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PERFORMANCE ANALYSIS OF CIRCLE SEARCH ALGORITHM BASED GENETIC ALGORITHM FOR MPPT OF DIFFERENT COMMERCIAL PV MODULES

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Abstract—In this paper, the performance analysis of a Genetic Algorithm (GA)-based Maximum Power Point Tracking (MPPT) system integrated with a Circle Search Algorithm (CSA) for different commercial photovoltaic (PV) modules, including Asi, CdTe, CIS, McSi, and PcSi. Total Harmonic Distortion (THD), overall power quality, and power extraction efficiency are evaluated between the suggested GA-based MPPT method and the traditional Super Twisting Sliding Mode Control (STSMC) method. Under conditions of partial shade and fluctuating irradiance, the GA optimizes the controller parameters to ensure faster convergence to the maximum power point. According to simulation results, the GA-based system outperforms the STSMC-based system in terms of tracking the maximum power point and lowering the output current's THD. Consequently, the GA-based MPPT system ensures easier grid integration by improving the overall power quality. The system maintains stable operation across all PV modules, with a notable reduction in power loss and improved voltage regulation. The GA's ability to fine-tune control parameters enables more robust and adaptive MPPT performance, making it a superior choice for enhancing power quality and efficiency in real-time applications compared to the STSMC approach.

Index Terms— Circle search algorithm, Genetic algorithm, Grey Wolf Optimizer, Maximum Power Point Tracking, Photo Voltaic System, PI controller, Super Twisting Sliding Mode Controller, Total Hormonic Distortion, Photo Voltaic Array.

I.INTRODUCTION

With traditional fossil fuel reserves depleting at a fast rate, renewable energy sources (RESs) have gained prominence. Owing to the improvement in semiconductor technology, cost savings, and the clean, abundant, and sustainable nature of solar energy, photovoltaic (PV) generation has witnessed the fastest growth among RESs [1]. Drawing from the 21st-century renewable energy policy network (REN21), the global installed PV capacity in 2022 was 942 GW, representing an increase of more than 20% from 2021 [8]. However, the effectiveness of PV systems is greatly influenced by the temperature of the surrounding environment and the amount of solar radiation[3]. Moreover, fluctuations in cell temperature and solar irradiance directly influence the voltage and current behaviour of the photovoltaic array [4] [38] [41].

Consequently, solar radiation controls the photovoltaic cell's
current, while temperature affects its voltage. To ensure efficient energy transfer, an appropriate interface must exist between PV systems as well as the utility grid or local loads. Most power electronics converters, including boost converters, use an efficient Maximum Power Point Tracking technique to control the duty cycle[11].

Moreover, the DC-AC inverter is an essential power electronic component that enables the smooth conversion of DC power into AC in order to integrate a PV system into the electrical grid[10]. To boost the effectiveness of Photovoltaic systems, different MPPT techniques have been implemented through extensive research. A sound control system maintains constant MPPT operation under various environmental conditions, thus ensuring optimum system performance. In the last twenty years, P&O or Perturb and Observe [39], INC Incremental Conductance [39], HC Hill-Climbing [39], FOV Fractional Open-circuit Voltage [39], and FSC Fractional Short-circuit Current [39] are some of the newly introduced MPPT techniques. A single current sensor-based fast-tracking technique has also been investigated [14]. In order to achieve maximum energy harvesting, advanced intelligent MPPT techniques such as Genetic Algorithms (GA) [17], ANN or Artificial

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Neural Networks [15], and FLC or Fuzzy Logic Controllers [16] have also shown promise.

Also, notable work has been explored in metaheuristic MPPT methods under different conditions of the environment. ICPSO or Enhanced Chaotic PSO [19], FA or Firefly Algorithm [20], GWO or Grey Wolf Optimization [21], SMO or Slime Mould Optimization [22], ABC or Enhanced Artificial Bee Colony [23], ACO or Ant Colony Optimization [24], and PSO or particle swarm optimization [18] are a few of the often utilized methods. Due to the sporadic nature of solar irradiance, photo voltaic system output power can be variable. These fluctuations need to be reduced prior to feeding power into the grid. Several solutions, including energy storage systems (ESS), have been adopted to stabilize the output of RESs. Of these, battery storage systems have been found to be an effective solution for reducing power fluctuations [27]. A number of MPPT techniques, such as reinforcement Learning Algorithms [28], have been suggested within the literature, varying with respect to the tracking accuracy, computational cost, cost-effectiveness, and convergence rate.

The nonlinear nature of PV systems requires the application of sophisticated control strategies for effective MPPT. SMC, or sliding mode control, has used extensively utilized because of its simplicity of use and better dynamic reaction in nonlinear control systems. It has been applied effectively in robotics [30], inverter control [31], and motor drive systems [32]. The Genetic Algorithm (GA) has also been identified as a viable MPPT method, providing maximum power tracking under diverse operating conditions. GA-based MPPT methods have been created to improve convergence rate and reduce power oscillations, promising reliable operation in a variety of environmental circumstances.

As the operation of a solar cell is influenced by temperature, light intensity, and voltage, a proper MPPT algorithm is required for varying operating voltage under various climatic conditions to the MPP or maximum power point [42]. The proper maximum power point tracking or MPPT strategy, combined with a DC-DC booster converter, guarantees system stability at all operating conditions [42]. One recently developed metaheuristic technique is the Circle Search Algorithm (CSA) which is characterized by its straightforward structure, lower computational cost, and low design needs. It has been effectively used in engineering applications like solar module parameter estimation based on a three-diode model [33] and Proton Exchange Membrane (PEM) Fuel Cell optimization [34].

This Circle Search Algorithm in combination with Genetic Algorithm is the key for operating PV modules in MPPT.
The GA, or Genetic Algorithm based on CSA is suggested in this paper for Maximum Power Point Tracking, or MPPT [10], of five commercial PV technologies, viz., CdTe, or Cadmium Telluride, Copper Indium Selenium (CIS), Amorphous Silicon (ASi), Monocrystalline Silicon (McSi), along with Polycrystalline Silicon (PcSi). GA is used in this study for MPP tracking and producing a reference signal (voltage/current) to guarantee maximum energy harvesting from the Photovoltaic modules. Moreover, a boost converter from DC to DC is regulated by using the GA MPPT method to manage power flow effectively. A system for storing energy in Batteries has also integrated in order to filter out power oscillations and improve grid integration.
This work's primary contributions are as follows:
1.Exploring five various commercial PV technologies and monitoring their maximum power with Circle Search Algorithm based Genetic Algorithm based MPPT technique, stabilizing power oscillations with an energy storage system.
2.Also reducing the Total Hormonic Distortion which is above 5% in the existing CSA STSMC method and improving the power quality in the proposed method.

