser diode placed on the exterior body of a human. The use of infrared radiation is preferred over traditional PV arrays due to its low penetration power and accessibility limitations. Moreover, when compared to daytime irradiation, near-infrared radiation provides higher

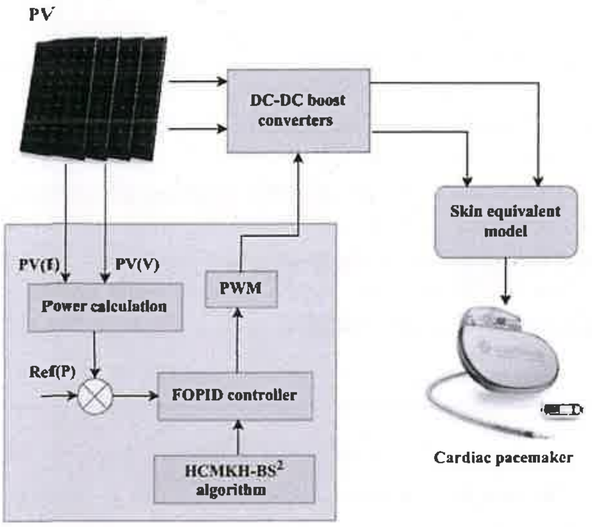


FIGURE 1. Proposed system model.

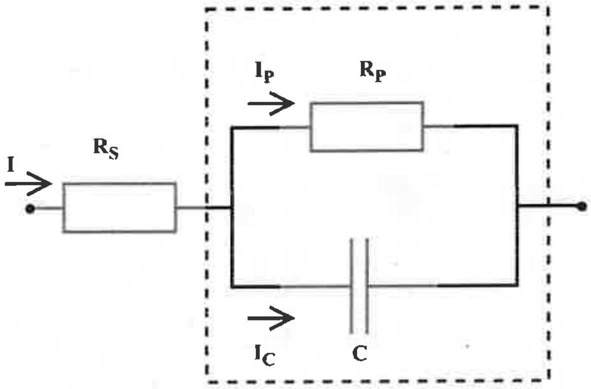


FIGURE 2. Skin equivalent circuit model.

power output to the PV system. Additionally, near-infrared radiation is less harmful to human skin. By concentrating the near-infrared radiation on a small-sized PV array, the proposed system is capable of generating high power. This power is essential for meeting the requirements of a conventional cardiac pacemaker, which typically operates in the micro-Watt (μW) range to manage the rhythmic function of the heart.

The proposed system aims to generate a battery-free pacemaker using a PV system and an MPPT controller based on the SEC model. The maximum power is extracted from the PV system by applying this controller and also regulates the power supply to pacemaker. To ensure the proper functioning of the pacemaker, a FOPID controller is employed. The FOPID controller is designed to monitor and regulate the activity of the pacemaker, ensuring accurate and reliable performance. The key aspect of the proposed system is the tuning of the FOPID controller. To achieve optimal tuning, the HCMKH-BS^2 algorithm is utilized. This algorithm assists in determining the appropriate gain parameters for the FOPID controller, ensuring that the pacemaker operates effectively.

3.1. Skin Equivalent Circuit Model

To accurately analyze the electrical behavior of the skin, a skin equivalent model is employed. This model helps in understanding the impedance characteristics of the skin. To construct the skin equivalent model, an RC circuit is combined with a comparable circuit. The resulting model represents the electrical properties of the skin. Figure 2 illustrates the skin equivalent circuit model. It serves as a comprehensive system that captures the electrical characteristics of the skin. The parameters and outcomes obtained from studying the skin are utilized to construct this circuit model. The equivalent circuit is commonly used to measure changes in impedance and has been designed to accurately represent the response of the skin. The skin equivalent model is a crucial component of the proposed system as it aids in understanding and analyzing the electrical behavior of the skin. It provides valuable insights into how the skin interacts with the photovoltaic system and helps in optimizing the performance of the overall system.

3.2. PV System Modelling

This section presents the PV system modeling. The sunlight energy is converted into electrical energy by the PV cells. During daylight, the PV cells capture the energy from sunlight and generate electricity. By the MPPT controller, the maximum power from the PV cells is extracted by optimizing their operation.

Figure 3 illustrates the PV system's general model based on an equivalent circuit. The equivalent circuit includes components such as equivalent resistance, light current, and a diode with a uniform circuit pattern. These components are designed to facilitate the flow of current as well as voltage within the PV system [29].

The current of a solar panel in terms of output power [30] is expressed as follows:

$$I_C^{PV} = \frac{I_{ph}}{1 - C^{-d}} \left[\exp^{\frac{V_{OC}}{\alpha}} \left(\frac{qV + qr_\nu I}{NKT} \right) - 1 \right] - \frac{V + R_S I}{R_{Sh}} \quad (1)$$

From the above equation, the terms such as V, r_ν, C, K, α, V_{OC}, R_S, R_{Sh}, N, T, $q = (1.6 * 10^{-19} C)$, I and I_{ph} are represented as diode thermal voltage, module parallel

