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Bioinspired STHVO Based MPPT Control for Grid Connected Photovoltaic Water Pumping Systems

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Abstract

Photovoltaic pumping systems have become a key solution for sustainable water supply, especially in remote and off-grid areas. Yet, their performance often drops under changing solar conditions. To address this,

we introduce *Spider-Tailed Horned Viper Optimization (STHVO)*, a novel nature-inspired MPPT technique specifically designed for such applications.

A PV generator, a step-up converter, and a radial-flow pump powered by an induction motor are all part of the suggested configuration. The system was subsequently tested under standard irradiance (1000 W/m²) and real-world irradiance variations obtained from the Bni Hadifa region. By achieving 98.92% efficiency, delivering a peak hydraulic power of 72 W, and sustaining a steady 0.65 L/s flow rate, simulation results demonstrate that STHVO performs better than traditional tactics. It also ensures rapid tracking in less than 0.6 seconds and constant motor speed at 195 rad/s. These outcomes show how the method can enhance solar-powered systems' energy reliability and water delivery.

Keywords- MPPT, Photovoltaic System, Bio-Inspired Algorithm, STHVO, Solar Pumping, Boost Converter, Grid-Connected System, Optimization, MATLAB/Simulink.

Nomenclature

Abbreviations		**Symbol**	**Description**
ABC	Artificial Bee Colony	C	Capacitance of the capacito (F)
AC	Alternating Current	G	Irradiance (W/m²)
ANN	Artificial Neural Network	I	Input current (A)
DC	Direct Current	I_{mpp}	Current at maximum power point (A)
DTC	Direct Torque Control	Isc	Short-circuit current (A)
FLC	Fuzzy Logic Controller	I_{sat}	Inverse saturation current (
GWO	Grey Wolf Optimizer	k	Boltzmann constant (1.38×10^{-23} J/K)
GMMP	Global Maximum Power Point	K_i	Temperature coefficient of short-circuit current
INC	Incremental Conductance	L	Inductance of the inductor

KCL	Kirchhoff's Law of Current	n	Diode ideality factor
KVL	Kirchhoff's Law of Voltage	Ncell	Number of cells per module
MPPT	Maximum Power Point Tracking	P_{mpp}	Power at maximum power point (W)
P&O	Perturb and Observe	q	Electron charge (1.602×10 C)
PLL	Phase-Locked Loop	R_s	Series resistance (Ω)
PSO	Particle Swarm Optimization	T	Temperature (K)
SMPS	Switched Mode Power Supplies	V	Voltage (V)
		V_t	Thermal voltage = (n·k·T)/q

1. Introduction

The world must now move toward sustainable energy; it is no longer an option [1]. Cleaner energy sources are more urgently needed than ever due to the growing consequences brought about by climate change, the slow depletion of fossil fuels, and the ongoing rise in greenhouse gas emissions [2,3]. Among the available options, solar power stands out due to its natural abundance, broad accessibility, and relatively low environmental footprint [4].

Photovoltaic water pumping systems are among the practical uses of solar energy, especially in rural and isolated regions [5]. They provide an off-grid and sustainable way to supply water, whether for farming, livestock, or domestic use [6]. By replacing diesel-powered pumps, they help reduce fuel dependency, environmental impact, and long-term operational costs [7,8].

However, the efficiency of these systems largely depends on how well they can harvest energy from solar panels something that becomes more difficult when sunlight conditions vary or when shading occurs [9–11]. Recent studies have shown that intelligent MPPT controllers, such as

hybrid fuzzy-based approaches, can significantly improve power extraction under partial shading conditions [12]. It is at this juncture that the function of the MPPT becomes imperative. In order to ensure that photovoltaic systems operate at their highest possible efficiency, especially in conditions of variable sunlight, it is crucial for them to continuously adjust in real time. The role of the MPPT is to dynamically adjust the operational parameters of the system, thereby ensuring the optimal extraction of power under any environmental condition [13].

As time progressed, an array of MPPT techniques was developed. The most common of these are classical methods such as (P&O) and (INC), which are valued for their simplicity and low implementation cost [14–16]. However, it has been demonstrated that the effectiveness of these systems is often diminished in environments characterised by fluctuating irradiance. It has been established that the efficacy of these methods is diminished by slow response times and power losses, which are attributable to persistent oscillations around the point of peak power output. In response to these limitations, recent research has explored more advanced MPPT controllers based on optimization techniques. For instance, hybrid metaheuristic approaches such as GWO–RBFNN have shown improved tracking precision and dynamic performance in grid-connected photovoltaic applications [17].

To address these shortcomings, researchers have explored alternative approaches inspired by natural phenomena. Algorithms inspired by biological systems, such as (PSO) [18], (GWO) [19] and the Artificial Protozoa Optimizer (APO) [20], emulate the behaviour of animals or microorganisms in search and adaptation scenarios. It has been demonstrated that these methods are more flexible and capable of faster convergence, especially in cases of abrupt changes in sunlight conditions [21].

Concurrently, intelligent control techniques have emerged as promising tools. Systems based on (ANNs) and (FLC) have the capacity to learn from historical system behaviour and make rapid, data-driven decisions. This capacity for real-time adaptation has been demonstrated to enhance the

precision and stability of the MPPT process, even in the presence of unpredictable weather patterns [22, 23].

Notwithstanding these advances, prevailing techniques continue to confront critical challenges, especially with regard to robustness, tracking speed, and reliability under unstable or rapidly changing conditions [24, 25]. *Recent investigations have also shown that enhanced MPPT* strategies combining simulation studies with experimental validation can significantly improve the controller's dynamic behavior under real operating conditions [26]. These limitations have given rise to a significant interest in the development of novel optimisation methods that seek to achieve a more balanced state between responsiveness, accuracy, and adaptability [27].

In this study, a novel bio-inspired optimization method STHVO is introduced and implemented, for the first time, within the framework of a photovoltaic water pumping system integrated into the grid. The principal objective of this approach is to enhance MPPT efficiency and ensure greater system stability under fluctuating solar irradiance conditions [28, 29].

This study's key contributions are presented as follows:

- **Extensive testing** of the proposed algorithm was carried out under different irradiation scenarios, ranging from consistent sunlight to real irradiance fluctuations. This allowed for a thorough evaluation of its adaptability and resilience in dynamic environments.
- The STHVO method demonstrated **remarkable dynamic performance**, characterized by fast tracking, swift convergence toward the optimal power point, and consistent pump stability throughout operation.
- In the context of a comparison with conventional MPPT strategies, such as (P&O), and other nature-inspired techniques, including the (ABC) algorithm, STHVO has been shown to consistently deliver more accurate and stable power tracking, particularly in situations that are characterised by unpredictability and challenge.

The system was evaluated under both standard irradiance and real non-uniform irradiance profiles obtained from the Bni Hadifa region to verify its robustness under realistic operating conditions.

The remaining sections of this paper are arranged as follows: The components and structure of the photovoltaic pumping system under study are described in Section 2. Explanation of the STHVO algorithm and how to implement it can be found in Section 3. The interpretation of the results of the simulations is presented in Section 4. We conclude in Section 5 where we discuss the conclusions of the paper and suggest some interesting directions for future research.

2. Description of the Photovoltaic System

In this work, the examined setup consists of a grid-connected photovoltaic water pumping configuration, comprising five core components: a PV array, a DC–DC boost converter, a three-phase inverter, an induction motor, and a centrifugal pump (as shown in Fig.1).

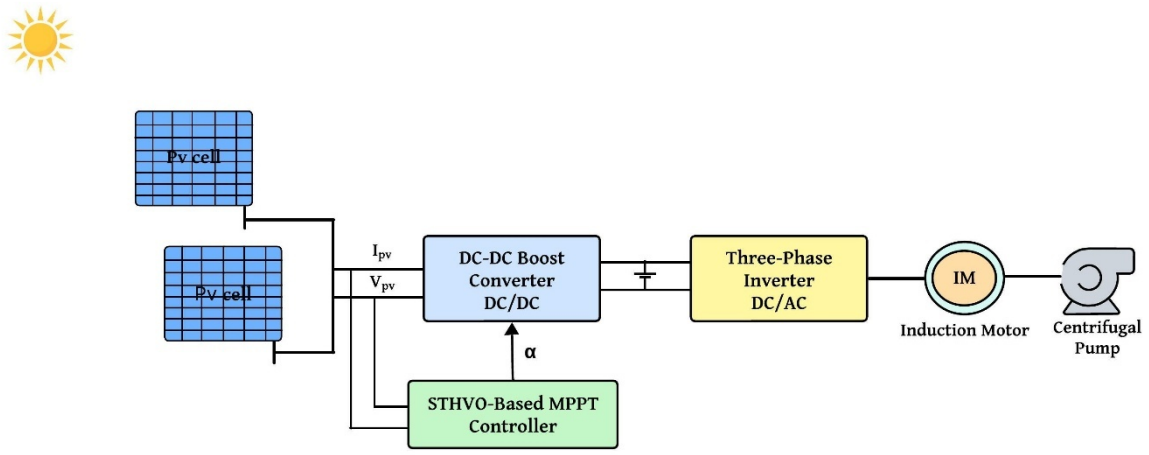

Fig.1. Proposed PVG system block diagram.

Solar panels initiate the conversion of sunlight into DC power. DC–DC boost converters raise the DC–DC output signal's voltage. A unique MPPT method based on STHVO is used to optimize the unit. Under varying irradiance conditions, the proposed technique adjusts the operating parameters in real time to achieve effective MPPT.