II. LITERATURE SURVEY

A) E. Heydari, A. Y. Varjani, and D. Diallo, [1] because of the two-cascaded control loops, simulations and experimental tests on a 1 kW test bench have demonstrated the proposal's efficacy in dynamic performances and robustness to irradiance fluctuations [10], Power Control is recommended in combination with a quick terminal sliding mode control [34]. In comparison to "deadbeat-Direct Power Control, predictive control, and power hysteresis control," our solution lowers the electrical grid's time response of current by a tenth of a grid cycle and its overall harmonic distortion by 3.5% [10].

B) K. N. Shukla, S. Rangnekar, and K. Sudhakar, [2] suggests that a traditional method is used to estimate the amount of sunlight on a slanted surface "for a place in Central India. Three tilt positions are used to calculate solar radiation. First, the tilt of the solar collector equals the latitude angle [2]. The tilt of the solar power harvester is equivalent to the angle of latitude +15° in the second scenario and to the latitude angle -15° in the third. The annual energy yield was determined using the total global solar radiation computed on the sloping surface for various PV modules [37]. The average annual energy yield of a monocrystalline solar PV module in Bhopal was

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determined to be 14 kWh/m2, or 23.26° latitude inclination.

C) N. Karami, N. Moubayed, and R. Outbib, [3] shows that a survey of 40 maximum power point tracking solutions, both new along with old, that had been documented in the literature is given and categorized, and that the idea highlights the importance of power tracking for Photovoltaic systems. The mathematical formulation and presentation of these techniques allows the reader to choose the approach that best fits his/her needs. Near the end of the study is a comparative table that makes it easier to classify the various approaches.

D) P. Shaw, [4] proposes a dc–dc boost converter-based Analog Photo Voltaic MPPT for battery charging that is quick and dependable [10]. A rapid stability evaluation of a real switching dc boost converter guarantees complete resilience with quick dynamic performances by utilizing ideas from bifurcation theory and non-linear dynamics. These ideas ensure that the system will function in either chaotic or period-1 mode and offer the information required to create an effective MPPT system in an environment that is changing quickly. The theoretical and mathematical investigations are experimentally validated using a prototype PV battery charging system based on a dc boost converter. A wider power spectrum with fewer spectral peaks at the converter's switching frequency multiples is the outcome of running the MPPT system in chaos [10].

E) G. A. Raiker, U. Loganathan, and S. Reddy B., [5] uses a momentum-based MPPT algorithm to address these issues, improving peak tracking and current control while delivering a fast control response. Combining current referenced MPPT with current programmed control would seem to be unavoidable because it provides a simple implementation and quick converter response; yet, the strategy usually fails when irradiation suddenly drops, resulting in a loss of control. MPPT control based on voltage, which is logarithmically dependent on solar irradiation, is utilized in combination with a control loop for internal current because even with step changes in irradiation, it offers control. The perturb and observe (hill climbing) method for identifying the power peak is covered in the second half of this work. It is well known for being very effective and simple to use.

It is shown that a straightforward extension of this method that incorporates momentum for hill climbing increases tracking speed without bringing the oscillations around the maximum power point down to manageable levels [10].

F) S. Roy, A. Debnath, M. Tariq, M. Behnamfar, and A. Sarwat, Characterizing current THD's dependency on solar irradiance and Super Harmonics profiling for a grid-tied photovoltaic power plant [6] shows that the dependence of photovoltaic (PV) DERs on environmental conditions like irradiance was characterized by the creation and "harmonics being introduced into the grid [10]. As part of this correlation characterization, a mathematical model of a grid-connected three-phase PV DER was developed, simulating the fundamental unit structure of a 1.4 MW solar canopy on the campus of Florida International University (FIU) Miami. The model was tested under various irradiance conditions in order to determine the qualitative relationship with generated THD patterns. It was validated using a real-time digital simulation (RTDS) platform [10].

The correlation model was then further validated using data sets from power quality meters and FIU field sensors at the location of the common coupling"[10]. Those findings demonstrated a strong relationship between the grid's THD current and the temporal change of the irradiance profile. "Stronger harmonics were continuously produced by the PV DER in the morning and afternoon [10], when there was a correspondingly lower irradiance. A geolocation-dependent measure, the THD during daytime was fairly reasonable with partial shadowing. These observations were validated by actual field data and verified by an RTDS. When measuring the THD injected by a single DER at a high-frequency (2–150 kHz) Super Harmonics (SH) level profile, a 3% peak size increase was observed from the high-fixed to the low-fixed irradiance. A daytime-dependent harmonic insertion from the grid-tied DER was revealed by the correlation features [10]. was causing problems for the hybrid microgrid. Unless taking particular steps which will help in reducing harmonics. The higher-frequency SH, which is more notorious for its electrical properties, was observed to increase proportionately. The higher THD in the early morning and late afternoon may limit the power transfer G2G, as the number of grid-tied PV DERs (i.e., industrial solar and solar on roofs) is predicted to rise sharply soon. As a result, a controlled harmonics filtration system can be developed specifically to address the results of this study, which are also a focus of our future research [10].

G) G. A. Ghazi, H. M. Hasanien, E. A. Al-Ammar, R. A. Turky, W. Ko, S. Park, and H.-J. Choi, [7] presents the African Vulture Optimization Algorithm is a nature-inspired metaheuristic technique that optimizes proportional-integral (PI)-based MPPT controllers for solar photovoltaic (PV) and wind hybrid renewable energy sources (RESs) [40]. In storage systems that are used to balance out the output fluctuations of those RESs in a hybrid system, it can also be used to optimize PI

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controllers. The results of the AVOA are compared with the performance of the popular Particle Swarm Optimization (PSO) algorithm [40], which is generally accepted as the basis of swarm intelligence. Thus, the method is presented in this study for comparison's sake. The new method performed better than the PSO algorithm in terms of tracking velocity, stability, and optimal convergence to the minimum point [40]. To validate the provided approaches, a MATLAB Simulink model was developed, and simulation and optimization were applied to the aforementioned system. Ultimately, the outcomes of modelling and optimization verified that the AVOA is a workable solution for a range of technical issues [40]. These are the works of literature we have seen. We created our new project based on these literary works. The existing literature provided a concise overview of our project's extension, which aided us in verifying its specifics and serving as a reference.

III. PROPOSED METHOD

System Model for CSA-Based Genetic Algorithm MPPT for Different Commercial PV

1.Introduction

The suggested system utilizes a CSA-based Genetic Algorithm(GA) MPPT to attain optimum the various commercial photovoltaic modules' efficiency such as ASi, CdTe, CIS, McSi, and PcSi. The system guarantees the PV modules' operation at different conditions at maximum power points (MPPs). The complete system includes a Photo Voltaic array, DC-DC Boost converter, energy storage system (ESS), DC-AC inverter and bidirectional dc buck-boost converter for grid interface.