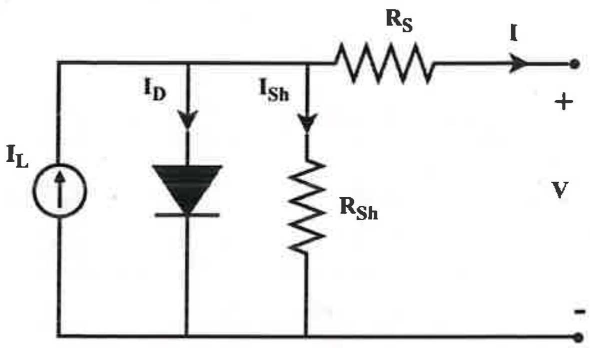


FIGURE 3. Basic structure of PV system with respect to equivalent circuit.

resistance, temperature coefficient, Boltzmann's constant, coefficient of temperature short circuit current, open-circuit voltage, series resistance, shunt resistance, ideal factor of PV, cell temperature, electron charge, current of the PV panel, and electric current of PV, respectively..

The PV system can be equipped with controllers to adjust its operation based on radiation (temperature) changes. Different radiation levels can be considered for each solar panel to optimize power production. The output power of the solar charger varies according to changes in radiation levels. A DC converter is used to maintain the desired control signals under uniform radiation conditions. The MPPT controller, based on its feedback, determines the appropriate duty cycle for the DC converter to achieve the PV system's MPP.

The duty cycle of the DC converter is adjusted based on its feedback by using a programmed MPPT-based. The PID (Proportional-Integral-Derivative) controller is utilized to achieve the maximum power through the MPPT regulator. External environmental conditions can impact energy generation, and hence the IMPPT (Improved MPPT) is developed to handle different weather patterns. The proposed MPPT regulator identifies the fault power and corrects it by providing a higher pulse to the power converter. The FOPID regulator, using the HCMKH-BS^2 algorithm, determines the optimal pulses for the system.

3.3. FOPID Controller

FOPID controller in the proposed approach is utilized to address the limitations of traditional PID controllers and improve the control of PV power in various ranges [31]. The FOPID controller offers advantages in dealing with fragmented demand conditions and allows for better customization of the control boundaries.

The overall PID framework has three control components, including proportional (*P*), integral (*I*), and derivative (*D*) controllers. By incorporating a FOPID regulator at the two control boundaries, the processing of the PID function can be further enhanced. The FOPID regulator extends the capabilities of the primary PID regulator by introducing two additional control limits, providing more freedom to tune the controller for improved power regulation.

The FOPID regulator yield was numerically developed and introduced [32] as follows,

$$U(t) = K_pE(t) + K_iD_t^{-\lambda}E(t) + K_dD_t^{-\mu}E(t) \quad (2)$$

$$E(t) = \Delta P_{tie}(t) + B_i\Delta\omega_i(t) \quad (3)$$

The transfer function of FOPID controller is presented as follows,

$$G(S) = K_p + \frac{K_i}{S^\lambda} + K_dS^\mu \quad (4)$$

In the proposed system, the reference value used for calculating error values ($E(t)$) and the control signal ($U(t)$) is the PV capacity's current value. This reference value serves as a benchmark for the control system to regulate the PV power generation. The FOPID regulator has five ranges that are carefully selected to achieve the best results for enhancing system performance. These ranges determine the control boundaries and help optimize the control strategy for different operating conditions. To enhance the distributed power system load regulation, various PID controller range modification techniques are employed. These techniques enable effective control and management of workload enhancements [33]. The utilization of techniques like HCMKH-BS^2 computation provides a possibility for demarcation and further improvement of the system's performance. The HCMKH-BS^2 algorithm-based rationality with hereditary leaders that manages the calculation abnormalities and overall broad basis measurements. By expanding the capabilities of the algorithm, the system can effectively detect and perceive anomalies, which is particularly useful for the ongoing process of the PV organization. In the presented study, the HCMKH-BS^2 algorithm is specifically employed to manage the MPPT of the PV structure and the projected PV-based MPPT controller. The algorithm assists in accurately determining the PV system's MPP, optimizing power generation, and improving the efficiency of the MPPT controller. Overall, the utilization of the HCMKH-BS^2 algorithm and its integration into the proposed system contribute to the effective management of

PV power and enhance the performance of the MPPT controller.

3.4. Hybridized Chaotic Multiverse Krill Herd-Based Backtracking Search Strategy

The section introduces the HCMKH-BS^2 for selecting the gain constraints of the FOPID controller. It combines two optimization algorithms such as CMKH algorithm and BS^2 algorithm to achieve better parameter tuning.

3.4.1. Chaotic Multiverse Krill Herd Algorithm. The chaotic multiverse Krill Herd (CMKH) is the optimization technique that mimics the behavior of Krill Herd. It utilizes three key factors: Krill motion, foraging characteristics, and random diffusion to model the movement and behavior of the Krill within the optimization process [34].

3.4.1.1. Krill Movement. In the CMKH algorithm, the movement of the Krill Herd is simulated to explore the search space. Each member of the Krill Herd represents a potential solution. On the basis of the maintenance of the herd and nodes present in the developed cluster, the movement is induced. The following equation describes the Krill movement mathematically.

$$C_j(T+1) = \mathrm{Max}_C \beta_j + \kappa_m C_j(T) \tag{5}$$

Inertial weights with respect to the base station κ_m, previous speed is denoted as $C_j(T)$, and the maximum node packet sending speed is represented as Max_C, respectively. The equation below is used to calculate the optimal node-based solution.

$$\beta_j^{target} = A^{be} k_{j,be} F_{j,be} \tag{6}$$

The targeted node's effectiveness β_j^{target} and its coefficient are A^{be}.

$$A^{be} = 2\left[\frac{R+1}{\mathrm{Iteration_{Max}}}\right] \tag{7}$$

A random variable's (R) range is from 0 to 1.