The regulated DC voltage is further fed to a 3-phase inverter for converting into AC so that the AC can be used for driving an induction motor. This motor turns a centrifugal pump which creates a reliable, steady water flow. The architecture under study clearly represents a strong and flexible solution to the dynamics needed for modern solar-driven infra- structure.

2.1 Photovoltaic Array Modeling

Modelling of the electrical characteristics of a (PV) cell is usually started by forming an equivalent (PV) cell circuit, which mathematically corresponds to the internal properties of the device. This model consists of a current generator represented by the light driven current, a diode whose behavior mimics that of the P-N junction, and two resistors. The first term is (R_s), that describes the internal conduction losses. The second term (R_s) denotes the leakage currents. As shown in Fig.2 this simple equivalent model can serve as an efficient tool to predict the working characteristics of the PV cell under diverse environmental and electric system conditions [30].

Using KCL at the output node results in a fundamental equation for the current flow in the PV cell – the basis for an accurate electrical analysis.

$$I = I_{ph} - I_d - I_{sh} \tag{1}$$

Using KVL, the diode voltage is defined by considering the series resistance and the circuit current, giving a realistic estimate of the PV cell's internal voltage.

$$V_d = V + I_d R \tag{2}$$

The current flowing through the diode is given by Shockley's equation:

$$I_d = I_s \left[\exp\left(\frac{qV}{nkT} \right) - 1 \right] \tag{3}$$

Meanwhile, the current through the shunt resistance is determined by Ohm's law:

$$I_{sh} = \frac{V_d}{R_{sh}} \tag{4}$$

By combining equations (1) to (4), and substituting the expression derived from equation (2), the complete form of the characteristic equation describing the output current of the photovoltaic cell is obtained.

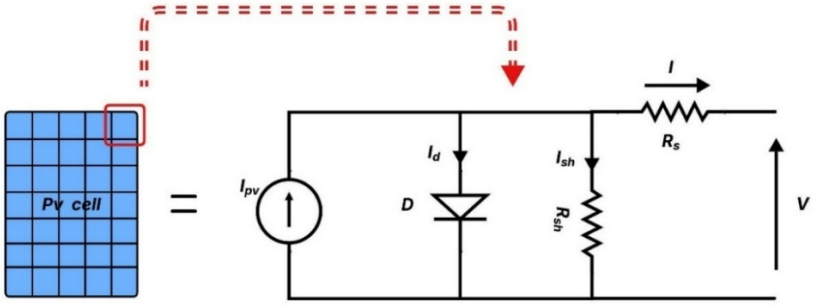

Fig.2. Equivalent circuit of a photovoltaic cell.

$$I = I_{ph} - I_s\left(e^{\frac{q(V+R_s.I)}{n.k.T}} - 1\right) - \frac{V+R_s.I}{R_{sh}} \tag{5}$$

After accounting for the number of cells composing the PV panel, Equation (1) is modified to take the following form.

$$I = I_{ph}.N_p - I_0.N_P.\left(e^{\frac{q\left(\frac{V+R_s.I}{N_s}\right)}{n.k.T}} - 1\right) - \frac{V+R_s.I}{R_{sh}.N_s} \tag{6}$$

The output power of the PV module, defined as the product of voltage (V) and current (I), can be expressed as follows:

$$P = V.I = V.\left(I_{ph}.N_p - I_0.N_p.\left(e^{\frac{q\left(\frac{V+R_s.I}{N_s}\right)}{n.k.T}} - 1\right) - \frac{V+R_s.I}{R_{sh}.N_s}\right) \tag{7}$$

Photovoltaic energy presents utilization challenges due to intermittency and mismatch between generation and demand [31].

In this study, the photovoltaic generator is based on a high-efficiency monocrystalline module rated at 375 W, as reported in Table 1. A total of eight modules are combined using a suitable series–parallel arrangement to achieve a nominal array power close to 3 kW.

For the simulation model, a monocrystalline PV module available in the Simulink library was adopted as the base component. Its electrical parameters were adjusted to match those of the 375 W reference module

presented in Table 1, ensuring that the simulated PV behavior remains consistent with the intended characteristics while maintaining compatibility with the predefined Simulink environment.

Table 1: Electrical parameters of the reference 375 W monocrystalline PV module.

Characteristic	**Value**
Maximum Power (P_{max})	375 W
Voltage at Pmax (V_{mp})	40.2 V
Current at Pmax (I_{mp})	9.34 A
Open Circuit Voltage (V_{oc})	48.0 V
Short Circuit Current (I_{sc})	9.82 A
Module Efficiency	21.7 %
Nominal Operating Cell Temperature (N_{OCT})	45 ± 2 °C
Dimensions	1690 × 996 × 35 mm
Cell Type	Monocrystalline

2.2 Boost converter DC-DC

Often referred to as a step-up voltage converter, the DC–DC boost converter is a power electronics circuit designed to increase an input voltage to a higher output level. It operates as a switched-mode power supply. An inductor stores energy when a controlled semiconductor switch, usually a MOSFET or an IGBT, is turned on, and when the switch is turned off, the stored energy is transferred to the output capacitor [32]. In this work, an N-channel MOSFET is employed as the main switching device due to its low conduction losses and high switching speed, making it suitable for the power rating of the photovoltaic system. As illustrated in Fig.3 the DC–DC boost converter increases the PV array voltage by regulating the switching duty cycle for MPPT operation.

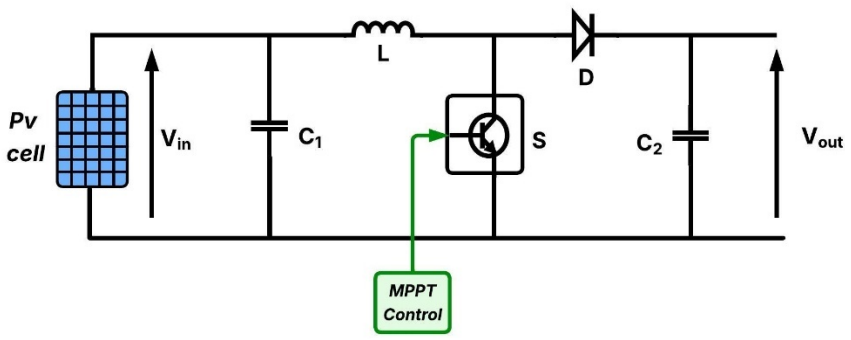

Fig.3. Simplified circuit diagram of the DC–DC boost converter used for MPPT control.

The functioning of a boost converter depends on the duty cycle, which specifies the fraction of the switching interval during which the switch stays closed. This factor is crucial in determining and controlling the output voltage [33].

Relationship between input voltage and output voltage:

The ideal boost converter equation describes the relationship between input voltage (V_{in}) and output voltage (V_{out}):

$$V_{out} = \frac{V_{in}}{1 - D} \tag{8}$$

where D represents the duty cycle, defined as the ratio of the time during which the switch is closed to the total switching period (i.e., $D = \frac{t_{ON}}{T}$).

Table 2 presents the detailed parameters of both the MPPT controller and the boost converter employed within the system. These parameters have been shown to be very important for making conversions more efficient and making sure that the system works properly in a variety of environmental and load conditions [34, 35].

Table 2: Boost Converter Coefficient Values.

Characteristic	**Value**
Input Inductance (L)	3.3 mH
Input Capacitor (C_{in})	220 µF
Output Capacitor (C_{out})	470 µF
Switching Frequency	25 kHz

2.3 Three-phase inverter

A three-phase inverter converts direct current (DC) into alternating current (AC) through an electronic switching process. It generates three voltages of equal magnitude that are shifted by 120° relative to each other. This phase displacement is crucial for the smooth operation of three-phase devices, such as induction motors, and ensures proper synchronization with the electrical grid. As shown in Fig.4 the inverter's structure allows the production of these voltages, providing reliable motor performance and efficient power delivery to the network [36,37].

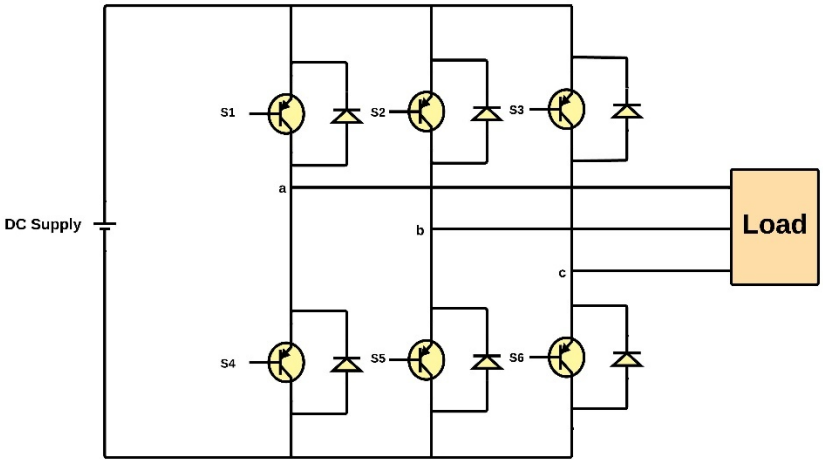

Fig.4.Basic Structure of a Three-Phase Inverter for AC Load Supply

The inverter output voltages can be expressed as follows:

$$V_A = V_m \sin(wt), V_B = V_m \sin(wt - \frac{2p}{3}), V_C = V_m \sin(wt + \frac{2p}{3}) \quad (9)$$

where V_m denotes the maximum amplitude of each phase voltage,ω refers to the angular frequency of the generated voltages.

