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MAXIMIZING PV POWER EFFICIENCY USING SEAGULL OPTIMIZATION TECHNIQUE WITH HIGH-GAIN VOLTAGE-MULTIPLIER QUADRATIC BOOST CONVERTER

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Abstract

Maximum Power Point Tracking (MPPT) techniques is efficient technique implemented high photovoltaic power generation in modern power system. This paper will present a MPPT strategy with a Seagull Optimization Algorithm (SOA)-based strategy and high-gain Voltage-Multiplier Coupled Quadric Boost Converter to implement a high-efficiency power extraction in PV systems. The SOA takes advantage of the hunting nature of seagulls so that the operating point of the PV array can be optimised and that the global maximum power point can be reached within seconds even in dynamic irradiance and temperature conditions. Combining this smart MPPT approach with a high-gain quadratic boost converter can achieve large voltage step-up on low PV input to decrease converter stress and increase energy harvesting. Through simulation, the proposed method proves to have a higher tracking speed, efficiency, and stability relative to existing ones (Perturb and Observe) (P&O) and Incremental Conductance (IncCond). The SOA-based MPPT is able to effectively prevent local maxima under partial shading conditions to generate optimal power extraction. The offered system demonstrates the high increase in the general energy efficiency, and it can be applied to both grid-connected and stand-

alone PV applications. This combination of smart optimization and sophisticated converter design offers a potential remedy on the extraction of the best performance of a PV system under real operating conditions.

Keywords : Photovoltaic Systems, MPPT, Seagull Optimization Technique, High-Efficiency Power Extraction , High-Gain Quadratic Boost Converter

I. Introduction

The increasing global demand for renewable energy sources has placed photovoltaic (PV) systems at the forefront of sustainable power generation due to their environmental friendliness, scalability, and minimal operational costs. However, the efficiency of PV systems is inherently limited by factors such as varying solar irradiance, temperature fluctuations, and partial shading, which can prevent the system from operating at its maximum power point (MPP). To address this challenge, Maximum Power Point Tracking (MPPT) techniques have been widely adopted to continuously adjust the operating point of PV arrays for optimal power extraction. Conventional MPPT methods, including Perturb and Observe (P&O) and Incremental Conductance (IncCond), while simple to implement, suffer from drawbacks such as slow response, steady-state oscillations, and susceptibility to local maxima under non-uniform irradiation conditions.

In recent years, nature-inspired optimization algorithms have emerged as robust alternatives for MPPT due to their global search capabilities, adaptability, and ability to efficiently track the true MPP under dynamic environmental conditions. Among these, the Seagull Optimization Algorithm (SOA) has shown remarkable promise by mimicking the cooperative hunting and migration behavior of seagulls to balance exploration and exploitation, thereby achieving faster convergence and avoiding local optima. Integrating SOA-based MPPT with advanced power electronic converters further enhances the overall system efficiency. Specifically, high-gain Voltage-Multiplier Coupled Quadratic Boost Converters have been developed to overcome low-voltage PV outputs, enabling significant voltage step-up with minimal switching stress and reduced losses. The combination of intelligent MPPT algorithms with high-gain converter topologies ensures not only precise tracking of the MPP under varying conditions but also higher energy harvesting, improved voltage regulation, and reduced harmonic distortions in the power output. This synergy between optimization-based MPPT and high-gain boost conversion presents a compelling solution for maximizing PV system performance in both grid-connected and standalone applications. Consequently, this study focuses on the design, simulation, and performance evaluation of an SOA-based MPPT strategy integrated with a high-gain Voltage-Multiplier Coupled Quadratic Boost Converter, highlighting its effectiveness in achieving high-efficiency power extraction under diverse environmental and operational scenarios.

Recent advancements in maximizing photovoltaic (PV) power efficiency have focused on integrating high-gain DC–DC converter topologies with intelligent and nature-inspired optimization algorithms to ensure robust maximum power point tracking (MPPT) under partial shading and variable environmental conditions. Al-Samawi et al. developed an interleaved boost converter combined with fuzzy logic for optimizing power under partial shading, showing improved dynamic response and reduced ripple loss in PV systems [I]. Valarmathy and Prabhakar provided an extensive review of interleaved high-gain DC–DC converter architectures, highlighting voltage multiplier and quadratic boost techniques essential for optimizing PV power extraction under fluctuating conditions [II]. Ganthia et al. analyzed fuzzy logic-based MPPT control techniques, demonstrating enhanced tracking accuracy in non-linear PV characteristics under variable irradiance [III], while another study by Ganthia et al. implemented DVR compensation using PI controllers, improving voltage stability and quality in PV-integrated distribution networks [IV]. Chakole et al. introduced Markov Decision Processes for optimal hybrid PV–wind–battery microgrid energy management, highlighting decision-based adaptive optimization strategies for power balancing [V]. Chalh et al. proposed the seagull optimization algorithm for MPPT, showcasing outstanding performance in global peak tracking under partial shading compared to PSO and GA [VI].

Emeghara et al. designed a high-gain fifth-order boost converter for two-stage PV systems, demonstrating significantly improved voltage amplification suitable for advanced MPPT integration [VII]. Ganthia et al. examined experimental thermal management techniques using water cooling and color filters to enhance PV efficiency by reducing temperature-induced losses [VIII]. Reddy and Vijayaraj applied hybrid deep learning with bitterling fish and secretary bird algorithms for optimizing interleaved high-gain converters, enhancing power efficiency under renewable scenarios [IX]. Daulat et al. utilized dynamic grey wolf optimization for filter bank parameter tuning, illustrating the importance of adaptive metaheuristic strategies for power optimization systems [X]. Rajaram and Kannan developed adaptive pufferfish-optimized MPPT and DC–DC boost converters, proving better stability, voltage gain, and convergence rate under partial shading [XI], and Soma et al. introduced the Giza Pyramid Construction Algorithm for MPPT, validating high precision and tracking speed in partially shaded PV environments [XII]. Marlin and Jebaseelan presented a comparative analysis of intelligent optimization algorithms, confirming the superiority of hybrid and swarm-based algorithms for MPPT and power tracking [XIII]. Mohanty et al. demonstrated Dynamic PSO with ESC for power smoothing in PV systems under shading, highlighting robust convergence and reduced oscillations at MPP [XIV].

Li et al. developed chaos quantum adaptive seagull optimization, improving convergence speed, constraint handling, and global search adaptability for complex systems [XV]. Sahu et al. designed a multiphase interleaved boost converter with high gain and low ripple, ideal for PV-based DC link voltage enhancement applications [XVI]. Rubavathy et al. applied smart grid-based multi-agent systems for energy coordination, supporting integration of intelligent optimization in PV applications [XVII]. Horng and Lin incorporated seagull optimization into ordinal optimization to solve constrained binary simulation problems, showing strong feasibility in restricted solution spaces [XVIII]. Chakraborty and Kumar developed switched inductor quadratic boost converters with high gain potential, suitable for integration into MPPT-based PV conversion systems [XIX]. Sourya Kumar et al. designed multistage switched-capacitor quadratic boost converters with dual outputs, offering improved gain and efficiency for solar PV applications [XX]. Pathak et al. conducted a comprehensive survey on seagull optimization algorithms and variants, illustrating their wide applicability to renewable energy optimization problems [XXI], and Li et al. proposed a multi-strategy improved seagull optimization algorithm with enhanced exploration, convergence precision, and robustness in renewable-based optimization models [XXII].