3.4.1.2. Foraging Attributes. The Krill's foraging strategy is described as follows:

$$ES_j(T+1) = ER_f \alpha_j + \chi_f ES_j(T) \tag{8}$$

At the foraging stage, the weight of inertia and speed are related χ_f and ER_f. The two food attractions are $\alpha_j = \alpha_j^{food} + C_j^{be}$ and C_j^{be}.

3.4.1.3. Wormhole Tunnels. There are two periods in the global optimum. In the random diffusion step of the CKH optimization, the relationship between exploitation as well as exploration is determined. The developed technique is called Chaos multiverse Krill Herd Optimization (CMKHO). Wormholes increase inflation and have a high possibility of offering local modifications in each universe, which are described as;

$$F_j^k = \begin{cases} F_k + RS \times ((UC_k - LC_k) \times rnd + LC_k) & rnd < 0.5 \\ F_k - RS \times ((UC_k - LC_k) \times rnd + LC_k) & rnd \geq 0.5 \end{cases} \tag{9}$$

Choose the node features RS according to kth parameter and F_k is the constant coefficient. The random (rnd) number is between UC_k and LC_k as its upper and lower boundaries.

3.4.1.4. Chaotic Model. The proposed method makes use of three different types of chaotic maps, including sinusoidal, cosine, and sine, to enhance the chaotic Krill optimization. The quick convergence-based global optimum is created during the exploitation stage. The following equation estimates the random values and chaotic maps:

$$H^{be} = 2\left(H(T) + \frac{1}{\mathrm{Iteration_{Max}}}\right) \tag{10}$$

Here, Best_C represents the best gain parameter, and $\mathrm{Iteration_{Max}}$ indicates the iteration at which the optimal gain parameter selection of the FOPID controller.

3.4.2. Backtracking Search Strategy Algorithm. A backtracking search optimization (BS^2) approach was used by the operator of nonuniform crossover. The problems with numerical optimization are swiftly resolved, enabling trial participants. The BS^2 algorithm showed better results than other genetic algorithms. The three main genetic operators of the BS^2 algorithm are crossover, selection, and stochastic mutation [35]. The following subsection outlines the steps that make up the BS^2 algorithm.

3.4.2.1. Initialization. In this stage, generate the initial population at random. The initial population is determined by the following equation.

$$P_{jk} \sim J(l_k, u_k) \tag{11}$$

Population sizes and the problem dimension are D and M, respectively. There is $k = (1, 2, 3, ..., D)$ also $j = (1, 2, 3, ..., N)$. The uniform distribution J applies to the target individual population (P).

3.4.2.2. Initial Selection. The search dimension matrix is computed by the BS^2 algorithm using the historical population. The population's age is determined by the equation below.

$$P_{jk}^{\text{old}} \sim J(l_k, u_k) \tag{12}$$

By using the BS^2 algorithm, the old population is redefined after each iteration. The statement that encapsulates if, and then, rules is shown below.

$$\begin{gathered} if B < A \\ then \\ P_{\text{old}} = P/B, A \sim J(0,1) \end{gathered} \tag{13}$$

From the above equation, $:=$ is the update operator. Choose a population from the previous generation P_{old} at random. When the BS^2 has memory, it compares the new population estimate. In the older population, the individual's order is changed at random as follows:

$$P_{\text{old}} := \text{PER}(P_{\text{old}}) \tag{14}$$

The permuting (PER) function is used by the random shuffling function.

3.4.2.3. Mutation. The mutation process [36] is used to create the initial representation of the trial population, which is written as,

$$\text{Mutation} = P + G \times (P_{\text{old}} - P) \tag{15}$$

Thus, the amplitude (G) for the mutation search direction matrix ($P_{\text{old}} - P$) is managed. Using P_{old}, the search direction matrix is computed. The experimental population is formed using the BS^2 algorithm while taking partisan advantage of the experiences of the previous generations.

3.4.2.4. Crossover. The BS^2 crossover procedure is used to create the trial population [37]. A mutant population is an experiment based on its original value. Target populations for individuals have evolved to use the optimization problem. The BS^2 crossover process comprises two key steps. Relevant individuals are selected and updated from the evolving population. Refresh $\text{Trial}_{jk} := P_{jk}$ as Trial and when BIM_{jk}. By enabling random selection, every trial is altered. Get a few people after the BS^2 crossover procedure. The search space is constrained by allowing overflow and regenerating the search space boundaries due to the BS^2 mutation idea.

3.4.2.5. Secondary Selection. Update using a higher fitness value according to the greedy selection. The population of the best individual contains the optimal fitness value and updates the global optimum value if the BS^2 has an optimum value.

3.4.3. Hybridized Chaotic Multiverse Krill Herd-Based Backtracking Search Strategy. In this section, to solve the gain parameter selection problems in optimization problems, a hybridized HCMKH-BS^2 is proposed. To improve the optimization process, the advantages of the CMKH as well as BS^2 algorithms are combined *via* the HCMKH-BS^2 algorithm.