Next, a PLL is used to find the phase difference between the motor and the inverter in real time :

In this relation :

$$Dq(t) = q_{motor}(t) - q_{inverter}(t) \quad (10)$$

Lastly, the PLL modifies the frequency and phase of the inverter. This will bring them into line with the motor's. The following relationship serves as the foundation for this:

$$w_{inverter}(t) = w_{motor}(t) - w_{corr}(t), q_{inverter}(t) = \int w_{inverter}(t)dt \quad (11)$$

where $w_{motor}(t)$ is the motor's angular speed, $w_{corr}(t)$ is the correction term, and $q_{inverter}(t)$ is the inverter's phase angle.

This mechanism ensures synchronization between the inverter and the motor, thereby improving the efficiency of energy conversion [38,39].

2.4 Induction Motor

Electrical power can be converted into mechanical power to effectively power a centrifugal pump. The induction machine is characterized by a system of mathematical equations that describes its behavior from the perspective of dynamic response between stator and rotor circuits and the production of electromagnetic torque. These internal features are characterized in Fig.5 by the equivalent- 2 per-phase circuit used for the analysis of the machine electromechanical behavior in different operating conditions [40].

To ensure accurate representation of the electromechanical behaviour of the pumping system,

the induction motor was modelled using manufacturer-grade parameters representative of 3 kW

squirrel-cage machines commonly employed in rural water-pumping applications. These parameters govern the electrical and dynamic response of the motor and allow the dq-axis model to reproduce both transient and steady-state operation with fidelity. Table 3 summarises the electrical and mechanical constants used in the simulation.

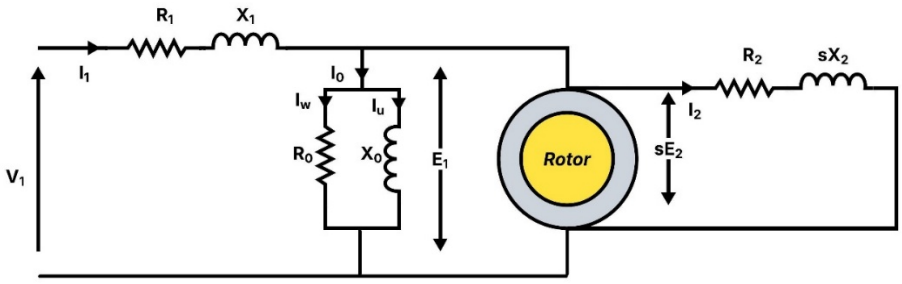

Fig.5. Single-phase equivalent model of the induction motor.

Table 3: Electrical and Mechanical Specifications of the Induction Motor.

Parameter	**Symbol**	**Value**
Rated Power	P_n	3 kW
Rated Line Voltage	V_n	380 V
Rated Frequency	f	50 Hz
Number of Poles	p	2
Stator Resistance	R_s	1.2 Ω
Rotor Resistance	R_r	1.0 Ω
Magnetizing Inductance	L_m	120 mH

The stator voltage equation in the dq reference frame can be expressed as follows:

$$V_{ds} = R_s.i_{ds} + \frac{df_{ds}}{dt}; V_{qs} = R_s.i_{qs} + \frac{df_{qs}}{dt} \quad (12)$$

The electromagnetic torque is expressed as:

$$T_{em} = \frac{3}{2}.\frac{P}{2}(f_{dr}.i_{qs} - f_{qr}.i_{ds}) \quad (13)$$

where $f_{ds}$and f_{qs} are the stator flux components, i_{ds} and i_{qs} are the stator current components, and $P$is the number of poles.

To precisely regulate both speed and torque, advanced control strategies such as Vector Control and DTC are employed. DTC offers fast dynamic control by acting directly on the electromagnetic torque and stator flux, eliminating current regulators and reference frame conversions. This method helps reduce torque ripple and contributes to more stable system operation [41,42].

2.5 Centrifugal Pump

A centrifugal pump transforms the mechanical output of an induction motor into hydraulic power, allowing water to be lifted and moved through the system [43,44]. Its simple design, dependable performance, and tolerance to variable flow rates make it a common choice in solar-powered pumping setups. Fig.6 shows the typical arrangement of a centrifugal pump connected to an induction motor [45-47].

In this study, the PV generator is intentionally oversized relative to the hydraulic load. This sizing strategy is widely used in photovoltaic pumping applications to ensure reliable motor start-up, maintain stable torque, and prevent flow interruption when irradiance drops. In a grid-connected configuration, the PV array does not need to match the pump rating, and the excess generation capacity provides operational stability under varying

solar conditions. The objective is to guarantee continuous pump operation while allowing a precise evaluation of the MPPT performance.

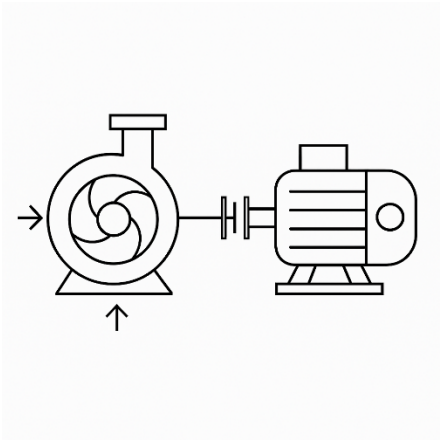

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Fig 6. Schematic layout of a centrifugal pump driven by an induction motor.

The behavior of the pump can be described using the following expressions.

The torque required by the pump is expressed as:

$$T_{load} = K_{ch}.W^2 \tag{14}$$

where, K_{ch} is a constant and W is the angular speed of the motor.

- ***Pump Performance Scaling Laws (Affinity Laws):***

When the rotor speed changes from N to N′, the resulting flow rate Q′, head H′, and power P′ can be determined using the following relationships:

$$Q' = Q.\frac{N'}{N}, H' = H.\left(\frac{N'}{N}\right)^2, P' = P.\left(\frac{N'}{N}\right)^3 \tag{15}$$

3. MPPT

MPPT control plays a fundamental role in maximizing photovoltaic energy utilization and maintaining the optimal operating point under environmental disturbances. In this study, an optimisation method inspired by biological processes, namely the STHVO algorithm, is introduced to improve tracking performance under fluctuations in solar irradiance and temperature. The algorithm is designed to respond rapidly to dynamic input variations, thereby reducing energy losses and ensuring stable power output.

Unlike conventional MPPT techniques that rely on predetermined control laws or an accurate mathematical model of the PV generator, the STHVO method achieves maximum power point tracking through a natural-inspired adaptive mechanism. Its ability to react effectively to a wide range of solar conditions makes it suitable for practical applications, including environments where solar intensity is highly variable and unpredictable, such as potential off-Earth installations.

3.1 Proposed Method: Bio-Inspired STHVO Algorithm for MPPT Control

In this section we give an introduction of the STHVO algorithm by considering the biological model that led to its design. It next proceeds to the mathematical modelling which reflects the spirit of the species' hunting behaviour. Finally, the main algorithmic features behind the implementation of this bio-mimetic logic within an MPPT control operation is presented in detail.

3.1.1 Definition

The STHVO is based on a hunting behavior of the Pseudocerastes urarachnoides viper species living in the Middle East. Instead of being fast, they employ a sneaky ambush tactic, “wriggling” the spider-like terminal part of their tail to trick insectivorous birds. It relies mainly on ambush behavior during the exploration phase, targeting prey that approach closely [48].

Such peculiar activity, based on waiting, planning and timely engagement, was the conceptual inspiration of the design of the algorithm. Similar to a snake that utilizes an adaptive hunting scheme to find the prey, STHVO conducts the search by producing an initial set of diversified solutions and successively converges its interest to those with potential success by iteratively refining them [49].

In photovoltaic MPPT applications, this process occurs in two main stages:

- *Exploration phase:* The algorithm begins by generating a random set of voltage candidates within the defined search area. This broad

search enables the detection of regions with high potential for power extraction.

- *Exploitation phase:* Once a promising voltage region has been identified, the algorithm shifts its focus locally. It refines the selected solution through smaller, targeted adjustments in order to converge toward the most optimal operating point observed so far.

Thanks to its adaptive nature, STHVO brings several strengths that make it particularly effective in real-world conditions where operating parameters change frequently:

- Fast convergence toward the (MPP),
- Responsiveness to variations in irradiance and temperature,
- Good capability to escape local optima,
- Stable performance under sudden disturbances.

To provide an overview of the algorithm, the next section presents a flow chart showing the primary steps of the algorithm from initializing candidate solutions to the iterative search through local search. A graphical flowchart of the method is also presented that illustrates the various steps in an organized form. This picture facilitates the application of the STHVO and forms an aid for the control in real-time situation contemplating the tacking control (MPPT) [50].

3.2 Mathematical Modeling of the STHVO Optimization Algorithm

The STHVO is a member of the nature-inspired metaheuristics family. It is intended to tackle hard optimisation problems via a two basic steps: exploring and exploiting. The remainder of the article discusses the mathematical basis these stages .