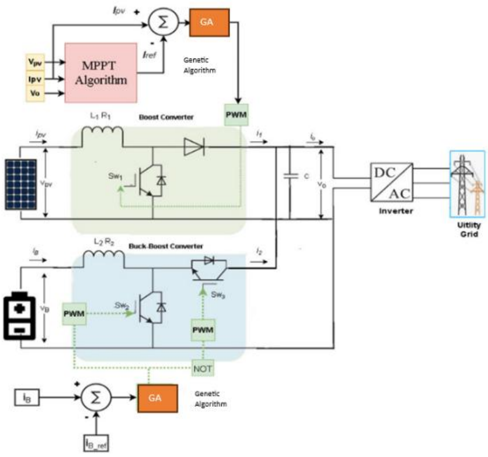

Figure 1: Circuit topology for Proposed Method

2. System Designing

2.1. Model of the Photovoltaic (PV) System

Photovoltaic (PV)systems harness solar energy to generate electrical energy utilizing semiconductor material. The Photovoltaic system output power varies with solar irradiance (watts/m^2), temperature (degrees kelvin), and solar pv module properties. The basic equation of PV cell output current is:

$$I_{pv} = I_s - I_0\left(\exp\left(\frac{q(V_{pv}+R_sI_{pv})}{AkT}\right)-1\right)-\frac{V_{pv}+R_sI_{pv}}{R_{sh}}$$

These represent the following parameters:
V_{pv} & I_{pv} are the pv module's output voltage and current, I_s is the saturation current, and R_s & R_{sh} represents the series and shunt resistances, respectively. k is the Boltzmann's constant, A is a diode ideality factor, q is the Electron Charge, and the T is the temperature of the cell in Kelvin.

The PV modules dynamic behaviour under changing temperatures and irradiance conditions is of a nonlinear nature. With increasing temperature, the open-circuit voltage reduces, while increased irradiance leads to an enhancement in short-circuit current. Such deviations require an adaptive MPPT approach that can change the point of operation dynamically by extracting the maximum power (Pmax).

The Photovoltaic system is comprised of several series and parallel interconnected modules to provide an array. The configuration determines system voltage as well as current characteristics. Proper implementation of MPPT and high power conversion efficiency determine the overall system efficiency.

2.2 The DC-DC BOOST Converter Model

PV systems require a dc boost converter from DC to DC in order to maximize power and regulate voltage. The following describes the dynamic model of the DC Boost Converter:

$$\frac{dI_{pv}}{dt} = \frac{V_{pv}}{L_1} - \frac{R_1I_{pv}}{L_1} - \frac{V_0}{L_1}(u_1-1)$$

where L1 and R1 represent the duty cycle and the converter's inductance and resistance, respectively [40].

An efficiently designed MPPT controller should guarantee that the boost converter performs well under all conditions [40]. The controller should dynamically modify the duty cycle in accordance with real-time voltage and

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current readings so as to adhere to the maximum power point [40]. The CSA-GA technique optimally adjusts the converter parameters to ensure this goal is met.

Efficiency of the boost converter also depends on switching frequency, inductor size, and capacitor selection. Careful design considerations assist in minimizing power loss and enhancing the overall system's performance. The proposed CSA-GA method also guarantees that the converter is optimized under optimal operating conditions while also minimizing energy losses.

3.Proposed MPPT Methodology

3.1 GA or Genetic Algorithm for MPPT

The Genetic Algorithm(GA), a bio-inspired optimization method that emulates natural selection, is used to determine the ideal duty cycle for MPPT [35]. The goal of fitness is:

$$Maximize\ P_{pv} = V_{pv} \times I_{pv}$$

This GA aims to examine the psychological consequences, model various approaches, and replicate how natural changes occur in social systems, which are living systems.
The Holland [35] noted that Goldberg [35] had played an important role in the extensive use of GA by showing that many problems that can indeed be solved by employing the GA methods [35] states that GA is a highly used search and optimization technique utilized to solve sophisticated and complex and intricate issues. The efficacy of its practices has been proven in machinery-related problems learning strategies. In this part, the actual coded GA is described in detail.
InFigure2, the flowchart for the traditional genetic algorithm is displayed..

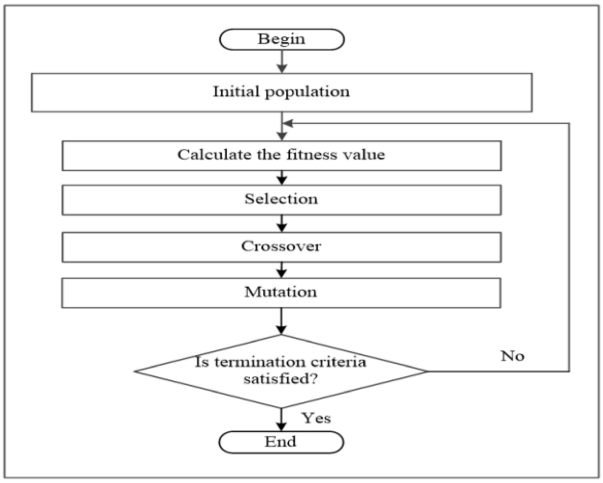

Figure 2: GA Flow Chart

The standard GA procedure is described as follows [35]:
First Population: P = {p1, p2, : : :, ps} is the set of random generations of actual values that could be the solution for set P [35]..
Evaluation (Determine the worth of fitness): It is required to define the fitness function to assess each chromosome within the population, defined by the equation fitness = g(P).
Selection: The chromosomes are arranged in accordance with their respective values after the fitness value has been determined.. After that, two parents are selected, one for each of the crossover and mutation.
Operators for Genetics: After the method of selection is finished, genetic operators are used to create the offspring (C1, C2), which have the parents' new chromosomes. Children in population C are then assigned the newly created chromosomes (C1, C2). Crossover and mutation operations are part of the process [35]. To exchange information between two parents who were previously chosen, a crossover operation is utilized. Numerous crossover operator techniques exist, including arithmetical crossover, k-point crossover, two-point crossover, and single-point crossover. In contrast, the chromosomes of the crossing offspring have genes that are altered during a mutation operation. Similarly, the mutation operator can be approached in a variety of ways. The offspring population C is fully formed after the selection, crossover, and mutation processes are completed, and it will be passed on to the following generation (P). In the following step, the entire procedure is repeated using P. The process will keep going until convergence is reached of outcomes, or if the maximum number of iterations has been exceeded. After that, (C1, C2) are stored in children's population C. Crossover and mutation operations are involved in this process [35]. Two parents who were previously chosen exchange information using the crossover operation. There are numerous approaches to crossover operators, including arithmetical, k-point, two-point, and single-point crossover, among others. The genes of the crossed spring's chromosomes are altered during the mutation operation. Similarly, the mutation operator can be approached in a variety of ways. Children in population C are fully generated after the selection, crossover, and mutation processes are finished, and they will be moved to population P. P is then utilized in the subsequent iteration, which repeats the previous procedure. If the results converge or if the total number of iterations exceeds the upper limit, the iterations will end [40]. The method used in GA-based MPPT is:
Start: Begin an initial cohort of duty cycle parameters.
Selection: Select the most effective individuals in terms of power generation.