The HCMKH-BS^2 algorithm aims to achieve higher search ability, minimize the occurrence of local optima, enhance convergence capability, and reduce computational cost and time compared to other existing optimization algorithms, including GWO, PSO, Krill Herd Optimization (KHO), Cuckoo Search Algorithm (CSA), Aquila Optimization (AO), and Slime Mold Optimization (SMO).

The hybridization of the CMKH and BS^2 algorithms allows for the generation of diverse solution outcomes. The algorithm compares these solutions and selects the optimal best solution for the parameter tuning process.

The HCMKH-BS^2 algorithm follows the steps outlined in Algorithm 1. It initializes the parameters of the CMKH and BS^2 algorithms, including population size, dimension, and maximum iteration, with respect to random numbers. The inertia weight is upgraded, and the fitness value is calculated. The algorithm then enters a loop until a termination condition is met, either the maximum iteration is reached or a specific criterion is satisfied.

Algorithm 1: HCMKH-BS^2 algorithm

Start
Parameter Initialization
Inertia weight upgrade β_j^{local}
Fitness value calculation
while $n <$ Maximum Iteration
or
Not met the maximum iteration
do
Best to worst populations are initiated
for ($j = 1; M_p$) **do**
Update the Krill's movement using Eq. (5)
Update foraging behavior using Eq. (6)
Update cross over $P_{\text{old}} := \text{PER}(P_{\text{old}})$
Update mutation $\text{Mutation} = P + G \times (P_{\text{old}} - P)$
Update worm hole tunnel model using Eq. (9)
Evaluate chaotic map by Eq. (10)
Compare both solutions from CMKH and BS^2
end for

$m = m + 1$
end while
Receive best solution
Stop

Within each iteration, the populations are ranked from best to worst. Equation (5) is applied to update the Krill movement, and Eq. (6) is applied to update the foraging behavior. Crossover and mutation operations are applied to update the population. Equation (9) is applied to update the wormhole tunnel model based on multiverse, and Eq. (10) is applied to update the chaotic map.

After each iteration, the new position is stored. Once the ending criterion is satisfied, the algorithm receives the optimal solution, which represents the best solution found by the HCMKH-BS^2 algorithm for the given optimization problem.

By combining the strengths of the CMKH and BS^2 algorithms, the HCMKH-BS^2 algorithm offers improved performance in terms of searching ability, avoidance of local optima, convergence capability, computational efficiency, and time efficiency. It provides a promising approach for solving gain parameter selection issues in optimization problems.

3.4.4. Constraints Handling Mechanism. For handling constraints, the HCMKH-BS^2 algorithm has the penalty function. The optimization problem is considered as a constrsined optimization problem. For each constraint's violation, the objective function is modified by adding penalty terms. When the constraints are violated, the penalty coefficients are generated by the penalty function that increases objective function value.

3.4.4.1. Objective Function Modification. The modified objective function is derived in Eq. (16) and the terms such as $f(y)$, $h_j(y)$, and $g_i(y)$ are represented as original objective function, inequality constraints, and equality constraints, respectively. where β_j and α_i are denoted as penalty coefficients.

$$F(y) = f(y) + \sum_{j=1}^{n} \beta_j \cdot h_j(y) + \sum_{i=1}^{q} \alpha_i \cdot |g_i(y)| \qquad (16)$$

3.4.4.2. Constraintsviolation Measurement. The measurement of the constraint's violation is depends on the terms $h_j(y)$ and $g_i(y)$. The inequality constraints violation indicates, $h_j(y)$ as positive and the equality constraint violation represents, $g_i(y)$ as negative.

3.4.4.3. Penalty Coeffieint Adjustment. During optimization process, the penalty coefficients are adjusted based on the satisfaction of constraints and convergence behavior. To dynamically adjust penalty coefficients, the adaptive mechanism is implemented that balances exploration and exploitation.

3.4.4.4. Feasibility Checking. At each iteration, the constraint functions are evaluated for helping the algorihm to check the feasibility of the obtained solution. The penalty terms are adjusted to guide the optimization toward feasible regions if the solution violates any constraints.

Overall, this constrain handling maechanism is integrated to find the optimal solution while satisfying specified constrains.

4. RESULTS AND ANALYSIS

This section conducts the experimental evaluation of HCMKH-BS^2 for enhancing the power generation of the cardiac pacemakers. The experiments are performed over the Python platform with two distinct phenomena such as constant irradiance and changed irradiance.

4.1. System Configuration

The system configuration contains some of the operation variables to perform the experiments of the proposed approach, and Table 1 outlines these operation variables.

4.2. Hyperparameter Configuration

The hyperparameter tuning is used to predict the optimal solution for the solar-powered pacemaker and the hyperparameters are described in Table 2.

S. no.	Depiction	Limits
1	Maximum power	0.035 W
2	Open circuit voltage	6 V
3	Maximal power point voltage	5 V
4	Temperature coefficient	0.061745 °C
5	Maximal power point current	0.007 A
6	Short circuit current	0.008 A
7	Module cells	1
8	Light generated current	0.0080306 A
9	Diode saturation current	1.5749ê15 A
10	Diode ideality factor	2.999
11	Shunt resistance	10000.005 ohms
12	Series resistance	0.0005 ohm

TABLE 1. Projected technique's operation variables.