3.2.1 Representation of Solutions

STHVO is a population based method where each agent is considered as a putative solution to an optimisation problem. These agents evolve within a predefined search space that is mathematically represented as a subset of an n-dimensional Euclidean domain.

$$S \in \mathbb{R}^n$$

Each solution X_i, where $i = 1, 2, \ldots, N$ is represented in vector form as follows:

$$X_i = [x_{i1}, x_{i2}, \ldots, x_{in}] \quad (16)$$

In this expression :

- X_i represents the i-th solution in the population,
- X_{ij} corresponds to the value of the j-th decision variable for agent i,
- N denotes the total number of agents considered.

This expression gives the possibility to the algorithm to scan in parallel the entire search space for all possible candidate solutions. It also sets the foundations for the interaction and update rules that drive the population towards better performance. In MPPT, the optimized values are typically photovoltaic system values like voltage or current [51].

3.2.2 Exploration Phase (Lure Movements)

Exploration is an essential part of the STHVO algorithm. It is inspired by the adaptive hunting strategy of the spider-tailed horned viper, which varies the way in which it strikes its tail to mimic different types of prey. This stochastic, but guided movement is implemented as a series of perturbations, that allow candidate solutions to spread in the search space. In mathematical formulations, the position of agent X_i is updated based on the following expression:

$$X_i^{t+1} = X_i^t + r.a.\left(X_j^t - X_k^t\right) \quad (17)$$

where

- X_i^t represents the current position of agent i at iteration t.
- X_j^t and X_k^t are two different candidates randomly selected from the current population.
- $r \in [-1, 1]$ is a random factor that simulates directional variation.
- a limits the step size in the search space.

Thus, this mathematical description represents a semi-stochastic motion, whereby each agent adjusts its position according to the surrounding population configuration. By adding a random factor (r), solutions have

enough diversity, since premature convergence to inferior regions in the search space is prevented.

Using this exploratory search allows the algorithm to search a variety of different options, avoiding a stagnation into local optima. The exploitation stage that follows, when the search is more focused and honed, is made possible by this rich variation phase.

3.2.4 Exploitation Phase (Targeted Strike)

After the exploration, the STHVO method moves to an exploitation phase, where the optimization is improved by collecting and focusing around the best candidate solution so far discovered. It mimics the way a viper hunts even when still until the prey gets close enough to strike and hit with accuracy.

This process is mathematically modeled as gradually leading each agent to the optimal solution discovered so far. The position of the agent updates according to the following eq:

$$X_i^{t+1} = X_i^t + b.\left(X_{best}^t - X_i^t\right) + d \tag{18}$$

where X_i^t represents the current position of agent I, X_{best}^t is the best global solution found at the current i iteration t.

- $b \in [-1,1]$ is a convergence control parameter that regulates the step size toward the best solution.
- d is a small random perturbation introduced to avoid premature stagnation.

This update mechanism aims to speed up convergence while maintaining enough diversity for local search near the best solution. Such a balance helps the algorithm adapt to changing conditions, which is especially important in PV systems exposed to variable solar irradiance [52].

3.3 Termination Conditions

To balance accuracy, efficiency, and runtime, the STHVO algorithm uses clear stopping conditions. The optimization ends either when convergence is reached or when the available computational time is used up.

Typically, two main criteria are adopted to terminate the algorithm:

- ***Maximum Number of Iterations (T_{max}).***

This is a standard criterion commonly used in metaheuristic algorithms. It consists of predefining the algorithm's maximum iterations or generations. When the stopping condition is satisfied, the process terminates, regardless of the degree of proximity between the current solution and the optimal value.

$$\text{If } t \geq T_{max} \Rightarrow Stop \tag{19}$$

This condition helps limit computation time, which is essential in contexts like embedded systems, real-time control, or extended simulations.

- ***Convergence Criterion (Tolerance ε)***

The second stopping condition is based on evaluating the change in the objective function between two consecutive iterations. When this variation becomes negligible, it indicates that the algorithm is likely approaching an optimum (either local or global), and further computation is no longer necessary.

$$\left| f\left(X^{t+1}\right) - f\left(X^{t}\right) \right| < \varepsilon \tag{20}$$

where $f(X)$ is the objective function (e.g., the produced power), ε is a user-defined tolerance threshold, typically in the range of 10^{-5} or 10^{-6}

This criterion helps prevent unnecessary resource consumption when improvements in the results become marginal, while ensuring that the solution quality remains acceptable.

3.4 Integration of STHVO into Photovoltaic System Control

After introducing and mathematically modeling the STHVO algorithm, it is essential to demonstrate how it can be concretely integrated into a control loop applied to a photovoltaic pumping system.

The idea is to use STHVO as an MPPT controller capable of identifying, at each iteration, the optimal voltage that maximizes the electrical energy generated by the photovoltaic modules.

The real-time electrical power is computed in real time using the relation:

$$P = V.I \tag{21}$$

where V is the measured voltage and I is the current supplied by the photovoltaic generator.

The STHVO algorithm determines the optimal operating voltage V^* that maximizes the PV output power.

$$V^* = \arg\max_V P(V) \tag{22}$$

where P(V) represents the PV power as a function of the operating voltage.

Once this optimal voltage is identified, it is converted into a modulation ratio D employed to operate the DC-DC Boost converter:

$$D = 1 - \frac{V_{in}}{V^*} \tag{23}$$

This duty cycle is then used within a PWM modulation scheme to generate the control signal for the MOSFET converter's switching device.

The converter's delivered output voltage feeds a three-phase inverter, which supplies the required voltage to the asynchronous motor. This motor drives a centrifugal pump, and its rotational speed ω depends directly on the supply voltage:

$$w \mu V_{motor} \tag{24}$$

The pump's flow rate Q is directly dependent on the rotational speed of the motor:

$$Q \mu w \tag{25}$$

Thus, improving the accuracy of the estimated optimal voltage directly enhances the quality of the pumping process. This demonstrates the ability of the STHVO algorithm to effectively manage the energy conversion chain in the photovoltaic system.

As shown in Fig.7 the algorithm is integrated into the MPPT control loop to continuously adjust the operating voltage according to real-time environmental variations. The controller iteratively evaluates the PV power, updates the population of candidate voltages, and guides the search through exploration and exploitation behaviors until the optimal operating

point is reached. Once the most suitable voltage is identified, it is translated into a corresponding duty-cycle ratio and applied to the DC–DC boost converter, ensuring that the PV array operates near its maximum power point and delivers stable energy to the pumping unit. To provide a clear and reproducible description of this process, the main computational steps executed during each iteration are summarized in Algorithm 1.

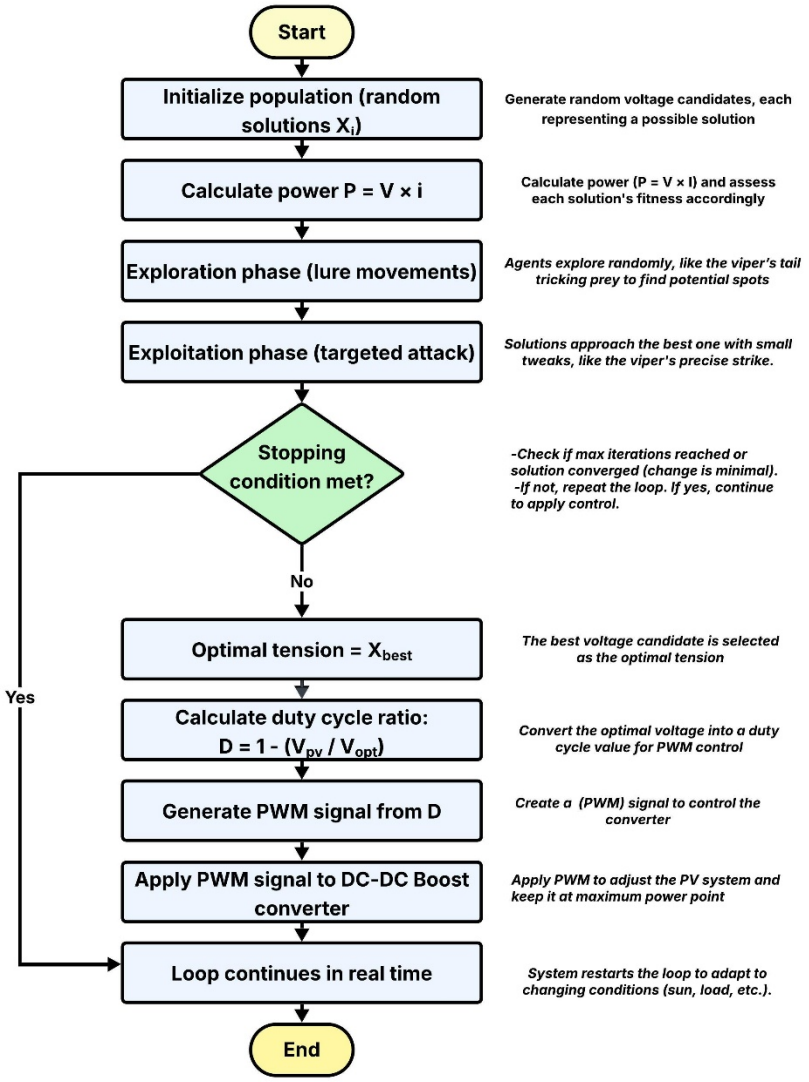

Fig. 7. STHVO-MPPT control flow for the PV pumping system.

 Algorithm 1. Concise Pseudocode of the Proposed STHVO–MPPT Method.