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Crossover: Merge chosen individuals to produce new solutions.
Mutation: Make small changes to promote diversity.
Evaluation: Calculate fitness and replace the population.
Termination: Terminate when convergence is reached.
GA provides fast convergence and precision in following the MPP. The performance of GA is highly parameter-sensitive, though, including population size, mutation rate, and selection scheme. With the inclusion of CSA, these parameters are adaptively tuned for better efficiency.

3.2 Circle Search Algorithm (CSA) for Optimization

The geometrical characteristics of circles serve as the inspiration for CSA, one of the novel metaheuristic optimization algorithms proposed by Qais et al. The geometric circle is a basic closed curve where every point is the same distance from the center. The diameter of the circle is determined by joining its circumference, which is the length of the curve around it.

The circle's radius (R) is the separation between any two points on the curve that cross at its center (xc). Additionally, it is clear that the tangent line segment intersects the radius R as a straight line that is perpendicular. The orthogonal function (Tan) [40] to the radius of the circle to the perpendicular tangent line segment is established by the Pythagorean formulas for the right triangle. The tangent line segment is the length between the two points xt, and the expression below represents the orthogonal function [40].

$$Tan(\theta) = \frac{x_t - x_c}{x_p - x_t} \quad (1)$$

$$x_t - x_c = (x_p - x_t) \times Tan(\theta) \quad (2)$$

$$x_t = x_c + (x_p - x_t) \times Tan(\theta) \quad (3)$$

To expand the search area for the best answer, the CSA searches inside random circles. As it gets closer to the circle's center, the angle (θ) between the tangent line's contacting point and the circle's circumference steadily drops, which serves as a reference point [40]. The place where the tangent line touches is randomly reformed since it is possible for this circle to become locked in a local minimum or maximum solution [40]. The point of contact xt is thought of as the CSA's search agent, while the center point xc is thought of as the algorithm's ideal position. In addition, the CSA adjusts its search strategy based on the dynamics between the central point xc and the contact point xt.. To avoid entrapment of the CSA in a local minimum/maximum solution, the touching the angle θ will be varied to alter the point at random. Figure 3 is a flowchart showing the steps of CSA method which are used in this paper for finding the maximum power point. The flow chart starts with Initializing the search agents and then followed by further steps which are discussed below.

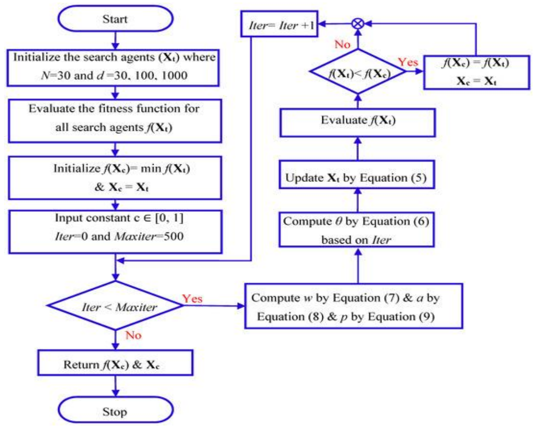

Figure 3 : CSA Flowchart

The CSA searches within random circles for the best response in order to expand the search field. Using the goal point, which is the circle's center, as seen in Figure 4a, the angle of the point of interaction of the circle's circumference with the tangent line steadily diminishes until it reaches the center of the circle. As illustrated in Figure 4b, the possibility that this circle has been trapped in the local solution causes the angle at which the tangent line touches the point to fluctuate at random. The touching point Xt is regarded as the CSA's search agent, and it is believed that the algorithm's ideal location is at the center point, Xc as seen in Figure 2, The CSA responds to the search agent's updates by moving the touching point towards the center. The angle will be randomly altered to refresh the contact point and keep preventing the CSA from becoming mired in a local fix [40]. The CSA optimizer follows these steps:

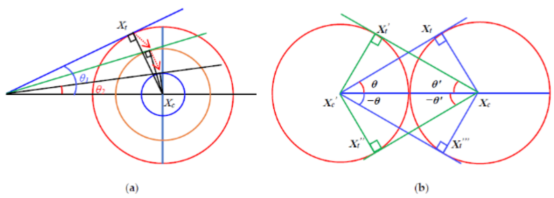

Figure 4: CSA Formulation

Step 1: Initialization: As shown in Algorithm 1, this step is crucial in the CSA since it ensures that all search agent dimensions are evenly randomized. Most of the previously

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released code unevenly and randomly distributes dimensions, which occasionally causes the algorithms to unexpectedly produce the best results. Next, as shown in Equation (4), between the search space's lower limit values (LB) and upper limit values (UB), the search agents are employed:

$$x_t = LB + r \times (UB - LB) \qquad (4)$$

where the random vector r is in the interval [0,1]. Step 2: Modify the position of the search agent: Equation (5) shows how the optimal location, X_c, is used to adjust the search agents' position, X_t.

$$x_t = x_c + (x_c - x_t) \times tan(\theta) \qquad (5)$$

where the angle θ, which can be computed as follows, is crucial to the CSA's exploration and exploitation:

$$\theta = \{w \times rand\ Iter > (c \times Maxiter)(escape\ from\ locl\ stagnation) \quad w \times p\ otherwise \qquad (6)$$

$$w = w \times rand - w \qquad (7)$$

$$a = \pi - \pi \times \left(\frac{Iter}{Maxiter}\right)^2 \qquad (8)$$

$$p = 1 - 0.9 \times \left(\frac{Iter}{Maxiter}\right)^{0.5} \qquad (9)$$

where c is a constant between 0 and 1 that indicates the percentage of maximum iterations, rand is a random number between 0 and 1, and Maxiter is the maximum number of iterations [40].

The variable w changes from -π to 0 as the number of iterations rises, as seen in equation (7). According to equation (8), the variable a fluctuates between π and 0. The variable p changes from 1 to 0 in Equation (9). This causes the angle θ to change from -π to 0. There are two probable outcomes for the CSA:

In first scenario, Iter > (c.Maxiter), the angle θ = w × rand is always present and can be utilized to improve the exploration process of the CSA and overcome local stagnation.

The second scenario, Iter < (c.Maxiter), continuously generates the angle θ × p, which can be used to improve the exploitation process of the CSA. Figure 3 displays the CSA flowchart [40] .