Methods	Name of the hyperparameters	Values
	Maximum number of iterations	500
	Motivated motion	0.005
	Explore to find food	0.05
	Population size	50
BS^2	Crossover probability	0.8
	Maximum number of iterations	2000
	Population size	30
	Mutation probability	0.1

TABLE 2. Hyperparameters and their values.

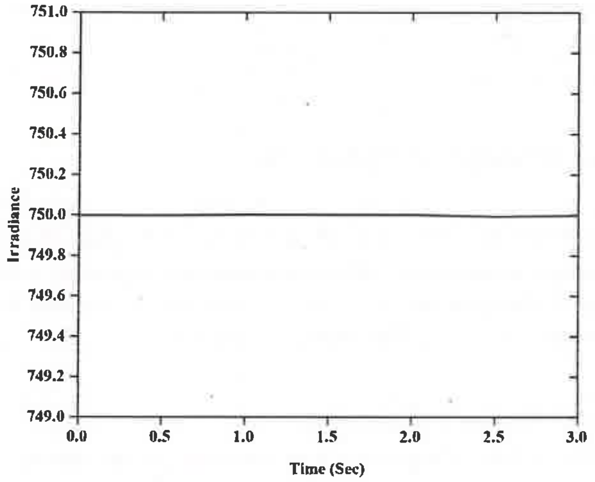


FIGURE 4. Irradiance.

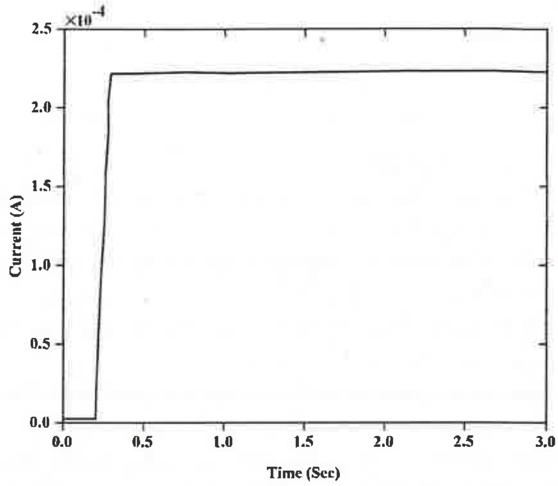
4.3. Performance Evaluation

The proposed technology is subjected to testing with two distinct phenomena known as,

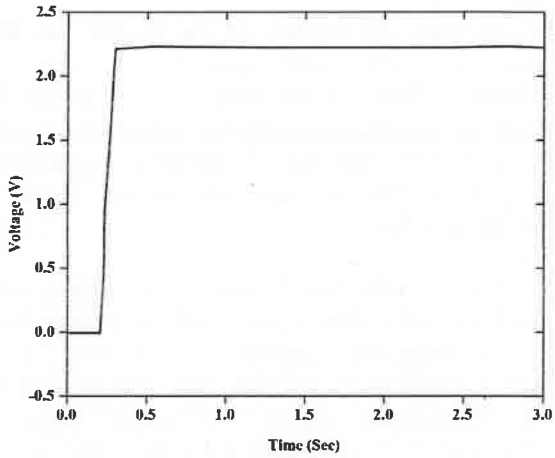
4.3.1. Constant Irradiance. The proposed technology is validated under constant irradiance conditions. The simulation uses an operational variable recorded in Nomenclature, and the standard radiation level is depicted in Figure 4. The radiation level is set to 750 W/m^2. During the radiation phase, solar energy is utilized to generate basic energy for the system.

Figure 5 shows the power, current, and generated voltage under constant radiation. In this scenario, the PV system generates energy based on the available sunlight. However, the constant radiation level may cause fluctuations in power, which can impact the functioning of a pacemaker in the human heart.

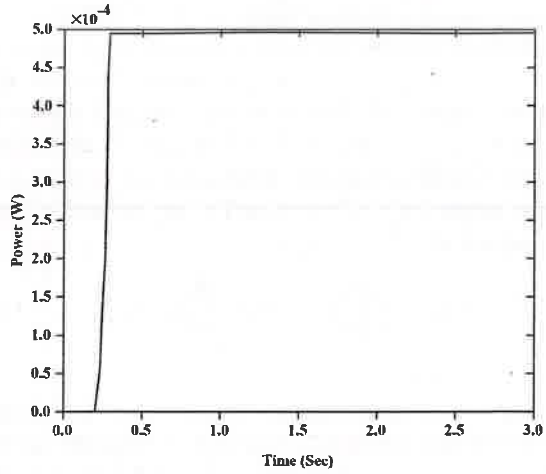
To address the stability issue in the cardiovascular pacemaker, the proposed regulator is developed. This regulator



(a)



(b)



(c)

FIGURE 5. Analysis for (a) current, (b) voltage, and (c) power.