Input: V_{pv}, I_{pv}, search interval [V_{min}, V_{max}]
Initialize population X_i within [V_{min}, V_{max}]
Initialize control parameters and internal coefficients
Determine initial best candidates X_{best1} and X_{best2}
Repeat:
    Evaluate fitness Pi = $V_{pv} \times I_{pv}$ for each X_i
    For each agent Xi:
        Generate random number r
        If r < 0.5:// Exploration
            Update Xi using the lure-movement rule (Eq. 17)
        Else: // Exploitation
            Update X_i toward X_{best1} using targeted rule (Eq. 18)
        Apply bounds and recalculate P_i
        Update global best if improved
Until stopping condition is met
Let V* be the best voltage candidate
Compute duty cycle D from V*
Return D

4. Simulation and Results

The operational efficiency of the STHVO-based control strategy applied to a photovoltaic-driven water pumping setup is analysed in this section. A comparative assessment is carried out against two popular MPPT techniques such as (INC) and Modified (ABC). Three main aspects are considered in evaluating the Meta-Heuristic: tracking precision; stability of the control signals; and dynamic response behavior under variations of the irradiance. A simulation model of the plant was built using MATLAB/Simulink and equipped with a RT-loop of STHVO, based- MPPT. The test cases cover various solar conditions, ranging from stable illumination to real irradiance fluctuations, in order to assess the performance of the algorithm under realistic operating environments.

Simulation findings show that the STHVO algorithm tracks status changes quickly and correctly and converges to the MPP quickly with good stable control. The program reduces power oscillation and maintains water flow output even with irradiation fluctuations.

These findings show that the STHVO method is robust and flexible and may be used in natural situations with random solar fluctuations.

4.1 System components and specifications

Detailed MATLAB/Simulink simulations of a solar water pumping system have been used to access the performance of the STHVO algorithm. They compared its behavior using two well-known (MPPT) methods: the modified (ABC) algorithm and the (INC) method.

To ensure transparency and reproducibility, a complete MATLAB/Simulink model of the proposed PV-powered water-pumping system has been developed. Fig.8 presents the full system architecture, including the PV generator, the boost DC–DC converter, the MPPT controller, the DC-link, the three-phase inverter, the induction motor, and the centrifugal pump. This integrated modeling environment enables dynamic end-to-end simulation from solar energy extraction to mechanical water delivery. It therefore provides a consistent evaluation of the electromechanical performance under the different irradiance scenarios discussed in the following subsections.

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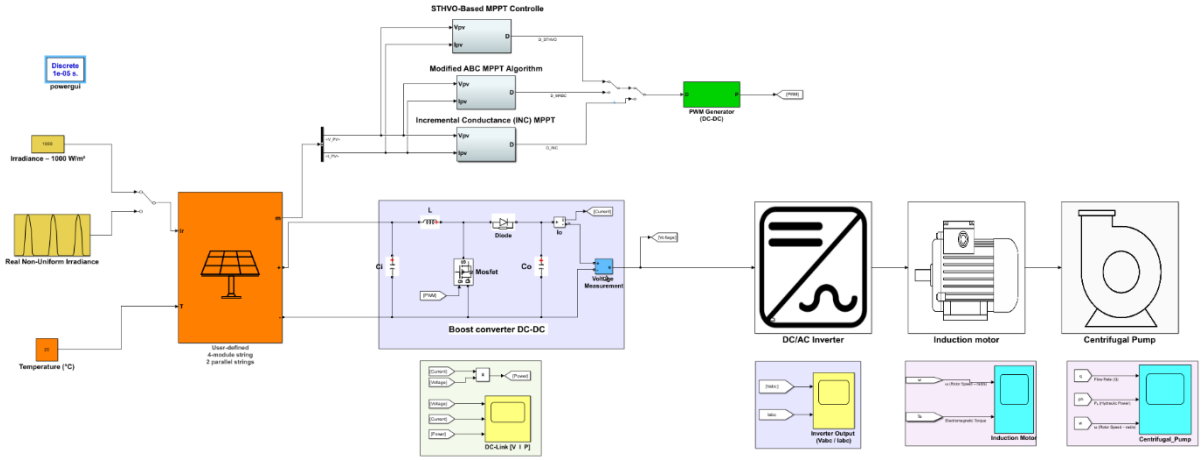


Fig. 8. Complete MATLAB/Simulink model.

To guarantee numerical consistency throughout the simulations, a discrete fixed-step solver was adopted with a time step of 1×10^{-5} s. This value provides an appropriate compromise between computational cost and the ability to capture the switching behaviour of the boost converter and the inverter. The MPPT controllers and sensing blocks were assigned a sampling period of 1×10^{-4} **s**, which allows the control loop to follow irradiance variations without imposing unnecessary computational load. The simulation sequence consists of reading the PV voltage and current, evaluating the instantaneous power, updating the duty cycle through the STHVO, Modified ABC, or INC algorithms, regulating the boost stage, feeding the inverter, and finally determining the dynamic response of the induction-motor and pump assembly. These numerical settings ensure coherent interaction between all electrical and hydraulic subsystems across all irradiance scenarios examined in the following sections.

To study the systems response under different operating conditions in a systematic way, two different test set points were developed with respect to the solar irradiance profile and the environmental dynamics.

- ***Case 1*** – Standard conditions: Under stable environmental conditions, the system is evaluated using a solar irradiance of **1000 W/m²** and an ambient temperature of 25°C. This case serves as the baseline benchmark for assessing the performance of each MPPT algorithm.

- ***Case 2*** – Real Non-Uniform Irradiance Conditions: This scenario examines the behaviour of the MPPT algorithms under realistic irradiance variations using meteorological data collected from Bni Hadifa, a rural village in the mountainous region of Al Hoceima, northern Morocco. This location was selected because of its relevance to off-grid water pumping applications and its terrain profile, which naturally produces irradiance drops due to surrounding hills, local microclimates, and frequent winter cloud cover.For this study, we considered the month of December, a period characterised by low sun angles, shorter daylight duration, and recurrent cloud-induced fluctuations. These environmental factors generate noticeable variations in the irradiance profile, particularly during early morning and late afternoon hours, creating non-uniform conditions that challenge MPPT performance.The irradiance and temperature data were obtained from the PVGIS–SARAH3 database using the exact coordinates of Bni Hadifa (35.003°N, −4.607°W). The resulting profile shows naturally fluctuating global horizontal irradiance, which serves as a realistic stress test for evaluating the robustness, tracking accuracy, and adaptability of the STHVO, MABC, and INC algorithms in real-world operating conditions relevant to rural solar water pumping systems.
- In each test case, the control signals generated by STHVO, MABC, and INC were applied to the gate terminal of a MOSFET within a DC-DC boost converter, whose output is directed to a three-phase inverter, delivers electrical energy to an induction motor that drives a centrifugal pump.

Throughout the simulation, the following electrical and mechanical variables were continuously monitored:

- DC-DC boost stage voltage and current output
- Three-phase voltage and current from the inverter,
- Rotational speed of the induction motor (ω),
- Hydraulic flow rate produced by the pump (Q).

These parameters were collected in each test case to evaluate the overall electromechanical performance of the system from solar energy harvesting to final water delivery output.

- **Case 1: Constant Irradiance and Temperature Conditions**

Fig.9 and Table 4 present a comparative analysis of three MPPT algorithms Proposed Method, Modified ABC, and INC under standard test conditions (1000 W/m², 25°C). The Proposed Method shows the fastest response, reaching the maximum power point in just 0.19 seconds, ahead of Modified ABC (0.23 s) and INC (0.56 s). In steady-state operation, both the Proposed Method and Modified ABC maintain stable power levels, while INC exhibits noticeable oscillations, which reduce overall performance. In terms of output and efficiency, the Proposed Method delivers the best results (2967.6W and 98.92%), followed by Modified ABC, with INC performing the least effectively (96.71% efficiency). These findings confirm the advantage of the Proposed Method in both response speed and output stability, making it a strong candidate for systems operating under stable environmental conditions.

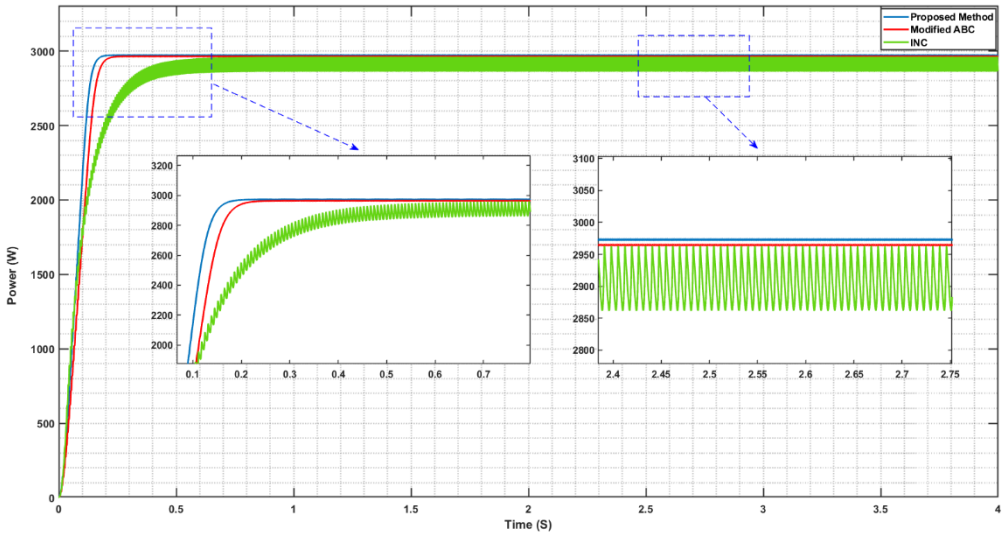


Fig. 9. Output power of the photovoltaic system under standard test conditions (1000 W/m², 25°C).