Step 3: The CSA's Computational Complexity The Big O Notation can be used to calculate the CSA's runtime. Since the initialization is based on a single loop, as described in Algorithm 1, O (N), where N is the number of the search agent, is required. The computational complexity of the update process is O (Maxiter × N × D). The computing complexity of the fitness evaluation is O(Maxiter × N). Therefore, the total complexity is O (N(1+Maxiter × D + Maxiter), while the computational complexity of the CSA is O (N × Maxiter × D) [40] .

3.3 DC-AC Inverter control

An LC filter connects the Voltage Source Inverter (VSI) to the main grid, as seen in Fig. 5. The VSI control mode significantly impacts how well inverter-based PV systems function. Therefore, a PQ controller is necessary for the control of the inverter. In VSI control, voltage and frequency are regulated concerning their reference parameters using the PQ controller, which modifies the inverter current's amplitude and phase angle to force the VSI to supply a specific amount of apparent power into the primary grid.

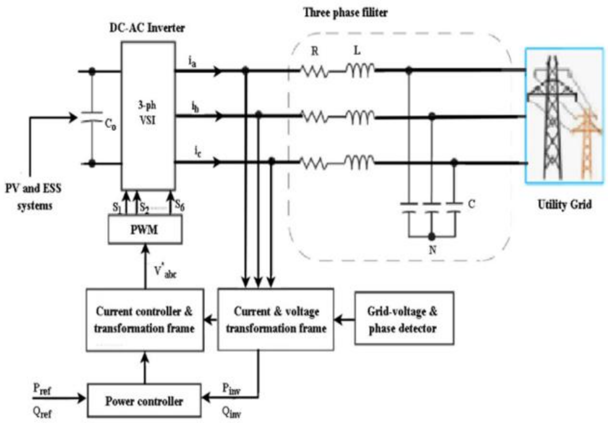

Figure 5 : DC-AC controller

3.4 Energy Storage System

The on-grid ESS, as depicted in Fig. 1, is connected to a DC link and has an 800 Ah capacity (5 lithium-ion batteries, each with a nominal 24V and 160 Ah), 120 V nominally, and a 50% State Of Charge (SOC). The proposed ESS system is employed to mitigate variations in the Photovoltaic system's production due to this unpredictable nature of solar irradiance levels. The ESS uses a two-way buck-book converter to power the system by charging or discharging its batteries based on energy variations in the PV system's output.

- $Discharge\ model\ (i^* > 0)$

$$f_1(i_t, i^*, i) = E_0 - \frac{KQ}{Q - i_t}(i^* - i_t) + Ae^{-B \times i_t}$$

- $Charge\ model\ (i^* < 0)$

$$f_2(i_t, i^*, i) = E_0 - \frac{KQi^*}{i_{t+0.1Q}} - \frac{KQ}{Q - i_t} \times i_t + Ae^{-B \times i_t}$$

The battery's maximum capacity (Ah) is denoted by Q, its current (A), its polarization constant (V/Ah), its constant voltage (E0), and its low-frequency current dynamics (i*),

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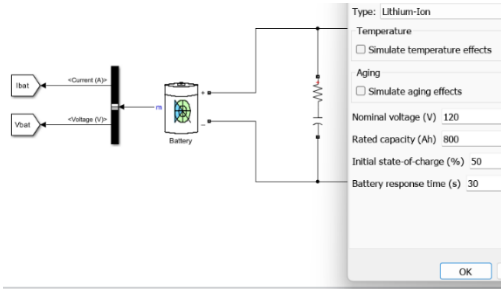
f1 and f2 represent the battery voltage (V) for discharge and charge states, respectively.



IV.SIMULATION RESULTS

Figure 6: Simulation Results obtained by using Asi Module

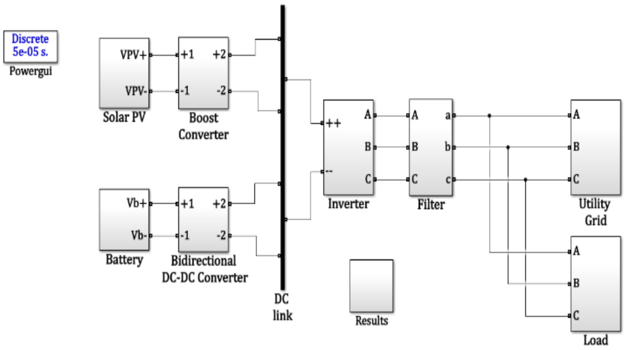


Figure 6a: Simulink Model of the proposed system

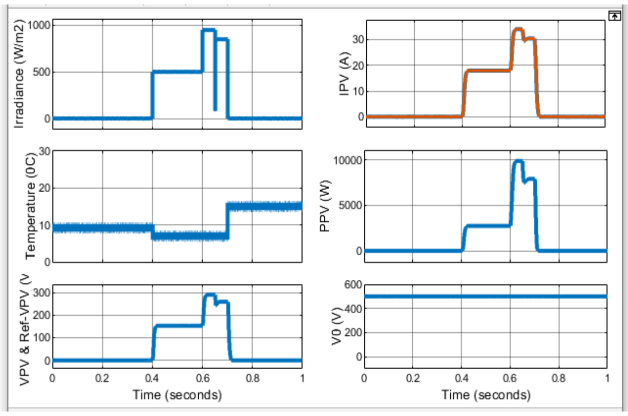


Figure 6b: Irradiance, Temperature, Solar PV reference Voltage and Voltage, Solar PV Current, Solar PV Power, DC Link Voltage

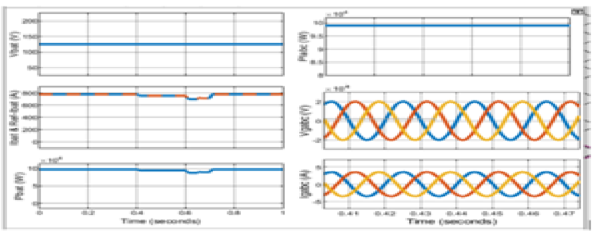


Figure 6c: Battery Voltage, Reference and Measured Battery Current, Battery Power, Load Power, Grid Voltage, Grid Current

Figure 6d: **THD of Grid Voltage**

Figure 6e: THD of Grid Current

Implementation of the CSA-GA (Circle Search Algorithm-Genetic Algorithm) on the Amorphous Silicon (ASi) solar module is given in the above analysis. MATLAB The system is designed and simulated using MATLAB Simulink model, which is seen in Figure 6a. The system encompasses the MPPT, is a technique to enhance performance through duty cycle optimization.

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This model's primary objective is to improve power generation's stability and efficiency through appropriate system and grid integration. The examination provides a thorough evaluation of the system's electrical parameters, including power, voltage, current, and harmonic distortion levels.