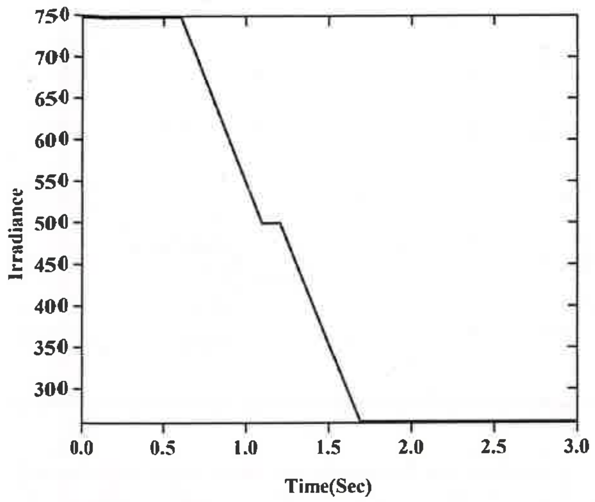


FIGURE 6. Variable irradiance analysis.

intends to handle constant power for pacemaker's administrators, which assures stable as well as reliable operation.

The power, current and voltage suggested controllers with the pacemaker are shown as Figure 6. By the stable radiation stage, PV produces a power of 0.01 W. The current and output PV voltage is 2.1 V and 4.2 × 10 − 4 A. Generally, a 2 V cardiovascular pacemaker above should provide a heartbeat. The test findings demonstrate that the proposed controller consistently produces 2 V. In this way, it is sensible for the PV system to organize the cardiac pacemaker even without a battery.

4.3.2. Changed Irradiance. The radiation level is variable, and it is evaluated using the proposed regulator. The base radiation level is 250 W/m^2, while the maximum radiation level is 750 W/m^2. Different levels of radiation can have an impact on the functioning of the heart's pacemaker. To ensure the cardiovascular pacemaker's stable operation when the radiation levels are varied, the proposed regulator with a PV system is designed.

Figure 6 depicts the variable radiation levels. The proposed regulator effectively manages the pacemaker's operation under changing radiation conditions.

Figure 7 illustrates the power, current, and voltage regulation suggested by the heart pacemaker using the proposed regulator. Under variable radiation, 0.01 W power is generated by the PV system. The values of the corresponding PV current as well as voltage are 4.2 × 10-5A and 2.1 V, respectively. It is expected that a voltage above 2 V will generate the heart rate. The proposed regulator consistently provides a voltage of 2 V without interruptions.

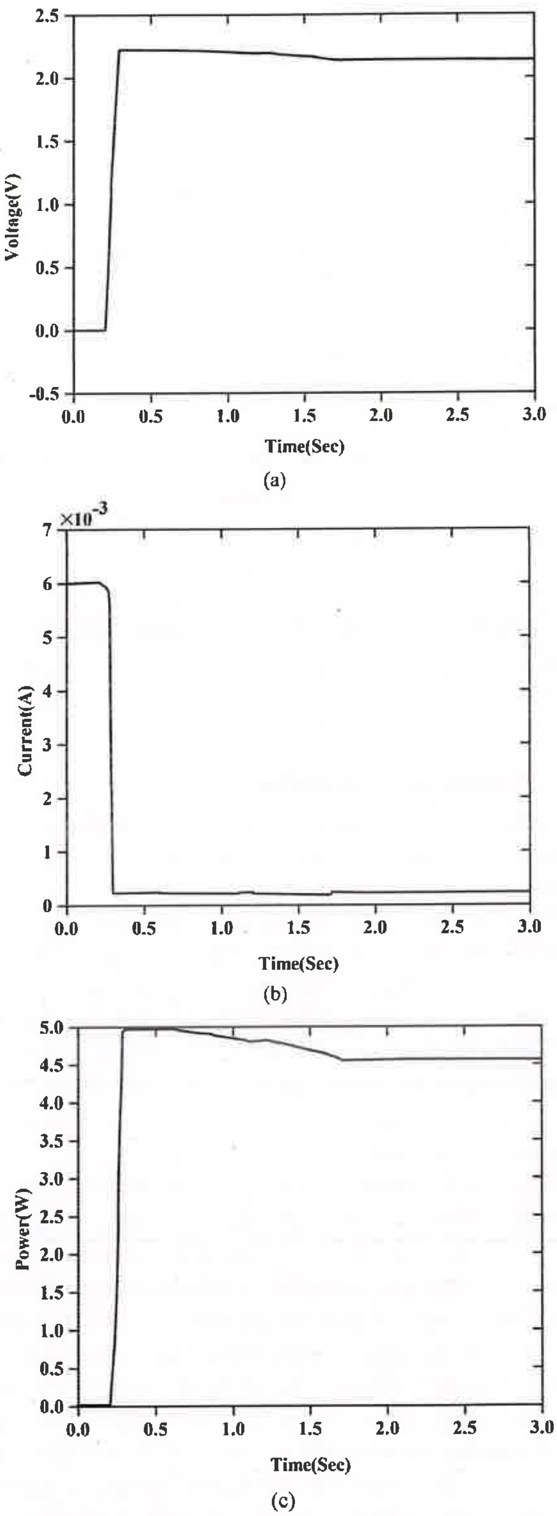


FIGURE 7. Performance analysis of (a) voltage, (b) current, and (c) power.