Table 4: Performance Comparison of MPPT Techniques – Proposed Method, Modified ABC, and INC

Technique	Power Output (W)	Tracking Speed (s)	Stability	Efficiency (%)
Proposed Method	2967.6	0.19	Stable	98.92
Modified ABC	2960.8	0.23	Stable	98.69
INC	2901.4	0.56	Unstable	96.71

- ***Comparative Analysis of the Proposed MPPT Method***

To position the proposed method within the landscape of recent research, the following provides a comparative overview of MPPT algorithms, covering both classical techniques and nature-inspired approaches applied to various photovoltaic systems.

This analysis aims to highlight advancements in tracking speed, energy conversion efficiency, and system stability. As shown in the table 5, the proposed method based on the STHVO algorithm demonstrates superior performance, particularly under standard operating conditions, outperforming other recent methods in terms of efficiency and response time.

Table 5: Comparative Performance of MPPT Algorithms under Different PV Applications

Ref	DC-DC	System	Efficiency (%)	Stability	Remarks
This Work	Boost + STHVO	Water Pumping System	98.92	Stable	Proposed method demonstrates the highest efficiency and fastest convergence under STC; ideal for systems requiring stable power delivery, such as solar-powered water pumping.
[53]	Boost	Residential PV System	94.5	Stable	Simple control and reliable performance for basic installations, but limited adaptability under changing conditions.
[54]	Boost + MPPT (P&O)	Rooftop PV Panels	95.2	Unstable	Effective under clear skies but suffers from power oscillations during shading conditions.
[55]	Modified SEPIC	Standalone PV System	96.1	Stable	Improves voltage regulation but exhibits moderate performance with increased circuit complexity.
[56]	Boost + FLC	Home Solar Energy Kit	96.7	Stable	Capable of nonlinear adaptation, but the convergence speed is relatively limited.
[57]	Interleaved Boost	Grid-Connected PV	97.0	Stable	Efficient in reducing current ripple and improving overall power quality at the grid interface.
[58]	Boost + PSO	Irrigation Solar System	97.5	Stable	Fast tracking enabled by bio-inspired optimization; performance depends on population tuning.
[59]	Boost + Modified ABC	Autonomous PV Platform	98.69	Stable	Delivers high efficiency and optimized convergence time but requires multiple iterations.
[60]	Boost + INC	Basic PV Testing Bench	96.71	Unstable	Traditional method that suffers from power fluctuations under rapidly changing irradiation.
[61]	Boost + GA-FLC	Solar Battery Charger	97.2	Stable	Combines the precision of GA with the flexibility of FLC; enhances MPP detection but requires complex computation.
[62]	Boost + ANN	Smart PV Controller	97.0	Stable	Provides good accuracy and learning capability but requires prior training and is computationally intensive.

[63]	Boost + SMC	Off-Grid PV System	97.3	Stable	Highly robust to disturbances and parameter variations; ideal for isolated energy applications.
[64]	Boost + Bat Algorithm	Mobile PV Tracker	98.1	Stable	Effective under dynamic conditions but requires careful tuning of hyperparameters to avoid local optima.

- **Case 2 : Real-World Shading Scenario – Bni Hadifa**

Referring to Fig.10, which depicts the actual daily solar irradiance pattern for the Bni Hadifa region a mountainous area in northern Morocco it is clear that the irradiance reaches its peak around midday, with values approaching 750 W/m² between 11:00 a.m. and 2:00 p.m. This realistic and dynamic solar profile provides a strong foundation for evaluating the behavior of MPPT algorithms under naturally fluctuating conditions. Fig.11 illustrates the output power responses of three MPPT methods: (INC), the Modified ABC algorithm, and the proposed STHVO-based strategy inspired by natural predator behavior. Among these, the STHVO method delivers a notably faster and smoother tracking performance, closely reaching the maximum power level of 3000 W in under 1.5 seconds. In contrast, the modified ABC method shows a slower and less stable response near the power peak, while the INC approach struggles to adapt, exhibiting noticeable delays and reduced efficiency. These results highlight the effectiveness and adaptability of the proposed STHVO algorithm in maintaining reliable and optimized energy extraction under real irradiance variations like those observed in Bni Hadifa.

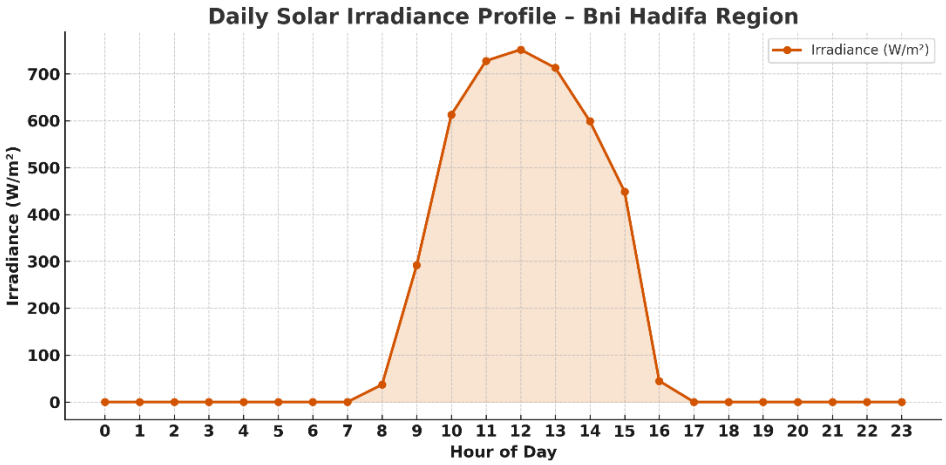


Fig.10. Daily solar irradiance profile for Bni Hadifa region based on real data.

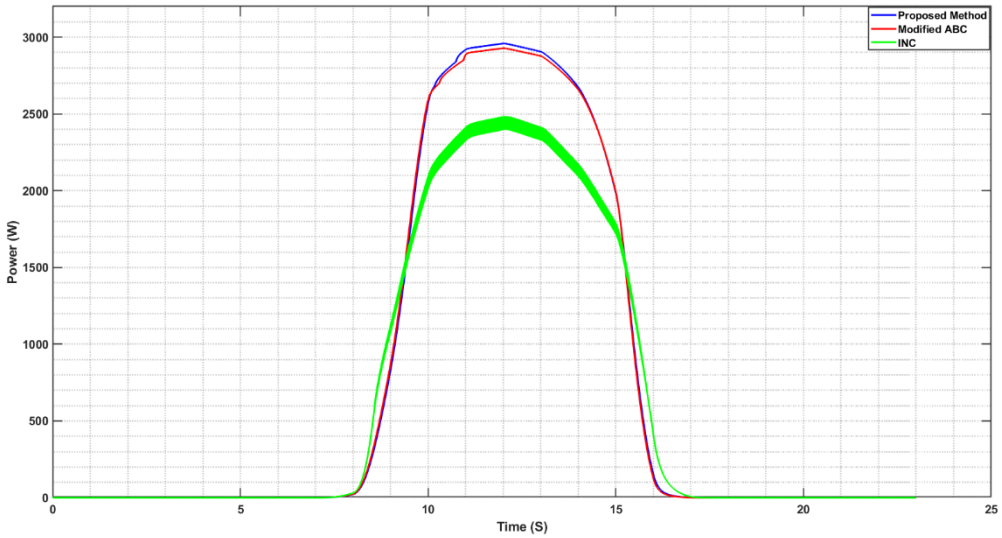


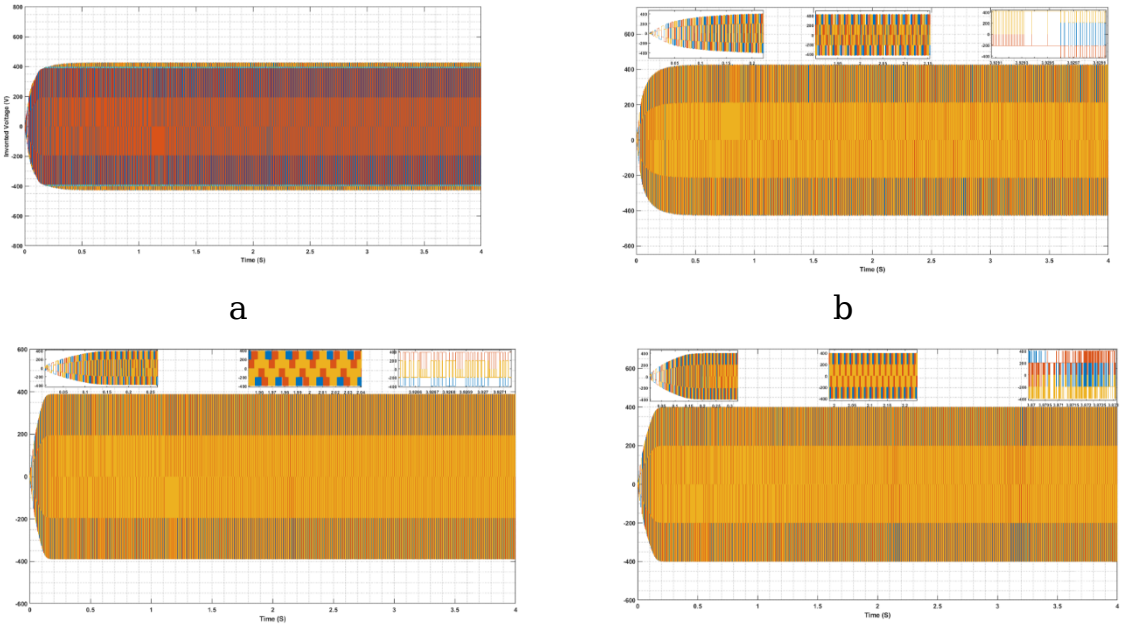
Fig .11. Output power of the photovoltaic system under real non-uniform irradiance conditions in the Bni Hadifa region.