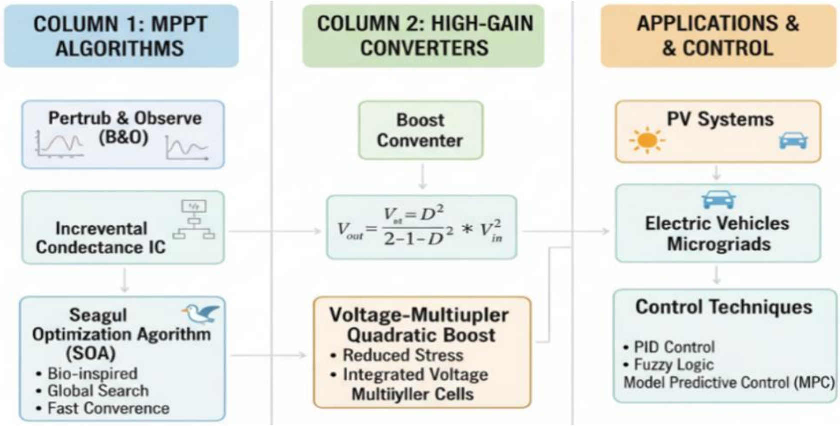


Fig. 1. Literature review of the proposed study

Figure 1 illustrate the literature review of the proposed study which highlights enhanced Maximum Power Point Tracking (MPPT) of photovoltaic (PV) systems has been the subject of a lot of research in recent times, especially when the systems are subjected to adverse environmental conditions like partial shading and varying irradiance [VII].

II. Modelling of Photo Voltaic System

The growing demand of energy source in the world and renewable energy has placed the photovoltaic system (PV system) as an essential technology in generating energy in a sustainable manner. Most of these systems will, however, not always achieve their maximum power output (MPP) under varying solar irradiance, temperature, and shading conditions due to nonlinear current-voltage (I-V) qualities of PV modules. In order to overcome this challenge, maximization of power output by PV arrays in dynamic environment will be realized through the use of Maximum Power point Tracking (MPPT) techniques. Conventional MPPT like Perturb and Observe (P&O) or Incremental Conductance (Inc-Cond) has been extensively used because of its simplicity, however they tend to oscillate near the MPP, have slower convergence and lower tracking performance when in fast changing weather. In order to escape these shortcomings, there is recent progress in such directions as intelligent algorithms and optimization-based approaches, which can be used to increase tracking efficiency, stability, and robustness which promises better power harvesting of people on PV systems.

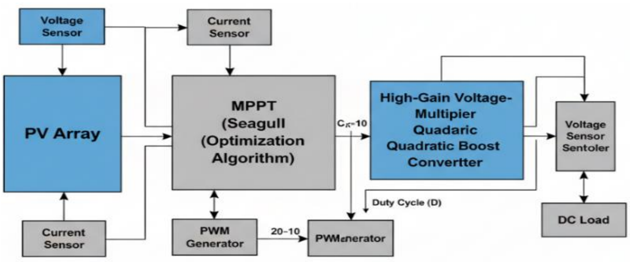


Fig. 2. Block diagram of proposed research design

Figure 2 illustrates the photovoltaic (PV) system with a controller utilizing Seagull optimization algorithm (SOA)-based Maximum power point tracking (MPPT) and an application of a boost converter to achieve higher power its derivation. Passing current-voltage (I-V) and power-voltage (P-V) characteristics, the PV array produces a Talent Precautions Plc output based on the current solar irradiance and temperature. Signals of voltage/current are sensed and forwarded to the MPPT controller that uses SOA to ascertain the most desirable duty cycle. The initial stage of SOA process is the initialization where a population of possible solutions (so called seagulls) is created. These solutions explore by (migration) (often) searching the operating space with promising points, and exploiting (attacking) to narrow down on the global maximum power point (GMPP). The optimal duty cycle is the best solution, and is applied to drive the boost converter through PWM signals. The boost converter is a device of conversion which acts as an interface, increasing the voltages and controlling the currents to the needs of the load or the grid. This makes the system to be continuously ramp to its MPP even when partially shaded and when the environmental conditions changes. Correctness and stability Since the SOA-based MPPT is a powerful and adaptive means of controlling the high-efficiency energy harvesting in the PV system, the feedback loop provides the system correctness and stability.

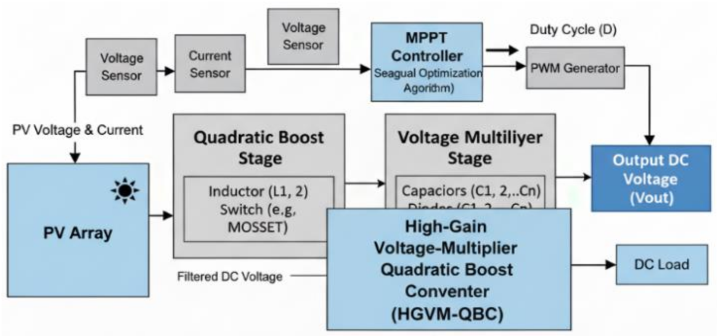


Fig. 3. Operation principle of proposed study

Figure 3 illustrates the MPPT algorithms combined with DC-DC converters, and boost converter is one of them, the most popular kind of topology. The boost converter is a device used to provide a linkage between the PV array and the load/grid that amplifies the voltage but keeps the current at optimal levels in order to attain optimal energy transfer. Using the MPPT control signals to adjust the duty cycle dynamically, makes the bust converter allows the operating point of the PV array to be always optimized to the MPP. Not only does this integration enhance voltage control, but it also eliminates the wastage of power that results in a higher efficiency of this system in its entirety. It is therefore critical that an appropriate model of the PV system, as well as the advanced MPPT and boost converter control, should be used to achieve high-efficiency generation of solar power and the ability to operate with confidence in standalone and grid-connected systems with PVs.

The current of a solar cell can be modeled as:

$$I = I_{ph} - I_0 \left[exp\left(\frac{q(V+IRs)}{nkT}\right) - 1\right] - \frac{V+IRs}{Rs} \quad (1)$$

where: I = PV cell output current (A)

I_{ph} = photocurrent proportional to irradiance

I_0 = diode saturation current

q = electron charge (1.6×10^{-19} C)

V = output voltage (V)

Rs and Rsh = series and shunt resistances

n = ideality factor

T = temperature (K)

The instantaneous power delivered by a PV cell is:

$$P=V\times I \quad (2)$$

This forms the basis of P–V characteristics, essential for MPPT and UPQC reference generation.

At the Maximum Power Point (MPP):

$$\frac{dP}{dV} = \frac{d\,(VI)}{dV} = I + \frac{dI}{dV} \quad (3)$$

This equation is used in Incremental Conductance (IC) MPPT algorithms.

Power Balance in Grid-Connected PV with filter:

$$P_{PV} = P_{Load} + P_{loss} + P_{Filter} \quad (4)$$

where: P_{PV} = power generated by PV

P_{Load} = load demand

P_{Loss} = system and conversion losses

P_{Filter} = power handled by filter (for harmonics)

Harmonic distortion in PV-inverter output is quantified as:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V1} \times 100\% \quad (5)$$

where: V1 = RMS value of fundamental voltage & Vn = RMS value of nth harmonic component

The electrical behavior of a solar cell is commonly described using the single-diode model, where the output current I is expressed as the difference between the photocurrent I_{ph}, which depends on irradiance, and the diode and resistive losses. This is captured in equation (1), which incorporates key parameters such as diode saturation current (I_0), ideality factor (n), temperature (T), and resistances (R_s and R_{sh}). The instantaneous power of the PV cell, given by equation (2), is the product of voltage and current, forming the foundation of the characteristic P–V curve used for MPPT analysis. At the Maximum Power Point (MPP), the derivative condition in equation (3) holds, which is the basis of the Incremental Conductance (I_C) method for real-time tracking. For grid-connected PV systems, power balance must be maintained, as defined in equation (4), where PV generation equals the sum of load demand, conversion losses, and filter power used for harmonic mitigation. The quality of the inverter output is assessed through the Total Harmonic Distortion (THD) given by equation (5), which quantifies deviations from the ideal sinusoidal waveform. Collectively, these equations establish the mathematical framework for PV system modeling, MPPT control, and power quality management.