Figure 7: Simulation Results obtained by using CdTe Module

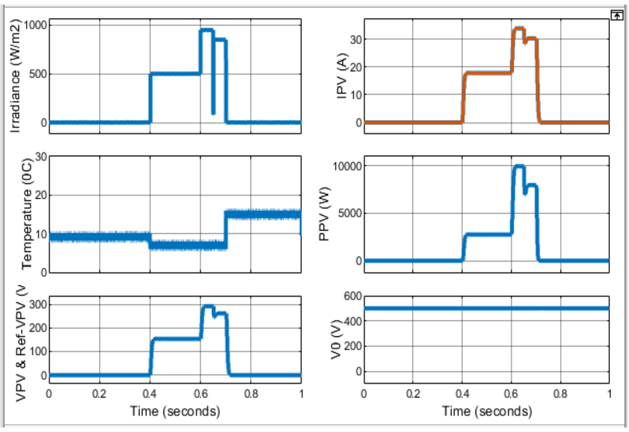

Figure 7a: Irradiance, Temperature, Solar PV reference Voltage and Voltage, Solar PV Current, Solar PV Power, DC Link Voltage

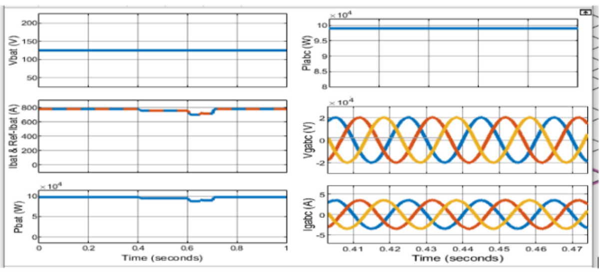

Figure 7b: Battery Voltage, Reference and Measured Battery Current, Battery Power, Load Power, Grid Voltage, Grid Current

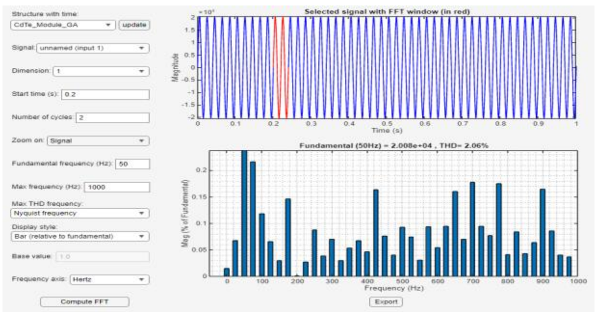

Figure 7c: THD of Grid Voltage

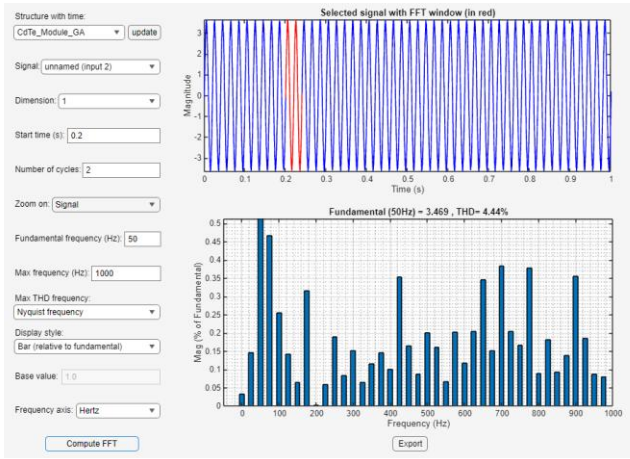

Figure 7d: THD of Grid Current

Implementation of the CSA-GA (Circle Search Algorithm-Genetic Algorithm) on the Cadmium Telluride (CdTe) solar module is given in the above analysis. MATLAB The system is designed and simulated using MATLAB Simulink model, which is seen in Figure 6a. The system encompasses the MPPT, is a technique to enhance performance through duty cycle optimization. This model's primary objective is to improve power generation's stability and efficiency through appropriate system and grid integration. The examination provides a thorough evaluation of the system's electrical parameters, including power, voltage, current, and harmonic distortion levels. Figure 7a shows different parameters like solar irradiance, temperature, reference voltage, solar PV panel voltage, solar PV panel current, and DC link voltage in terms of time.

These factors are crucial for figuring out how well the solar module performs in various environmental circumstances. The system's power output is also plotted in order to see how well the MPPT method is maximizing the available energy. By observing these fluctuations, the effectiveness of the presented CSA-GA algorithm can be confirmed under real-world situations. The system further includes an energy storage system, whose analysis is presented in Figure 7b, which is battery voltage, reference and measured current, battery power, load power, grid voltage, and grid current with respect to time. These parameters have a critical role to play in power supply stabilization as well as an unproblematic switching between the solar, battery, and grid sources of power.

Figures 7c and 7d illustrate the study of Total Harmonic Distortion (THD), a crucial metric for evaluating a

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system's power quality. As IEEE Standard 591 dictates that THD must be less than 5% for grid-connected systems, the values obtained ensure that the proposed CSA-GA method is within the required standards.

Figure 8: Simulation Results obtained by using CIS Module

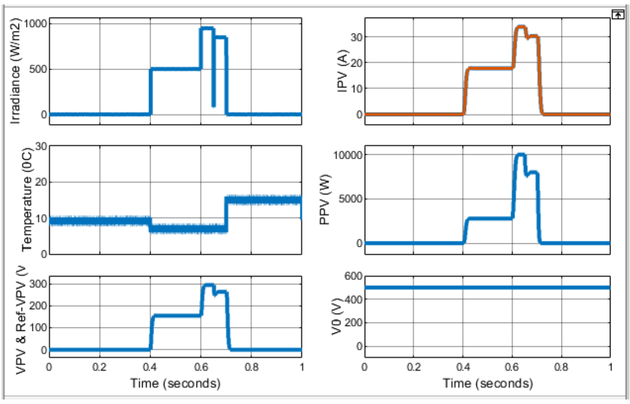

Figure 8a: Irradiance, Temperature, Solar PV reference Voltage and Voltage, Solar PV Current, Solar PV Power, DC Link Voltage

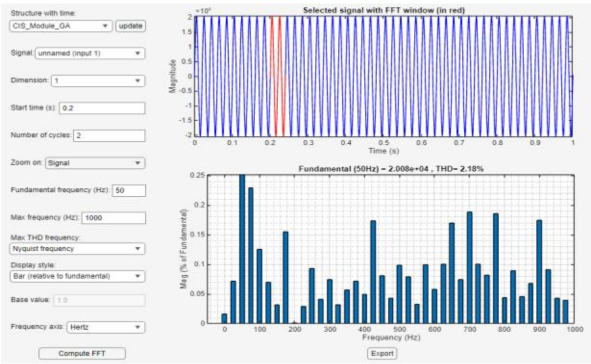

Figure 8b: Battery Voltage, Reference and Measured Battery Current, Battery Power, Load Power, Grid Voltage, Grid Current