4.2 Analysis of Inverter Output in a Three-Phase Grid-Connected PV System

- ***The output voltage of the inverter***

Fig.12.a presents the three-phase inverter voltage waveforms obtained using three different MPPT techniques : STHVO, Modified ABC, and INC. All methods generate alternating voltages with acceptable amplitude and frequency after the initial startup period. However, the waveform quality differs significantly among the approaches, particularly in terms of distortion, symmetry, and settling time.

Fig.12.b focuses specifically on the inverter voltage generated using the proposed STHVO algorithm. The output exhibits excellent waveform consistency and phase balance, indicating a smooth and stable transition to steady-state conditions. The signal structure suggests an effective PWM control strategy that minimizes voltage ripple and harmonic distortion.



a b c d

Fig.12. Three-phase inverter output voltage waveforms: (a) all MPPT methods, (b) STHVO, (c) Modified ABC, and (d) INC.

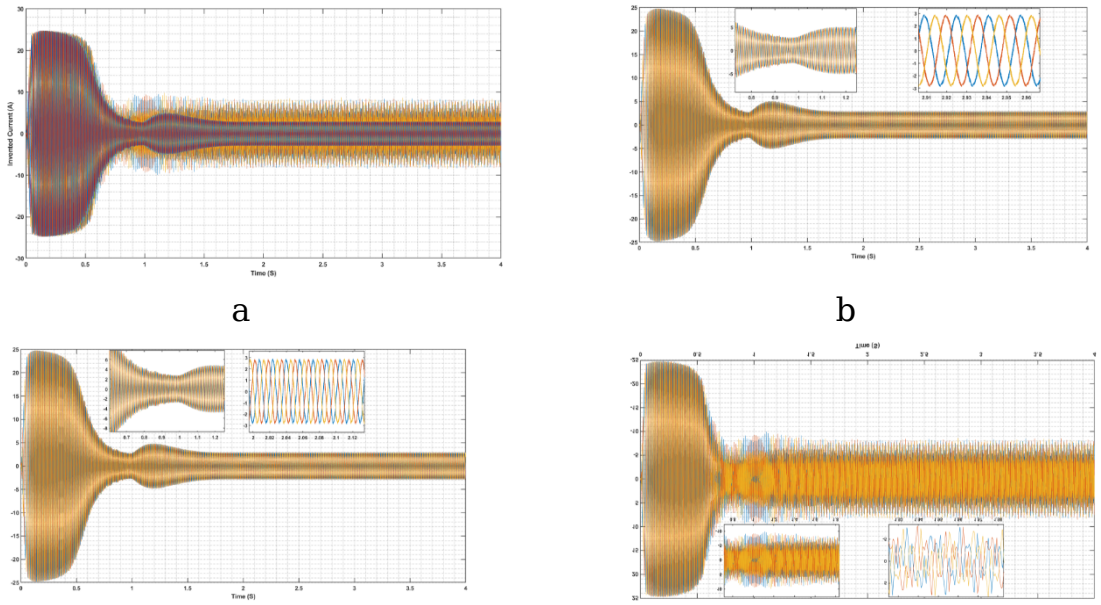
In summary, the inverter voltage produced with the STHVO method demonstrates superior performance in terms of stability, waveform quality, and dynamic response, making it well-suited for solar water pumping applications in grid-connected systems.

- **The Output Current of the Inverter**

Fig.13.a displays the three-phase inverter output current waveforms generated using three MPPT techniques: STHVO, Modified ABC, and INC. Initially, all approaches experience transient fluctuations before settling. However, the shape, amplitude symmetry, and level of distortion vary noticeably between methods. The INC technique, in particular, shows irregular oscillations during the steady-state period, which may negatively impact load behavior and system efficiency.

Fig.13.b provides a zoomed view of the inverter current response when the proposed STHVO algorithm is applied. It reveals a clean, sinusoidal waveform across all three phases, with minimal distortion and quick convergence to steady-state. The balanced amplitude and phase separation

confirm proper synchronization, reflecting the effectiveness of the STHVO method in managing real-time current regulation.



a b c d

Fig.13. Three-phase inverter output current waveforms: (a) all MPPT methods, (b) STHVO, (c) Modified ABC, and (d) INC.

Overall, the inverter current achieved using the STHVO method demonstrates excellent waveform quality and dynamic performance, confirming its ability to ensure stable and efficient power delivery particularly important in solar pumping applications where current distortion can compromise motor operation.

- **Induction motor**

The induction motor functions by generating a rotating magnetic field in the stator. This field interacts with the rotor, inducing an electric current that drives its rotation and produces the required mechanical motion. This dynamic is reflected in the simulation results, where the rotor speed evolution is shown in Fig.14 and the torque applied by the pump is illustrated in Fig.15.

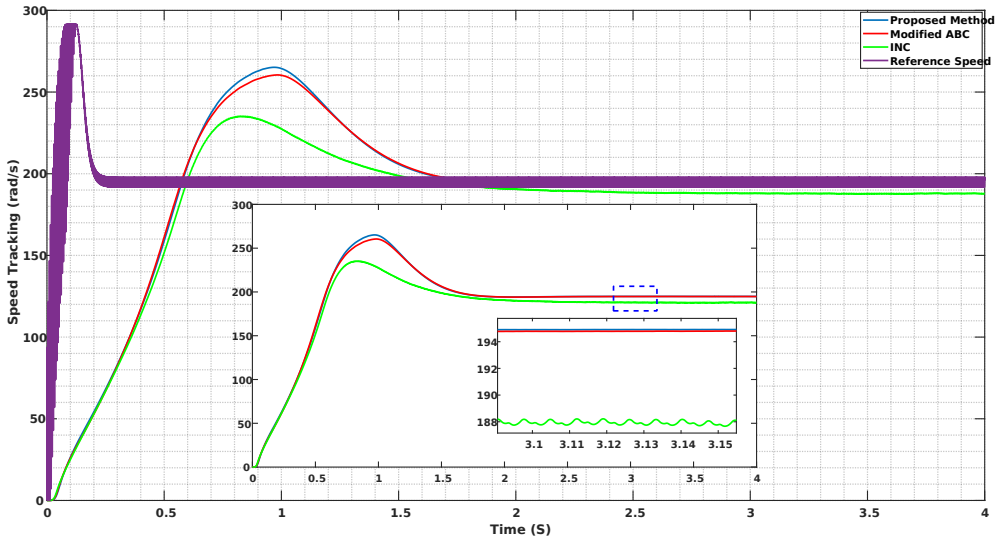


Fig.14. Rotor speed response of the induction motor under different MPPT methods.

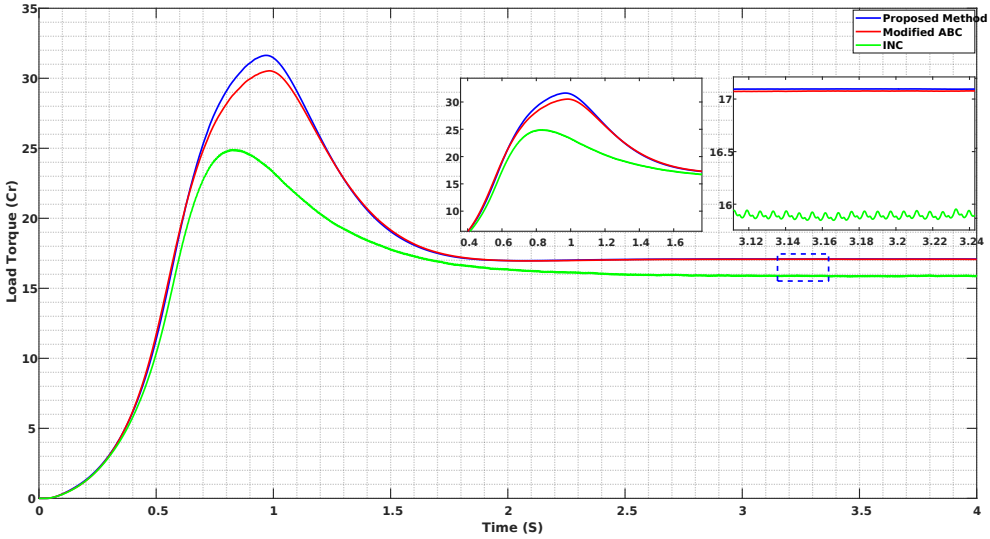


Fig.15. Load torque response under different MPPT methods

The dynamic behavior of the induction motor is evaluated using rotor speed and load torque, as shown in Figs.14 and 15, and detailed in Table 6. The proposed MPPT method (STHVO) exhibits a fast and stable response in both variables, outperforming the Modified ABC and INC methods.