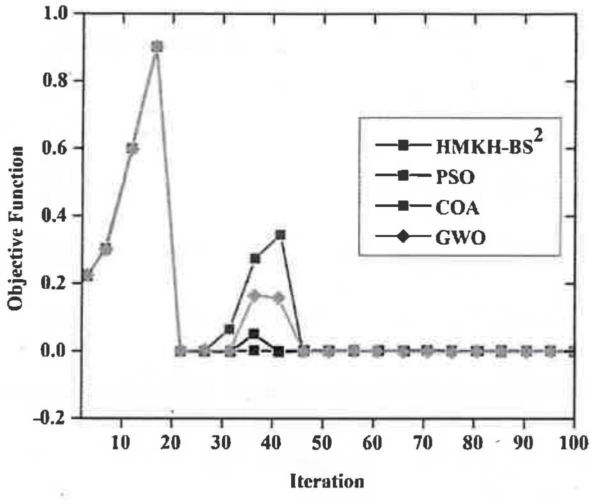


FIGURE 8. Comparative analysis for convergence.

Based on these findings, it can be concluded that a PV configuration, integrated with the proposed regulator, is a viable solution for designing battery-less cardiac pacemaker.

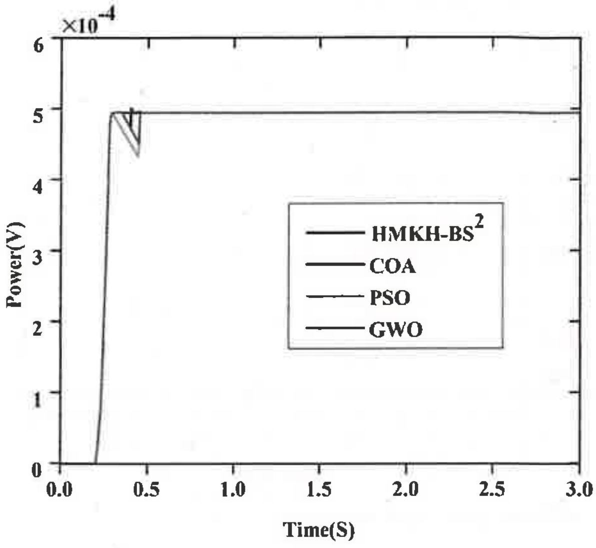
4.4. Comparison Examination

To validate the proposed approach's effectiveness, a comparison examination is conducted against conventional strategies, including GWO, PSO, and CSA.

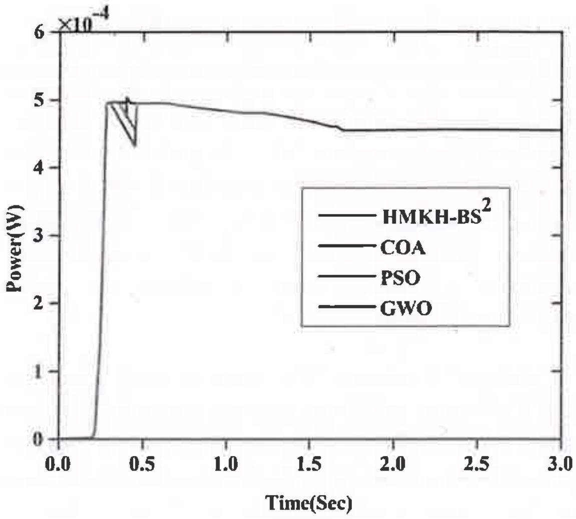
Figure 8 presents the convergence study of the proposed method. The goal is to reach a fitness function value of 0.01. It can be observed that the GWO achieved a fitness function value of 0.18, PSO achieved 0.38, and COA achieved 0.15. In comparison, the proposed method outperformed these conventional techniques by achieving the best results in manipulating the static activity of the solar-powered heart pacemaker.

Figure 9(a) displays the experimental trial results for constant irradiance, specifically the end voltage. The proposed technique consistently provided the desired voltage, while the traditional techniques exhibited alternating voltages. The proposed method demonstrated excellent performance in delivering consistent power to the pacemaker.

For changed irradiance, the relational study of the end voltage is depicted in Figure 9(b). Once again, the proposed technique consistently achieved the desired end voltage, while the traditional techniques exhibited varying voltages. Through the experiment, it is evident that the proposed method excels in providing consistent power to the heart pacemaker.



(a)



(b)

FIGURE 9. Comparative results for (a) constant irradiance and (b) changed irradiance.

The detailed variations and performance of the proposed method can be further examined and analyzed in Study Table 3.

5. DISCUSSION

The proposed model is generated by combining the FOPID controller and HCMKH-BS^2 algorithm that tried to generate a battery-free pacemaker using a PV system. In the PV

Description	Voltage in volts	Duty cycle (D)	Power in watts	Current in mA
Pacemaker requirement	2.1	0.5	0.0105	0.005
Proposed Algorithm	2.1	0.48	0.0105	0.005
COA	2.1	0.5	0.0084	0.004
GWO	1.5	0.8	0.0015	0.001
PSO	1.7	0.7	0.0034	0.002

TABLE 3. Comparison analysis.

system, the sunlight is converted into electrical energy. To regulate the pacemakers, the MPPT controller extracts maximum power from the PV system. The external environmental condition impacts the energy generation, so the improved form is implemented to handle different weather conditions. This model identifies the fault power and it is corrected by providing a higher pulse to the power converter. The ranges of FOPID regulator are selected for enhancing system performance and the optimal pulses of the system are determined using the optimization algorithm. The proposed HCMKH-BS^2 algorithm is applied in this article that is responsible for higher search ability, minimum local optimum, higher convergence capability, less computational cost and less computational time. The skin equivalent model measures the changes in impedance and also measures the electrical behavior of the skin. To enhance the power generation of the cardiac pacemaker, the validation is performed with two distinct phenomena such as changed irradiance and constant irradiance. The proposed model achieved a fitness value of 0.01 from the convergence analysis. For comparative analysis, the proposed model is compared with normal pacemaker, COA, GWO, and PSO models by using significant metrics such as voltage, duty cycle, power, and current.