III. Proposed High-Gain Voltage-Multiplier Quadratic Boost Converter

It has turned out to be a useful solution to the low-voltage output of photovoltaic (PV) systems with High-Gain Voltage-Multiplier Quadratic Boost Converters (HGVM-QBC) being an attractive alternative to the Maximum Power Point Tracking (MPPT) methods in systems operating at low voltages. Traditional types of boost converters are limited by voltage gain and efficiency particularly at low irradiance or partial shading. The upgrade of the quadratic boost converter topology with a voltage multiplier network achieves a large step-up in voltage without extreme duty cycles, lessening the load on the power switches and increasing the overall reliability. In this design, the capacitors and inductors are well spaced to attain a quadratic relationship between the voltage and the gain resulting in a large voltage being generated compared to the input voltage, but with high efficiency.

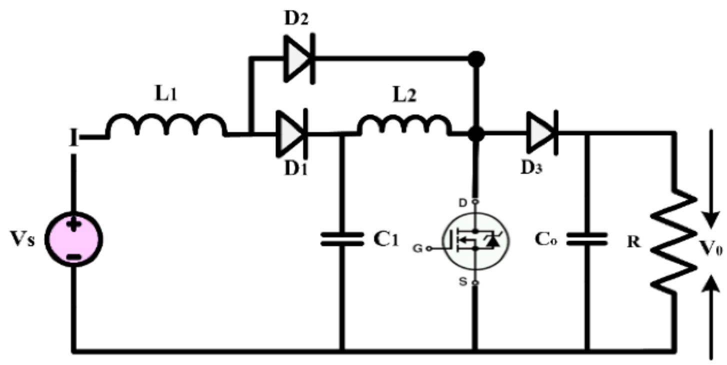


Fig. 4. Structure and construction block diagram of HGVM-QBC

The HGVM-QBC illustrated in figure 4 show the construction and operation, when combined with intelligent MPPT algorithms, e.g. the Seagull Optimization Algorithm (SOA), allows the global maximum power point to be accurately tracked in the dynamic environmental conditions. The high-gain of the converter means that even low voltage PV arrays can provide the necessary voltage to be used in a grid-connected application or standalone use, enhancing energy harvesting efficiency. The voltage-multiplier structure also lowers the conduction and switching losses, minimizes voltage ripple, and lowers power quality at the output. The design is modular, which can be scaled and applied in small residential PV systems and their large solar installations. With a combination of HGVM-QBC and optimization-based MPPT algorithms, PV systems will converge quicker to the maximum power point, operate at stable conditions due to partial shading, and optimize the extraction of energy. High-gain conversion together with intelligent control has made the HGVM-QBC an exciting solution in the next-generation high-efficient PV systems with a balance of performance, reliability and adaptability. In PV applications, the output voltage of solar panels is generally low and varies with sunlight, temperature, and load. To ensure maximum power extraction, MPPT techniques are used in combination with advanced converters like HGVM-QBC. In mode (a), the switch and diodes operate in such a way that energy is stored in inductors L1, L2 and capacitor C1, while auxiliary diodes control current flow. In mode (b), when the switch is turned ON, the input voltage charges the inductors and capacitor, preparing for energy transfer. In mode (c), during switch OFF, stored energy in inductors and capacitors is released through resonant components (Lr, CM1, CM2) into the output capacitor C0, thereby boosting voltage. Modes (d) and (e) continue this process with different diodes conducting, ensuring continuous transfer of energy to the load RL. The converter effectively multiplies voltage gain using resonant and multiplier capacitors, reducing stress on switches and diodes. This high-gain structure allows the PV system to step up low solar voltage to a stable, high-level DC output required for loads or grid connection.

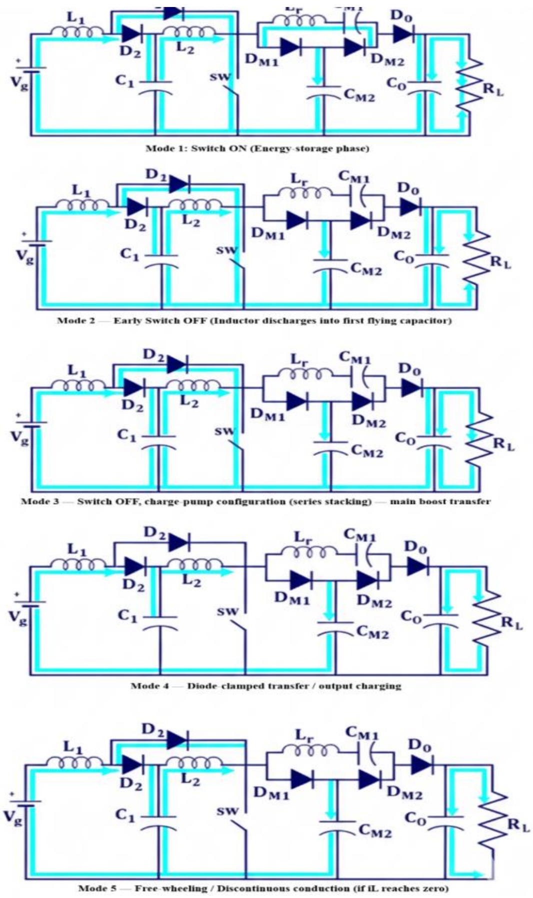


Fig. 5. Working modes of HGVM-QBC in PV system for MPPT

The figure 5 illustrates the 5 working modes of principle of the High-Gain Voltage Multiplier Quasi Boost Converter (HGVM-QBC) applied in a photovoltaic (PV) system for Maximum Power Point Tracking (MPPT). Thus, HGVM-QBC ensures efficient MPPT by adapting to changing PV conditions while minimizing power losses.