In terms of rotor speed, the proposed strategy ensures rapid convergence to the reference value (195 rad/s in 0.6s) with minimal oscillations, reflecting better dynamic control. For load torque, it achieves a peak of approximately 32 Nm and stabilizes around 17.2 Nm, which indicates efficient energy transfer from the PV source to the mechanical load.

Compared to the other techniques, the INC method shows slower response and more pronounced oscillations in both speed (188-188.5 rad/s) and torque (15.9-16.2 Nm), while the Modified ABC provides moderate performance.

The results validate the efficacy of the STHVO technique in augmenting motor stability and strengthening the overall performance of the solar pumping system.

Table 6 : Summary of Rotor Speed and Torque Performance

Metric	**STHVO (Proposed)**	**Modified ABC**	**INC**
Speed Response	Fast (0.6s) Very Stable	Moderate Acceptable	Slow Oscillatory
Steady-State Speed	195 rad/s	194.6 rad/s	188–188.5 rad/s
Peak Torque	32 Nm	30 Nm	24 Nm
Steady-State Torque	17.2 Nm	17.18 Nm	15.9 Nm

- **Centrifugal Pump**

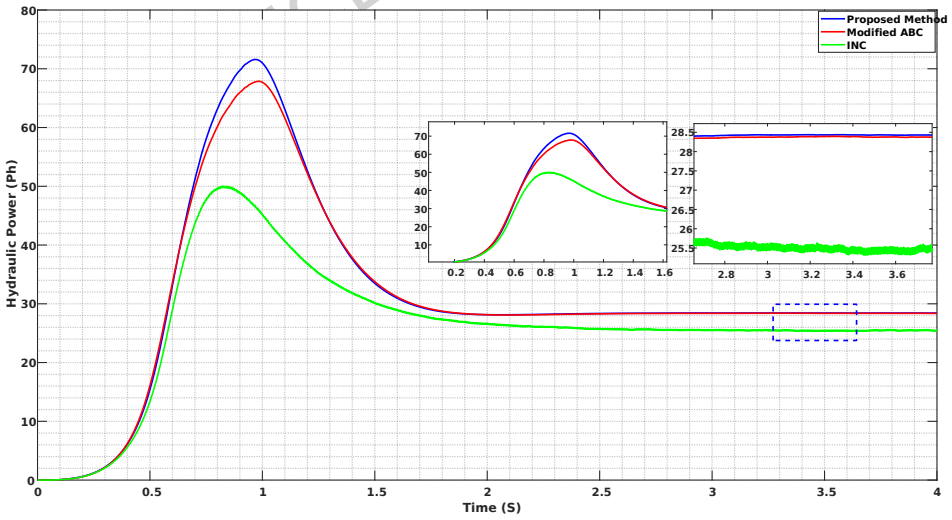


Fig.16. Hydraulic power delivered by the centrifugal pump.

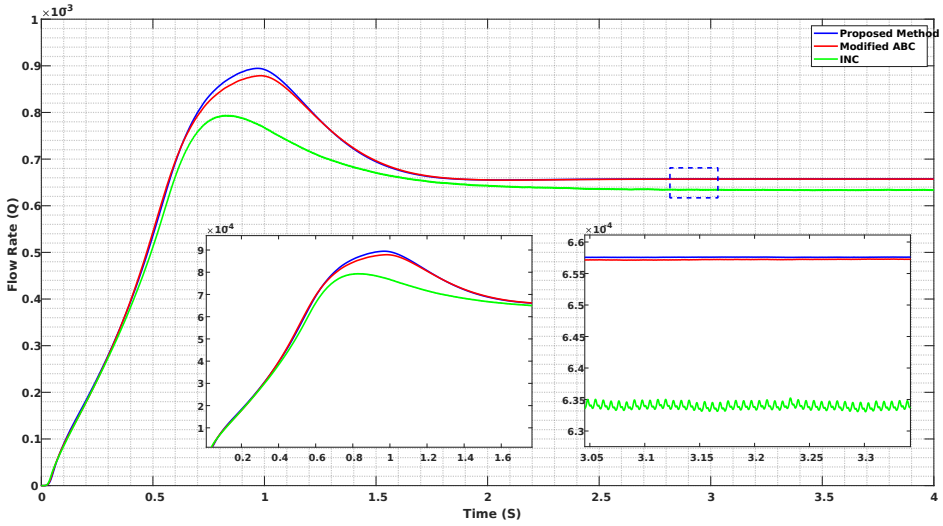


Fig.17.Water flow rate produced by the centrifugal pump.

The centrifugal pump plays a crucial role in converting the mechanical energy provided by the induction motor into hydraulic energy used for water delivery. The performance of the pump is evaluated using two main parameters: flow rate and hydraulic power, illustrated in Figs 16 and 17 and summarized in Table 7.

With the STHVO-based MPPT method, the system achieves a peak flow rate of approximately 0.95 L/s and stabilizes near 0.65 L/s. In terms of hydraulic power, the maximum value reaches 72 W, with a steady-state output around 28.4 W.

The results obtained by the Modified ABC are little suboptimal but reliable. In contrast, INC method shows higher instability and lower maximum peaks with visible oscillations in both hydraulic power and flow.

These findings demonstrate the greater ability of STHVO algorithm to keep the pump performance stable and constant despite high variations on the solar irradiance.

Table 7: Comparison of Flow Rate and Hydraulic Power Performance

Metric	**STHVO (Proposed)**	**Modified ABC**	**INC**
Peak Flow Rate	0.9 L/s	0.88 L/s	0.78 L/s
Steady-State Flow Rate	0.65 L/s	0.63 L/s	0.65-0.63 L/s

Peak Hydraulic Power	72 W	68 W	50 W
Steady-State Hydraulic Power (INC): W	28.4 W	28.45 W	25.3 W

4.3 Limitations and Future Work

The present study focuses on a simulation-based assessment because the experimental phase of the project has not yet been launched. Developing a complete solar water-pumping platform,where the PV source, the power-conditioning stage, the motor drive, and the hydraulic load operate together as an integrated system requires several elements to be prepared, calibrated, and validated. Establishing such an experimental setup constitutes a separate phase of the project and demands technical preparation, equipment coordination, and safety verification. For this reason, the current work concentrates on numerical modeling as an essential preliminary step, while the hardware stage will be undertaken once the full platform is ready for laboratory operation.

Although the proposed STHVO-based MPPT strategy has been extensively evaluated through MATLAB/Simulink simulations, some limitations remain. The simulation environment, while detailed, cannot fully reflect real-world non-idealities such as switching noise, sensor inaccuracies, electromagnetic interference, and temperature-dependent parameter variations. These factors may influence the electrical and mechanical behavior of the PV system and affect the controller’s response under practical conditions [65]. Furthermore, the interaction between the DC–DC converter, the induction motor, and the centrifugal pump involves nonlinear dynamics that are difficult to reproduce with high precision in simulation. Elements such as hydraulic losses, startup transients, and variations in pump head can alter the operating point and impact MPPT performance.

Another limitation concerns real-time implementation. When deployed on embedded hardware, constraints such as limited processing capability, ADC resolution, quantization noise, and timing jitter may affect

convergence speed and steady-state accuracy. These aspects require additional investigation before field deployment [66].

Future work will therefore address the development of a laboratory prototype integrating the PV generator, the DC–DC converter, the embedded STHVO controller, and the motor–pump subsystem. Experimental tests will be conducted first under controlled indoor conditions and subsequently in outdoor environments with naturally varying irradiance. Additional research will examine the robustness of the controller under measurement noise, rapid irradiance transitions, and partial shading, and will explore the extension of STHVO toward multi-objective optimization to improve both electrical output and hydraulic performance.

Conclusion

This study introduced STHVO, a bio-inspired MPPT method designed to improve the efficiency and operational stability of photovoltaic-powered water pumping systems. By drawing inspiration from natural predation dynamics, the algorithm provides a balanced compromise between rapid convergence, robustness, and steady performance under varying environmental conditions.

The proposed method was benchmarked through extensive MATLAB/Simulink simulations and demonstrated superior performance compared to traditional approaches such as INC and modified ABC. Under standard test conditions, STHVO achieved a response time of 0.19 seconds and an efficiency of 98.92%. Its robustness was further confirmed using real irradiance profiles from the Bni Hadifa region, where significant solar variability occurs due to mountainous terrain. The algorithm maintained stable power output, demonstrating strong adaptability to realistic disturbances.

At the system level, STHVO supported stable induction motor and centrifugal pump operation, ensuring reliable water delivery in grid-connected settings. Beyond this specific application, the flexibility of the

algorithm suggests its potential applicability to autonomous control systems, electric mobility, and hybrid renewable-energy networks, particularly when integrated with predictive models or data-driven techniques.

Declaration of Competing Interest

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

Data availability Statement

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

CRediT authorship contribution statement

Abdelkarim Ballouti, Mohamed Chouiekh: Conceptualization, Formal analysis, Software, Writing original draft.

Hatim Ameziane, Alia Zakriti, Youness El Mourabit: Methodology, Project administration, Supervision, Validation, Writing – review & editing.

Nebojsa Bacanin, Bosko Nikolic, Hicham Karmouni and Mohamed Abouhawwash: Data curation, Funding acquisition, Resources, Investigation, Visualization.

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