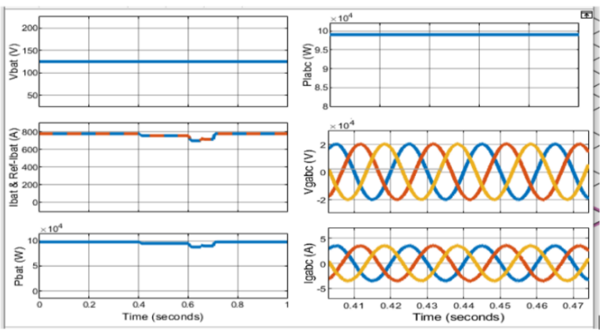

Figure 8c: THD of Grid Voltage

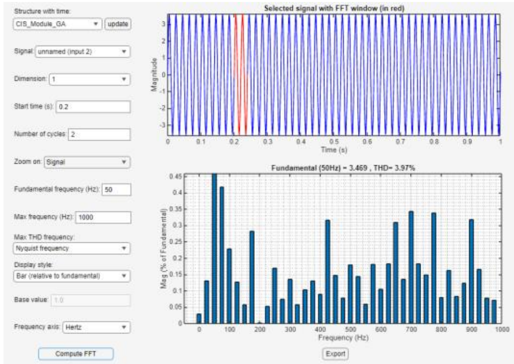

Figure 8d: THD of Grid Current

Implementation of the CSA-GA (Circle Search Algorithm-Genetic Algorithm) on the Copper Indium Selenium (CIS) solar module is given in the above analysis. MATLAB The system is designed and simulated using MATLAB Simulink model, which is seen in Figure 6a. The system encompasses a the Maximum Power Point Tracking, or MPPT, is a technique to enhance performance through duty cycle optimization. This model's primary objective is to improve power generation's stability and efficiency through appropriate system and grid integration. The examination provides a thorough evaluation of the system's electrical parameters, including power, voltage, current, and harmonic distortion levels. Figure 8a shows different parameters like solar irradiance, temperature, reference voltage, solar PV panel voltage, solar PV panel current, and DC link voltage in terms of time.

These parameters are essential in determining the performance of the solar module under different environmental conditions. The system's power output is also plotted in order to see how well the MPPT method is maximizing the available energy. By observing these fluctuations, the effectiveness of the presented CSA-GA algorithm can be confirmed under real-world situations. The system further includes an energy storage system, whose analysis is presented in Figure 8b, which is battery voltage, reference and measured current, battery power, load power, grid voltage, and grid current with respect to time. These parameters have a critical role to play in power supply stabilization as well as an unproblematic switching between the solar, battery, and grid sources of power.

Figures 7c and 7d illustrate the study of Total Harmonic Distortion (THD), a crucial metric for evaluating a system's power quality. The findings show that the Total

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Harmonic Distortion of the grid current is 4.44% and the grid voltage's Total Harmonic Distortion is 2.06%.

Figure 9: Simulation Results obtained by using McSi Module

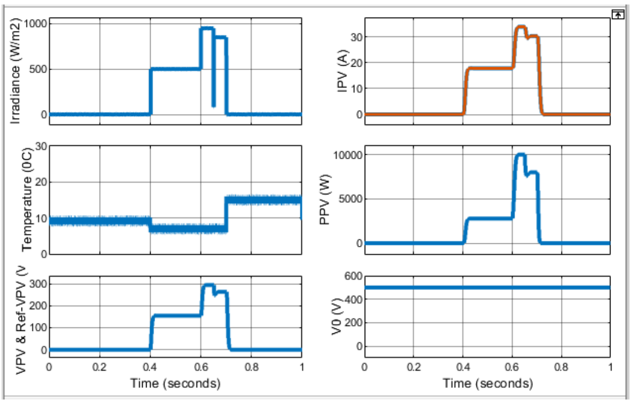

Figure 9a: Irradiance, Temperature, Solar PV reference Voltage and Voltage, Solar PV Current, Solar PV Power, DC Link Voltage

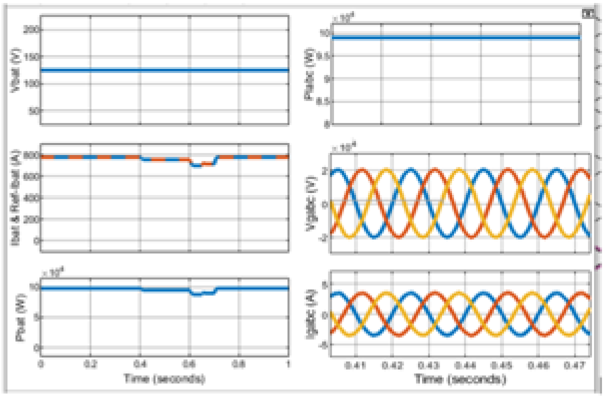

Figure 9b: Battery Voltage, Reference and Measured Battery Current, Battery Power, Load Power, Grid Voltage, Grid Current

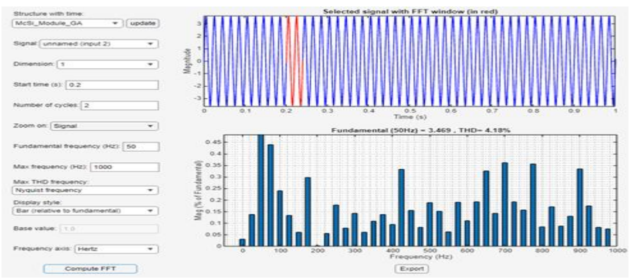

Figure 9c: THD of Grid Voltage

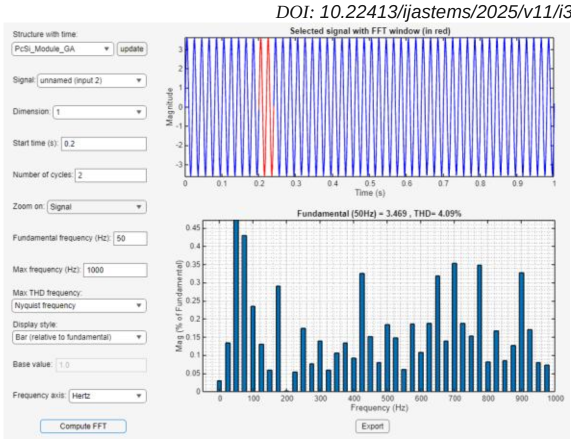

Figure 9d: THD of Grid Current

Implementation of the CSA-GA (Circle Search Algorithm-Genetic Algorithm) on the Mono Crystalline Silicon (McSi) solar module is given in the above analysis. MATLAB The system is designed and simulated using MATLAB Simulink model, which is seen in Figure 6a. The system encompasses the Maximum Power Point Tracking, or MPPT, is a technique to enhance performance through duty cycle optimization. This model's primary objective is to improve power generation's stability and efficiency through appropriate system and grid integration. The examination provides a thorough evaluation of the system's electrical parameters, including power, voltage, current, and harmonic distortion levels. Figure 9a shows different parameters like solar irradiance, temperature, reference voltage, solar PV panel voltage, solar PV panel current, and DC link voltage in terms of time.