5.1. Ethical and Potential Implications

The ethical and social implications of using solar powered implantable devices are as follows,

5.1.1. Cost of the Device.

- *Issue:* Implantable medical devices that incorporate innovative technologies such as solar power require higher production costs.
- *Mitigation:* To facilitate research funding and subsidization, proposed model need to be an collaboration with medical institutions, technology developers, and governmental or nonprofit organizations that makes implantable devices more economically accessible.

5.1.2. Accessibility to Patients.

- *Issue:* The accessibility of the advanced medical devices technologies often depends on geographic location, economic disparities, and healthcare infrastructure.
- *Mitigation:* The subsides and financial supports will be provided to patients those who are in the region with limited resources which enhances accessibility, and also require collaboration with international health organization for extending access.

5.1.3. Energy Harvesting Efficiency.

- *Issue:* The envioronmental factors affects the efficiency of the solar energy harvesting system that leads to insufficient power generation.
- *Mitigation:* The effieicny of the proposed model can be inproved due to applying continuous advancements in solar cell technology and energy harvesting techniques. The secondary energy storage system is required to ensure the stable power during low solar irradiance.

5.1.4. Medical Ethics and Informed Consent.

- *Issue:* Implanting devices inside the human body for energy harvesting purposes raises ethical considerations related to informed consent and patient autonomy.
- *Mitigation:* Ensuring thorough informed consent processes, transparent communication between healthcare providers and patients, and respecting patients' autonomy in decision-making are essential. These innovative medical interventions are evaluated and approved based on the ethical review reports.

5.1.5. Long-Term Safety and Reliability.

- *Issue:* The long-term safety and reliability of the implantable divices for new technologies are taken as a major consideration.
- *Mitigation:* The crucial fields of this solar power implantable devices are post-market surveillance, long-term studies, and comphrehensive pre-clinical testing. The open communication about potential risks and benefits should be maintained with both healthcare professionals and patients.

5.1.6. Equitable Distribution.

- *Issuse:* The challenging task is to ensure equitable distribution of the implanatable devices without considering ecomonic status or geographical locations.
- *Mitigation:* The distribution disparities can be addressed by introducing global health policies and frameworks that prioritize equitable access to medical technologies. Additionally, the collaboration between governments, international organizations, and manufacturers plays a major role in equiatable distribution.

5.1.7. Environmental Impact.

- *Issue:* The production and disposal of electronic medical devices can contribute to electronic waste and environmental concerns.
- *Mitigation:* The environmental impacts can be minimized implementing environmentally sustainable practices in the manufacturing process, including recyclable materials and eco-friendly disposal methods.

6. CONCLUSION

This work presents the development of a solar-based pacemaker utilizing the FOPID controller combined with the HCMKH-BS^2 for efficient power supply. The designed pacemaker aims to deliver improved heart pulses to patients. The FOPID regulator selects the optimal pulses and enhances system performances. The proposed HCMKH-BS^2 algorithm is used for achieving some advantages such as higher search ability, minimum local optimum, higher convergence capability, less computational cost, and less computational time. However, the performance of solar power generation can be affected by partial shading conditions, which were addressed by integrating the FOPID controller with HCMKH-BS^2. Through extensive simulations and experimental studies, the proposed approach demonstrated superior performance compared to existing techniques, including GWO, COA, and PSO. The convergence analysis of 0.01, power delivery of 0.0105 Watts, and duty cycle of 0.48D are attained from the proposed method that outperformed compared to state-of-the-art approaches. The results indicate that the developed approach effectively handles partial shading conditions and ensures a reliable power supply to the pacemaker. This achievement is attributed to the combination of the FOPID controller and HCMKH-BS^2, which optimizes the power generation process and minimizes the impact of shading.

In terms of future scope, further enhancements and advancements can be explored. One potential direction is to investigate the integration of energy storage systems, such as batteries or capacitors, to store excess solar energy and ensure continuous power supply during periods of low solar irradiance. Additionally, the proposed approach can be applied to other medical devices and implantable systems that rely on sustainable power sources. Moreover, it is worth considering the real-world implementation of the developed pacemaker system and conducting clinical trials to evaluate its performance and safety. Collaboration with medical professionals and regulatory bodies would be essential in ensuring compliance with medical standards and guidelines.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

HUMAN AND ANIMAL RIGHTS

This article does not contain any studies with human or animal subjects performed by any of the authors.

INFORMED CONSENT

Informed consent was obtained from all individual participants included in the study.

CONSENT TO PARTICIPATE

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

FUNDING

Not applicable.

AVAILABILITY OF DATA AND MATERIAL

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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