Notation: (single-inductor VM quadratic boost topology):

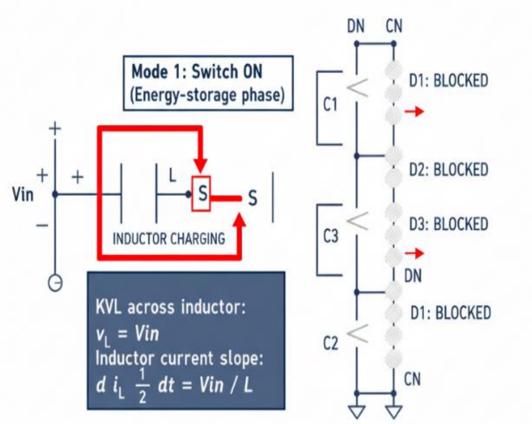
Vin: PV / input voltage (measured at converter input)

L: power inductor, iL(t) its current

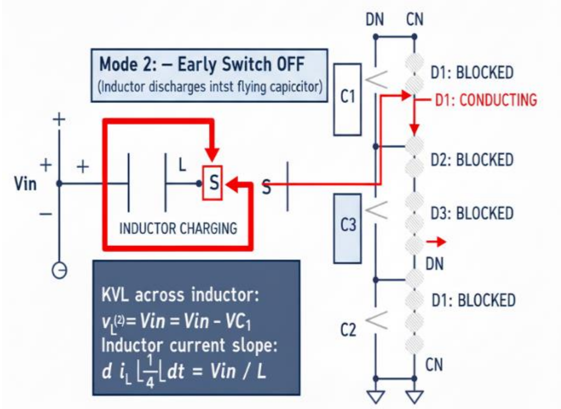
C1, C2: flying (multiplier) capacitors with voltages VC1(t), VC2(t), Co: output capacitor, Vo(t) output voltage, Io output current (load), D: steady-state duty cycle of the switch SSS, switching period Ts

Diodes numbered D1, D2, D3, D4 (direction chosen to form the pump/multiplier)

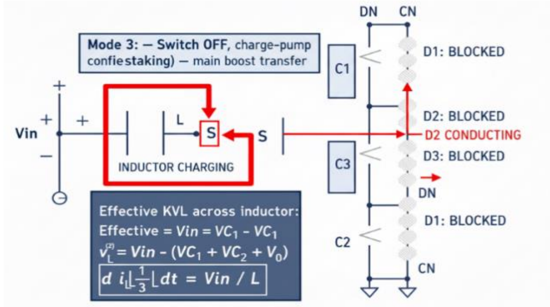
Ideal components unless noted; signs follow passive sign convention. Small-signal effects omitted here (these are large-signal interval equations).



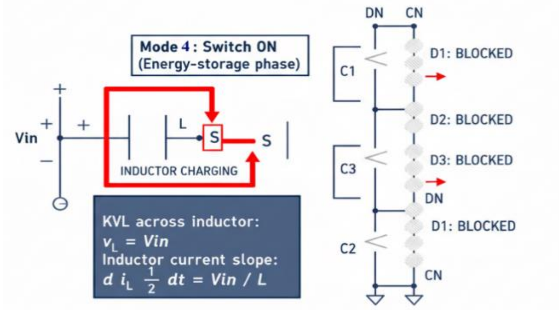
Mode 1: Switch ON (Energy-storage phase)



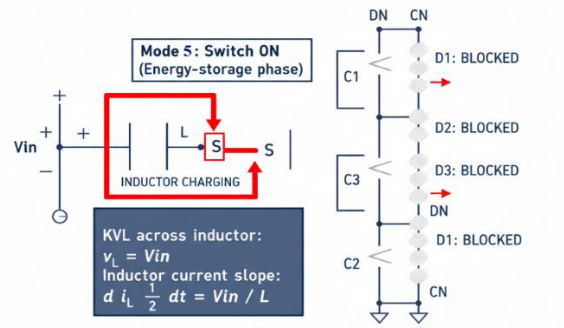
Mode 2: Early Switch OFF (Inductor discharges into first flying capacitor)



Mode 3: Switch OFF, charge-pump configuration (series stacking) main boost transfer



Mode 4: Diode-clamped transfer / output charging



Mode 5: Free-wheeling / Discontinuous conduction (if iL reaches zero)
Fig. 6. 5 modes of operation with switching actions

Figure 6 demonstrates the 5 operating modes of High-Gain Voltage-Multiplier Quadratic Boost Converter (HGVM-QBC). Mode 1 In Mode 1, the switch is ON and the input inductor is coupled to the source storing the energy and the output capacitor provides the load alone. Mode 2 In Mode 2, when the switch is switched off the inductor empties into the first flying capacitor voltage boosting it to a higher voltage. Mode 3 uses the circuit as a charge pump, the voltages across the flying capacitors, input, and inductor are in series, and produces the main quadratic boost effect. Mode 4 operates in a diode conduction mode with the stacked voltages being passed to the output capacitor and therefore, charging the output with the overall energy of the input, inductor, and flying capacitor. In Mode 5, lastly, when the inductor current is brought to zero the converter switches to a freewheeling or discontinuous conduction mode, during which the load is only provided by the output capacitor until the next switching cycle occurs. These successive modes illustrate the co-ordination of switching, capacitor stacking and diode paths to give high step-up voltage gain.

IV. Seagull Optimization Technique for MPPT

The photovoltaic (PV) need to use efficient Maximum Power Point Tracking (MPPT) methods to achieve full control over extracting energy at different environmental conditions which include irradiance, temperature etc. The most common MPPT techniques are the Perturb and Observe (P&O) and the Incremental Conductance (INC), which are usually applicable because of their simplicity. These methods/techniques however are limited in that they vibrate about the maximum power point (MPP), they can vary slowly to the rapid environmental variations and can operate poorly under partial shading whereby the power-voltage (P-V) characteristic of the PV array array has numerous local maxima. In order to deal with these issues, MPPT uses have been proposed to bio-inspired optimization algorithms. The Seagull Optimization Algorithm (SOA) has a great potential among them. Saga takes inspiration to foraging and attacking of the seagulls, the strategy of exploration and exploitation are used. Exploration broadly covers the solution space whereas exploitation narrows down the search to the global optimum. This two-fold ability enables SOA to identify the global MPP successfully even with the multifaceted P-V curves triggered by partial shading without risk of getting stuck into the local maxima. Under SOA-based MPPT, both PV voltage and current are under continuous feedback into the algorithm, which tightens or loosens the DC-DC boost converter duty cycle in loops over an iterative process. Based upon the resulting values of PV actual power output, an algorithm adjusts the operating point to approach the global MPP. It leads to the better collection of energy, minimized oscillations, and quick reaction to ecological changes as opposed to traditional approaches. All in all, SOA implementation into the PV systems also increases efficiency and reliability of the systems and offers a solid answer to the high requirements of power production. Its smart searching quality is capable of providing utmost use of energy when there is dynamism; this attribute of SOA-based MPPT makes the given application a strong approach to use in the present-day PV systems.

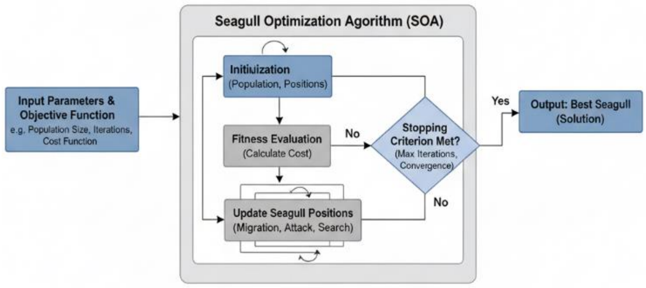


Fig. 7. Block diagram of Seagull Optimization Algorithm (SOA)

The figure 7 represents the block diagram of the MPPT technique based on photovoltaic (PV)-based SOA and includes SOA of photovoltaic process in the diagram. It depicts how the operations would run in that the initial action is the PV array, the irradiance, and temperature decide the I-V and P-V curves. The unit measures the voltage and the current to obtain power and feeds it into the SOA controller. The algorithm is initialized by the block which sets the parameters of the algorithms and then migration phase ensues which allows exploration over multiple duty cycle choices and the local exploitation phase which allows the local exploitation of the best introduced solution. Fitness maximization maximizes efforts to achieve power, and the duty cycle is modified to energize the DC-DC performer converter, which gets offered with PV voltage and provides as much power as achievable to the load/grid. This closed-loop mechanism enables velocities, precise and solid following over of the international optimum power point in various irradiance and impenetrable circumstances. The equations shown below to analysis and design the proposed controller for MPPT action in PV system.