These parameters are essential in determining the performance of the solar module under different environmental conditions. The system's power output is also plotted in order to see how well the MPPT method is maximizing the available energy. By observing these fluctuations, the effectiveness of the presented CSA-GA algorithm can be confirmed under real-world situations. The system further includes an energy storage system, whose analysis is presented in Figure 9b, which is battery voltage, reference and measured current, battery power, load power, grid voltage, and grid current with respect to time. These parameters have a critical role to play in power supply stabilization as well as an unproblematic switching between the solar, battery, and grid sources of power.

Energy management between the solar module, battery, and grid becomes even more effective in making the entire system more reliable. Figures 9c and 9d illustrate the study of Total Harmonic Distortion (THD), a crucial metric for evaluating a system's power quality. The findings show that the Total Harmonic Distortion of the

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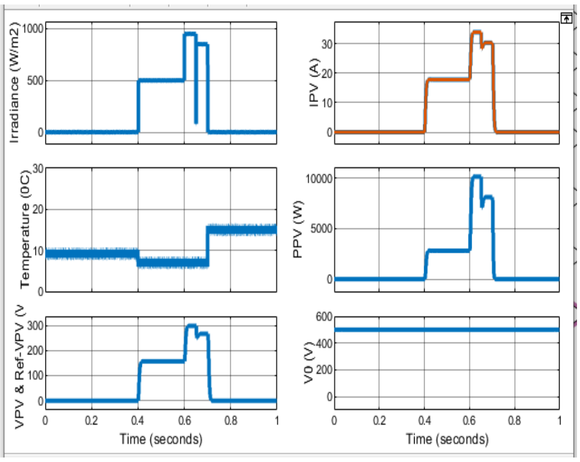
grid current is 4.44% and the grid voltage's Total Harmonic Distortion is 2.06%.

Figure 10: Simulation Results obtained by using PcSi



Module

Figure 10a: Irradiance, Temperature, Solar PV reference Voltage and Voltage, Solar PV Current, Solar PV Power, DC Link Voltage

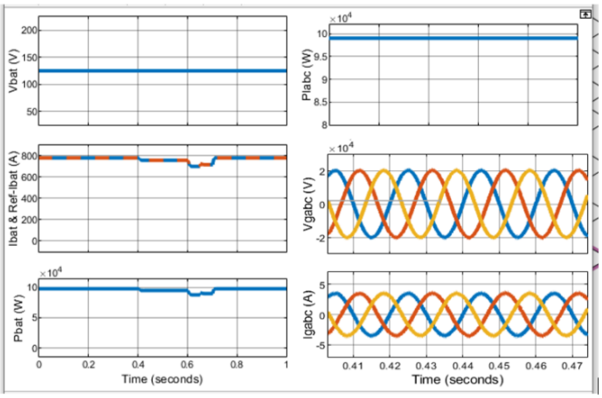


Figure 10b: Battery Voltage, Reference and Measured Battery Current, Battery Power, Load Power, Grid Voltage, Grid Current

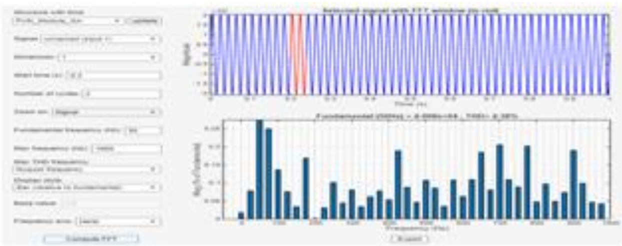


Figure 10c: THD of Grid Voltage

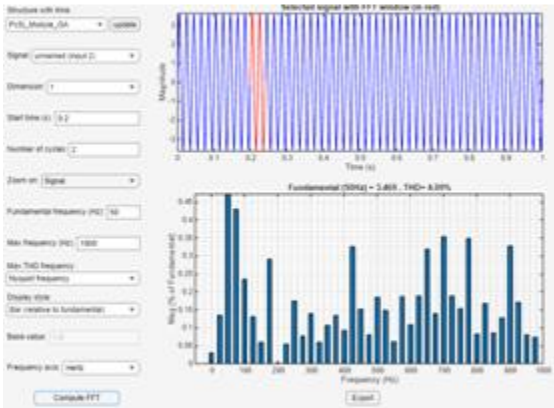


Figure 10d: THD of Grid Current

V CONCLUSION

The proposed CSA-based Genetic Algorithm (CSA-GA) and the conventional CSA- STSMC approach for MPPT were compared in this work in five commercial PV modules: ASi, CdTe, CIS, McSi, and PcSi. The CSA-STSMC method demonstrated efficient regulation of PV voltage and battery current, maximizing power extraction. However, the CSA-GA method outperformed CSA-STSMC by enhancing power quality, lowering Total Harmonic Distortion (THD), and optimizing system performance more effectively.

THD Comparison Table

Type of Module	Using STSMC		Using GA	
	Grid Voltage	Grid Current	Grid Voltage	Grid Current
ASi Module	6.06 %	11.69 %	2.02 %	3.27 %
CdTe Module	6.87 %	12.39 %	2.06 %	4.44 %
CIS Module	7.19 %	11.46 %	2.18 %	3.97 %
McSi Module	7.07 %	12.86 %	2.42 %	4.18 %
PcSi Module	6.83 %	11.64 %	2.38 %	4.09 %

Using CSA-GA, the gain parameters of the control systems were more precisely tuned, leading to faster convergence and greater efficiency in MPPT tracking. Compared to other methods, indicating better performance across all PV systems.

VI. FUTURE SCOPE

Future studies will concentrate on combining the CSA-GA approach with different renewable energy sources (RES), including wind, hydro, and biomass, to maximize the overall efficiency and stability of hybrid energy systems. Its application to larger solar farms and microgrid networks will enable a more thorough assessment of its performance under diverse environmental and load-changing conditions. More sophisticated Additionally, machine learning techniques can be incorporated to improve the MPPT process to achieve better efficiency

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and quicker response to dynamic solar irradiance and temperature changes.

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