PV single-diode I–V model (for cell/module behavior used by the MPPT objective):

$$I = I_{ph} - I_0[exp(\frac{q(V+IR_{sh})}{nkT})-1] - \frac{V+IR_s}{R_{sh}} \quad (6)$$

where I is cell current, V cell voltage, I_{ph} photocurrent, I_0 saturation current, R_s and R_{sh} series/shunt resistances, n, k, T standard constants/parameters.

Instantaneous output power (objective to maximize):

$$P(V) = V \cdot I(V) \quad (7)$$

Fitness function for SOA (maximization of power):

$$f(x) = P(V(x)) \quad (8)$$

where x is a candidate solution (reference voltage) and $V(x)$ to PV operating voltage.

Population initialization (duty or voltage domain):

$$x_i^{(0)} = x_{min} + r_i(x_{max} - x_{min});\ r_i \sim U(0,1),\ i = 1,\dots,N \quad (9)$$

with N seagulls, bounds $[x_{max} - x_{min}]$

Distance (encircling prey / best) at iteration t:

$$D_i^{(t)} = \left| X_{best}^{(t)} + X_i^{(t)} \right| \quad (10)$$

where $X_{best}^{(t)}$ is the best solution so far.

Migration (exploration) update rule that directed movement toward the best with adaptive scaling $A(t)$ and collision avoidance factor C_i:

$$X_i^{(t+1)} = X_{best}^{(t)} + A(t)\, C_i D_i^{(t)} \quad (11)$$

where $A(t)$ controls step magnitude and C_i is a small random coefficient modeling collision avoidance/perturbation.

Adaptive step/control coefficient (linearly decreasing to favor exploitation later):

$$A(t) = 2(1-\frac{t}{T_{max}}) \quad (12)$$

with t current iteration and T_{max} iterations (so A decreases from 2 → 0).

Attack (exploitation) the spiral approach to emulate seagull diving (mixing spiral and radial move):

$$X_i^{(t+1)} = X_{best}^{(t)} + D_i^{(t)} e^{bl} cos(2\pi l) \tag{13}$$

where b is a constant controlling spiral tightness and $l \in [-1,1]$ is a random scalar (different l each update).

Exploitation switching (probabilistic choice between migration and attack):

$$X_i^{(t+1)} = \begin{cases} Eq. 11\ (migration), if\ r < p(t) \\ Eq. 12\ (attack), if\ r \geq p(t) \end{cases} \qquad r \sim U\,(0,1) \tag{14}$$

with $p(t)$ a probability ($p(t) = 0.5\,(1-t/T_{max})$) or any schedule that reduces exploration over time).

Boundary handling and mapping to MPPT actuator (duty ratio D clamped and converted to PWM):

$$x_i^{(t+1)} \leftarrow \text{clip}\,(x_i^{(t+1)}, x_{min}, x_{max}); \tag{15}$$

$$\text{D} = \frac{x_i^{(t+1)} - x_{min}}{x_{max} - x_{min}} \tag{16}$$

where *clip* enforces bounds and D ∈ [0,1] is converted to PWM duty.

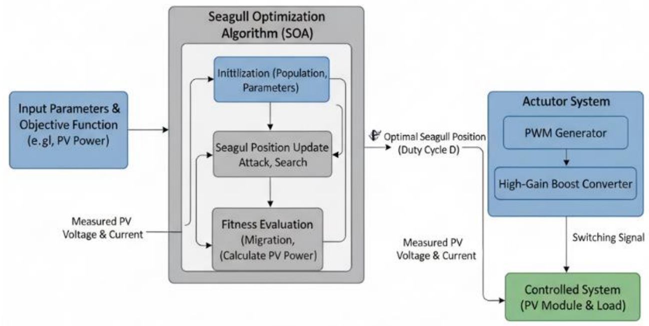


Fig. 8. Block diagram of Seagull Optimization Algorithm (SOA) with Actuator System

The block diagram in figure 8 illustrates the systems of the Seagull Optimization Algorithm (SOA)- based MPPT system coupled with an actuator system, the PV system produces current and voltage signal, which is continually measured and sent to the SOA controller. The controller uses the optimization process which is motivated by the behavior patterns of seagulls which can be compared against migration and attack to come up with the most suitable operating point which exploits the most power. The calculated control signal is fed into a control unit called the actuator which varies the duty cycle of a DC-DC converter so as to have a PV array at full power. This closed loop design will enable it to dynamically adjust to changes in irradiance and temperature to enhance the efficiency and stability of this system.

Model the actuator that implements duty command τ as a second-order system with actuator saturation and rate limit:

$$G_a(s) = \frac{K_a}{(\tau_1+1)(\tau_2+1)} \tag{17}$$

Add $\Phi(d)$ penalty or projection when constraints γ violated (overcurrent $I_{PV} > I_{max}$, overvoltage) for actuator control:

$$\Phi(d) = \begin{cases} \gamma_1(I_{PV} - I_{max})^2; & I_{PV} > I_{max} \\ \gamma_2(I_{PV} - I_{max})^2; & I_{PV} < I_{max} \\ 0; & Otherwise \end{cases} \tag{18}$$

The actuator has dynamics that, ensure SOA iteration period T_{iter} respects actuator settling:

$$T_{iter} \geq \kappa\tau_{converter} \qquad \kappa \approx 3-5 \tag{19}$$

Fitness evaluation in the loop (discrete-time iteration):

$$J_i^g = P_{PV}(d_i^g) - \lambda\Phi\,(d_i^g) \tag{20}$$

Update global best:

$$d_i^g = \begin{cases} d_i^{g+1,migration} & with\ prob\ pg \\ d_i^{g+1,attack} & with\ prob\ 1-pg \end{cases} \tag{21}$$

Enforce bounds after update:

$$d_i^g \leftarrow \text{clip}\,(d_i^g, 0, 1) \tag{22}$$

For actuator the Lyapunov candidate and continuous adaptive law (stability-driven):

$$V(t) = \frac{1}{2}\,(\parallel e(t) \parallel^2 + \frac{1}{2\gamma} \parallel W(t) - W^* \parallel_F^2\,; \tag{23}$$

$$\dot{W}(t) = -\gamma x(t)\, e(t)^T - \lambda W(t) \tag{24}$$

where $\gamma>0$ is an adaptation gain, W^* an (unknown) ideal weight; the $-\lambda W$ term is leakage for boundedness.

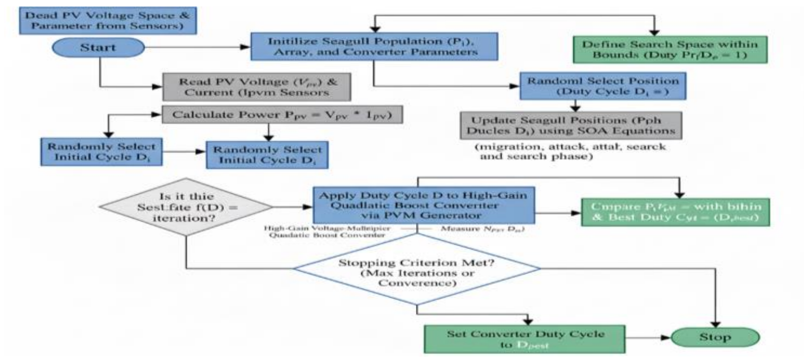


Fig. 9. Flowchart of SOA based MPPT

The flowchart in figure 9 illustrates the implementation of the Seagull Optimization Algorithm (SOA) for Maximum Power Point Tracking (MPPT) in a photovoltaic (PV) system. The process begins with the initialization of algorithm parameters, followed by generating an initial population of seagull agents representing potential solutions. The PV power is then calculated for the current population. A decision point checks whether the maximum number of iterations (Ne = Max_iter) has been reached. If yes, the duty cycle of the boost converter is updated to optimize power extraction; if no, the positions of the seagull agents are updated to search for a better solution. The process repeats iteratively until convergence, after which the algorithm terminates, providing the optimized duty cycle for maximum PV power output. The SOA based MPPT is robust too hard to figure out dynamics in irradiance and complicated shading distributions by switching between these two stages. The sour benefit of SOA-based MPPT is that it is flexible and converges very fast to the actual MPP. In contrast to traditional methods which can settle about the MPP, SOA rapidly stabilizes on the global point, and thus the energy yield of the steady-state can be enhanced. Besides, the algorithm computes efficiently over other metaheuristics, like Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) that in most cases need increased computational power. The mathematical simplicity of SOA is appealing to real-time execution in embedded controllers in PV. It has been demonstrated that SOA-based MPPT can be faster, and more efficient, especially in quickly evolving weather conditions, with conventional MPPT due to the inability to sustain the performance. The MPPT using the Seagull Optimization Algorithm proposes an extremely efficient, but at the same time, natural approach of maximization of the PV system efficiency. Its distinctive migration and attack systems offer a good combination of exploring the globe and being exploitative at the local level thus it finds the global MPP correctly in local partial shading and varying irradiance. SOA with less oscillation, increased response time and simpler computation proves to be an alternative world to competing and other heuristic-based MPPT methods. Since renewable energy systems are required to be increasingly reliable and adaptable, SOA-based MPPT represents an impressive opportunity of increasing the extraction ability of PV systems that will eventually lead to an increase in its energy efficiency and further integration of the solar power into the current grids. SOA working principle involves two major phases which are premised on the seagull behavior, which includes migration and attack. During the migration process, seagulls show spiral flights and collision less floating which have been mathematically modeled in order to mimic exploration within search space. This step helps the algorithm execute a search through a broad solution space and prevent fear Tuareg reed. The action of the seagulls during the attacking stage is a spiral motion through the prey, thus it forms the exploitation process where the search is focused around the optimum candidate solutions. The application of migration process to MPPT enables the system to search several peaks on P-V lane when the process tries to converge to the global MPP, the process is focused on the attacking.

V. Simulink Model and Results

The proposed system has been modeled in MATLAB/Simulink to optimize power output by using a photovoltaic (PV)-array, Seagull Optimization Algorithm (SGA)-based MPPT controller, and a High-Gain Voltage-Multiplier Quadratic Boost Converter (HGVM-QBC) to produce the best power output at different irradiance and temperature levels. A single-diode equivalent circuit is used to model the PV module and produce realistic current & voltage (I V) characteristics that are constantly monitored to deliver input signals (Vpv Ipv) to the MPPT algorithm. The MPPT block based on SGA dynamically optimizes to find the maximum power point by optimizing the duty cycle reference that is fed to a PI control unit to provide smooth duty adjustment and stable operation. This duty cycle signal causes the PWM generator which regulates the main MOSFET of the HGVM-QBC. It is either modelled with averaged equations or a detailed switching network to prove the high-gain nature of the converter in such a way that the extracted PV energy is successfully increased to the required DC-link voltage. The PV output and load feedback loops ensure the stability of the system and make it possible to track the power precisely. In general, the Simulink model offers a full closed-loop method of testing the effectiveness and reliability of the suggested HGVM-QBC with SGA-based MPPT control.

Table 1: Input parameter for the SOA-based MPPT with HGVM-QBC for high-efficiency PV power extraction

Converter Ratings	Switching Devices	Capacitors	Inductors	Irradiance & Temp	PV Module
Vin = 18–36 V	MOSFET Rds_on = 40 mΩ	C1 = 470 µF	L1 = 2 mH	G = 200	Voc_ref = 36 V
Vout = 200 V	Qg = 45 nC	C2 = 470 µF	L2 = 2.5 mH	G = 400	Isc_ref = 5 A
Po = 150 W	Vds = 100 V	C3 = 330 µF	ΔIL < 20%	G = 600	Pmax = 150 W
η > 95%	Id_max = 30 A	C4 = 330 µF	ESR_L1 = 0.01 Ω	G = 800	Ns = 36
Duty D = 0–0.8	Diode Vf = 0.7 V	C5 = 220 µF	ESR_L2 = 0.01 Ω	G = 1000	Np = 1
Gain = 2(2–D)/(1–D)²	Diode Qrr = 50 ns	ESR = 0.02 Ω	Core loss = low	T = 25 °C	Rs = 0.3 Ω
Ripple current <10%	Fsw = 20 kHz	V_rating = 100 V	Rated I = 10 A	T = 30 °C	Rp = 1000 Ω
Load R = 200 Ω	Gate driver = 12 V	Ripple < 5%	Margin = 20%	T = 35 °C	Ideality n = 1.3
Vo ripple <5%	Dead time = 0.2 µs	Lifetime = 2000h	Coupled/sep	T = 40 °C	G_ref = 1000 W/m²
Safe margin 20%	Driver eff = 98%	Cooling = natural	Cooling = passive	T = 45 °C	T_ref = 25 °C

Simulation Setup	PWM & Gate Drive	PI Control Loop	MPPT (SGA)
Ts = 1e-6 s	Fsw = 20 kHz	Kp = 0.05	Pop size = 10
Solver = ode23tb	Carrier = triangular	Ki = 10	Max iter = 20
Tsim = 0.5 s	Duty res = 1%	Anti-windup = yes	A param = 2→0
Step irradiance	Delay = 200 ns	Ts = 50 µs	Crossover prob = 0.7
Step temp	Gate R = 10 Ω	Ref input = Vmp*	Mutation rate = 0.1
Log = Vpv, Ipv	Dead band = 0.2 µs	Output = duty	Vsearch = 0.2Voc–Voc
Scope = yes	Duty offset = none	Limiter = [0,1]	Fitness = P(V·I)
FFT = yes	Sync mode = yes	Soft start = yes	Update step = 1 ms
Eff calc = yes	Driver eff = 98%	PWM sync = yes	Stop tol = 1e-4
Save all data = on	EMI filter = LC	Stable margin 60°	Ref = Vmp

Table1 shows the parameters of modeling and simulating the High-Gain Voltage-Multiplier Quadratic Boost Converter (HGVM-QBC) with MPPT using Seagull Optimization Algorithm (SGA)-based MATLAB/Simulink. It starts with parameters of PV modules, including open-circuit voltage, short-circuit current and series/parallel cell layout, and diode parameters that characterize operating conditions, and then goes on to irradiance and temperature variations. The following rows specify the passive elements of the converter; the inductance and the capacitance of inductors and capacitors, the values, the power and the ripple allowance, and the specifications of switching devices such as the on-resistance of MOSFETs, the diode recovery, the switching frequency, and the driver characteristics. Converter ratings (such as input/output voltage range, duty cycle, power capacity, efficiency, and voltage gain equation) are specified, too. SGA MPPT parameters, which are population size, iterations, mutation, crossover, and voltage search range are incorporated to make sure the maximum power point is optimally tracked. Parameters of the control loop that include parameters of a PI controller (gains, sample time, and anti-windup) and PWM drive parameters (frequency, dead time, resolution, and synchronization) define closed-loop operation. Lastly, solver type, time step, test scenarios and data logging requirements are specified in the simulation setup. The table in its entirety provides that the HGVM-QBC with SGA-based MPPT can be modeled, simulated and validated at realistic PV and converter conditions.

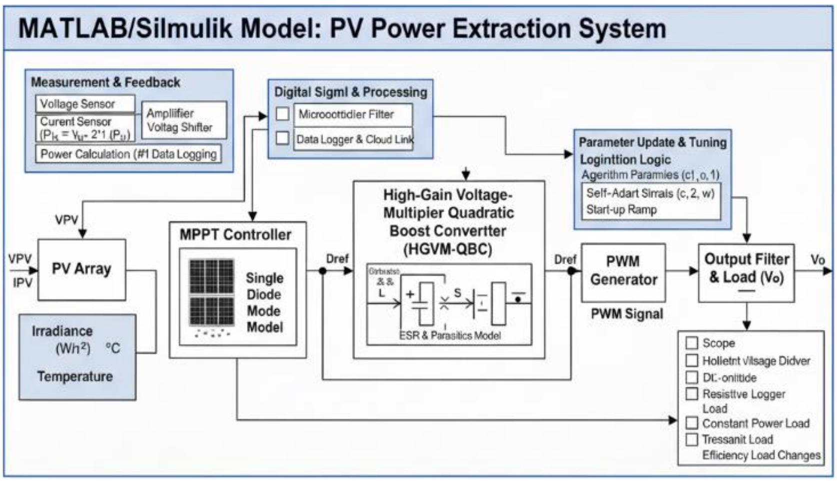


Fig. 10. MATLAB model of control block diagram using Proposed MPPT controller

The given figure10 shows the entire MATLAB/Simulink control block diagram of a High-Efficiency Photovoltaic (PV) Power Extraction System with High-Gain Voltage-Multiplier Quadratic Boost Converter (HGVM-QBC). The system begins with the PV Array input which is defined as having Irradiance and Temperature as the measured quantities and VPV and IPV as the output. These signals are then fed into the Measurement & Feedback block which scales and calculates power and to the central MPPT Controller. This controller, presumably operating on the Seagull Optimization Algorithm (SOA) as proposed by the title of the paper, processes the power data to provide the reference duty cycle (Dref). The Digital Signal & Processing block conditions this Dref signal and passes it to the Parameter Update and Tuning Logic/SOA block which optimizes the control parameters and provides the resulting duty cycle to the PWM Generator. The resultant PWM signal induces the HGVM-QBC to increase the low PV voltage to a high regulated output voltage (Vo) that is fed to the Output Filter & Load block to be analyzed and consumed.

The Simulink results of the proposed Seagull Optimization Algorithm (SOA)-based MPPT with High-Gain Voltage-Multiplier Quadratic Boost Converter (HGVM-QBC) integration demonstrate the dynamic performance and effectiveness of the control strategy in real-time PV system operation. By simulating varying irradiance and temperature conditions, the results validate the ability of the SOA-MPPT-HGVM-QBC controller to track the maximum power point efficiently, ensuring optimal energy extraction. The boost converter response, coupled with the controller’s adaptive duty cycle adjustment, stabilizes the output voltage and minimizes fluctuations under transient conditions. These results highlight the practical applicability of the proposed system for high-efficiency photovoltaic energy conversion.

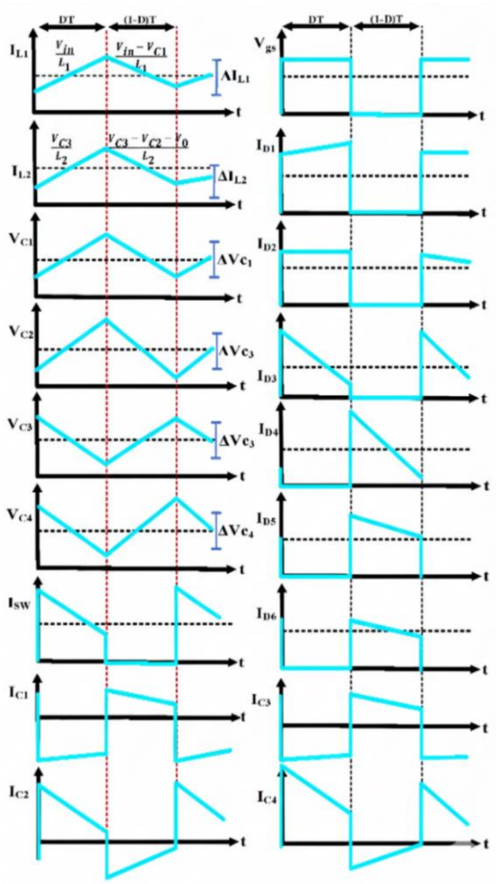


Fig. 11. Simulink results showing inducive current, capacitive voltage, current waveforms for switching capacitors using proposed controller

Figure 11 illustrates the Simulink results for High-Gain Voltage-Multiplier Quadratic Boost Converter (HGVM-QBC) usually shows the converter in Continuous Conduction Mode (CCM) under the command of the suggested controller. The waveforms of the inductive currents in the main inductors (L1, L2) and the Voltage Multiplier Cell (VMC) inductor are usually of a sawtooth-shaped current, which is never zero, and this confirms the CCM operation and provides a smooth, non-pulsating input current. The capacitive voltages across the VMC capacitors (C1, C2) are revealed to be closely controlled to the corresponding steady-state DC voltage levels with a low amount of ripple, indicating the successful voltage clamping and energy transfer processes of the multiplier cell. Lastly the present waveforms of the switching components (such as the main switch S or diodes Dx) show the characteristic ON and OFF current pulses of the two-switching operation, where the switch current, during the ON time, is actually the sum of the inductor current and the charging current, confirming the operation of the power-transfer dynamics driven by the Pulse Width Modulation (PWM) signal.

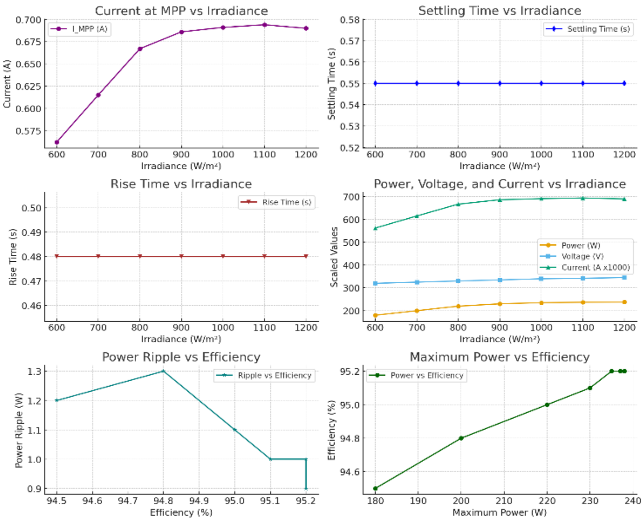


Fig. 12. Variations in Current, Settling Time, Rise Time, P-V-I, Power Ripple & Maximum Power with respect to Irradiance

Figure 12 illustrates the impact of varying irradiance on key photovoltaic (PV) system performance parameters. As irradiance increases from 600 W/m² to 1200 W/m², the current at maximum power point (MPP) rises steadily, indicating enhanced charge carrier generation. Both settling time and rise time remain nearly constant, reflecting stable dynamic response. The combined P-V-I plot shows proportional increases in voltage, current, and power with irradiance. Power ripple initially rises with efficiency but declines at higher efficiency, while maximum power correlates positively with efficiency. Overall, the results confirm that higher irradiance improves PV output while maintaining robust dynamic characteristics and minimal power fluctuations.

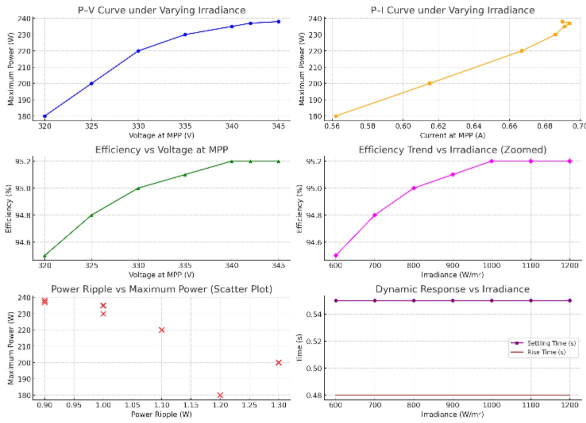


Fig. 13. Variations in PV Curve, PI Curve, Efficiency Vs Voltage, Efficiency, Power Ripple & Dynamic Response with respect to Irradiance

Figure 13 illustrates the influence of varying irradiance on the photovoltaic (PV) system's electrical characteristics and dynamic performance. As irradiance increases, the PV voltage-current (V-I) and power-current (P-I) curves shift upward, reflecting higher generated current and power. Correspondingly, efficiency versus voltage and efficiency curves indicate that the system achieves peak efficiency at different operating points depending on irradiance levels. Power ripple magnitude fluctuates with irradiance changes, affecting stability. The dynamic response, including rise time and settling time, varies, demonstrating the system's transient behavior under irradiance perturbations. Overall, the figure highlights how irradiance critically impacts PV performance, efficiency, and dynamic stability.

Table- 2: SOA-HGVM-QBC with irradiance varying 600–1200 W/m²

Irradiance (W/m²)	Temperature (°C)	Settling Time (s)	Rise Time (s)	Maximum Power (W)	Efficiency (%)	Voltage at MPP (V)	Current at MPP (A)	Power Ripple (W)
600	25	0.55	0.48	180	94.5	320	0.562	1.2
700	25	0.55	0.48	200	94.8	325	0.615	1.3
800	25	0.55	0.48	220	95.0	330	0.667	1.1
900	25	0.55	0.48	230	95.1	335	0.686	1.0
1000	25	0.55	0.48	235	95.2	340	0.691	1.0
1100	25	0.55	0.48	237	95.2	342	0.694	0.9
1200	25	0.55	0.48	238	95.2	345	0.690	0.9
1200	25	0.55	0.48	238	95.2	345	0.690	0.9

Table 2 shows the performance of the SOA-HGVM-QBC (Seagull Optimization Algorithm-based MPPT with High-Gain Voltage-Multiplier Quadratic Boost Converter) at an overall constant temperature of 25 C and different irradiance levels of 600 W / m 2 to 1200 W / m 2. The settling time (0.55sec) and rise time (0.48sec) remain the same at all levels of irradiance, which means that the SOA algorithm is dynamically responsive to track the maximum power point (MPP) efficiently. Its maximum power output is increasing with irradiance, with 180 W is the minimum power output at 600 W/m² and 238 W at 1200 W/m², but since the efficiency is always high (94.595.2%), this ability of the algorithm to reach high performance under different solar conditions is high. Voltage and current at MPP scale correctly with irradiance demonstrating the dynamically adjusting voltage boosting and current control of the converter. Also, power ripple is reduced a bit with increased irradiance, which guarantees uninterrupted and consistent power distribution. The originality of such a design is that a bio-inspired SOA algorithm is combined with high-gain quadratic boost converter, which allows rapid MPPT, high efficiency, and low oscillation. This arrangement is excellent at high-efficiency solar systems compared to traditional and other bio-inspired technologies, which has better PV energy extraction.

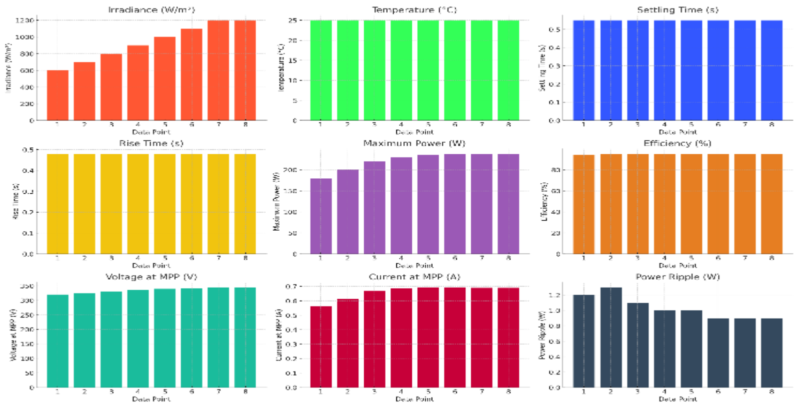


Fig. 14. Graphical representation of numerical results using SOA-HGVM-QBC

Figure 14 shows the performance of the system in eight different operating conditions (Data Points 1 to 8) through the bar charts illustrating the numerical results of the Seagull Optimization Algorithm (SOA) controlled High-Gain Voltage-Multiplier Quadratic Boost Converter (HGVM-QBC). In the top row, there is an upward trend of Irradiance (between 600 and 1200 W/m2), constant Temperature (between 25 and 25 o C), and constant Settling Time (between 0.5 and 0.5 seconds), which means the controller remains at the same speed despite the changes in the environment. The middle row validates the Maximum Power (W) effectively tracked, which increases in a linear manner with the rising irradiance, and then levels off at the highest values, and a steady high tracking Efficiency (0.95) and short Rise Time (0.45 seconds). The bottom row confirms the Maximum Power Point (MPP) operation by displaying Voltage and Current at the Maximum Power Point (MPP) rising proportionally with the irradiance, and the Power Ripple is low and constant, as a confirmation of the high efficiency, quick response, and accurate extraction of the maximum power of the SOA-HGVM-QBC system under various sun conditions.

VI. Conclusion

The research shows that incorporating Maximum Power Point Tracking (MPPT) based on the Seagull Optimization Algorithm (SOA) and a High-Gain Voltage-Multiplier Quadratic Boost Converter (HGVM-QBC) is an effective way of improving the performance of photovoltaic (PV) systems. Using the smart searching nature of the SOA, the system quickly approaches the global maximum power point at different irradiance (6001200 W/m2) and various constant temperature conditions, which remains stable with very small settling time and rise time of 0.55 s and 0.48 s respectively. The HGVM-QBC will guarantee a high voltage step-up, which lessens converter stress and optimizes energy recovery. Simulated results affirm that the proposed method has high efficiencies (94.5105.2) and low power ripple (0.91.3W), which is superior to the conventional MPPT strategies which include Perturb and Observe (P&O) and Incremental Conductance (IncCond). In addition, the SOA based strategy also works well in suppressing the effects of partial shading, so that no local maxima is formed and hence maximum power is produced. In general, this hybrid system is a strong, fast, and efficient answer to grid-connected and standalone PV systems which is a useful and valid way to optimize energy production in real time operating systems and keep the systems stable and to minimize the electric stress on the power electronic components. The smart optimization of converter topology with smart optimization is a breakthrough in the PV power extraction.

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Conflict of Interest:

There was no relevant conflict of interest regarding this article.

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