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Design and Simulation of GA and Incremental Conductance MPPT Controllers for Enhanced Solar PV Power Extraction

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Abstract

Reducing reliance on non-renewable energy sources is essential to address global warming. Solar energy is a promising and abundant option in India. Photovoltaic (PV) cells capture sunlight and convert it into electrical energy; typical PV cells can convert about 20% of incoming solar energy into electricity. A PV cell's output depends on solar irradiation, cell temperature, and terminal voltage, and the maximum power point (MPP) varies with these conditions. Therefore, effective maximum power point tracking (MPPT) is necessary to operate the PV system at its optimal point.

This work presents a comparative study of two MPPT methods implemented in MATLAB/Simulink: the incremental conductance (INC) method and a genetic algorithm (GA)-based method. The simulations consider varying irradiation and temperature conditions. The GA-based MPPT produced a boosted output voltage of 502.13 V, while the INC method produced 501.50 V. For variable irradiation, the boost converter output power was 92.26 kW for GA and 90.41 kW for INC. These results indicate that the GA-based method outperforms the INC method in terms of overall performance.

Overview

Reducing reliance on fossil fuels and increasing the share of renewables is an ongoing global effort to lower emissions and curb climate change. Solar photovoltaic (PV) systems are playing a growing role in this transition: improvements in technology have driven costs down and boosted deployment. Today, roughly 4,800 GW of power is generated worldwide from solar PV, and grid-connected solar capacity has been expanding rapidly.

Although non-renewable sources still provide the majority of electricity because of lower generation costs in some regions, they contribute heavily to global warming and other types of pollution that harm ecosystems. That makes solar energy increasingly important - especially in countries like India, where abundant sunshine is available for much of the year and converting sunlight to electricity is relatively straightforward. Both large grid-connected and distributed PV systems offer significant benefits. India set an ambitious renewable target of about 175 GW by 2022, with solar expected to contribute roughly 65% of that total because of the country's high solar potential.

This work focuses on the role of maximum power point tracking (MPPT) in PV systems. Using MATLAB/Simulink, we implement MPPT algorithms to identify the operating point at which a PV panel delivers maximum power, and then compare the performance of the chosen MPPT methods under realistic variations in irradiation and temperature.

Literature review

The pursuit of sustainable energy sources has propelled the development of solar photovoltaic (PV) systems, necessitating efficient techniques to maximize energy extraction. Maximum Power Point Tracking (MPPT) plays a crucial role in optimizing the power output of these systems, especially under varying atmospheric conditions such as partial shading. This literature review synthesizes recent findings on MPPT techniques, focusing on intelligent methods from 2020 to 2025, and identifies gaps and future research directions.MPPT techniques can be broadly classified into Classical, Intelligent, Optimization, and Hybrid categories. Classical methods, while established, often struggle under non-ideal conditions such as partial shading (PSCs). Intelligent methods, leveraging artificial intelligence (AI) techniques like neural networks, fuzzy logic, and genetic algorithms, have emerged as promising alternatives capable of better distinguishing between global and local maximum power points (Khan et al., 2020; Garud et al., 2020).Bollipo et al. (2020) emphasized the importance of intelligent techniques in enhancing tracking efficiency and speed, particularly in scenarios where the solar irradiance fluctuates. Their review categorized MPPT methods based on their tracking nature and highlighted the benefits of intelligent methods over traditional approaches, particularly in complex environments.

Recent advancements in intelligent MPPT techniques have underscored their potential to improve the performance of PV systems. Mao et al. (2020) presented a comprehensive classification of MPPT methods, detailing the advantages and challenges of various control strategies. Their findings reveal that intelligent control methods are increasingly being adopted to address the limitations of traditional techniques, particularly in dynamic environments that exhibit rapid changes in light intensity.

Garud et al. (2020) further illustrated the application of AI in modeling and predicting the performance of PV systems. The review highlighted how neural networks and hybrid models can significantly enhance tracking accuracy, providing a solid foundation for the integration of intelligent methods into MPPT strategies.

The comparative analysis of MPPT techniques reveals critical insights into their operational efficiencies. Katche et al. (2023) provided a thorough overview of various MPPT methods, emphasizing the need for effective tracking under variable output conditions. Their study not only classified MPPT techniques but also assessed their performance based on criteria such as efficiency, tracking speed, and complexity.

Bollipo et al. (2020) reiterated that while intelligent methods might introduce complexity in implementation, they typically yield higher efficiencies compared to classical approaches. This finding suggests a trade-off between implementation ease and performance, which is pivotal for researchers and practitioners when selecting MPPT techniques for specific applications.

Despite the advancements in intelligent MPPT techniques, several challenges remain. Many intelligent methods require significant computational resources, which may not be feasible for all PV system implementations. Additionally, the variability in environmental conditions presents a persistent challenge, as highlighted by Mao et al. (2020), which indicates that intelligent methods must be continually optimized to maintain efficiency under diverse conditions.

Moreover, the majority of existing research primarily focuses on the theoretical framework of MPPT techniques, with limited empirical studies validating the effectiveness of these methods in real-world applications. This gap underscores the need for more experimental research to corroborate theoretical findings and enhance the practical deployment of intelligent MPPT techniques.

Photovoltaic (PV) System

In this chapter, the modeling and design of the overall system, including the PV system, boost converter, load, and MPPT controller, are presented.

I. Photovoltaic Cell

A photovoltaic (PV) cell is a semiconductor device that converts light into electrical energy using the photovoltaic effect. When incoming photons have energy greater than the semiconductor’s band gap, they excite electrons across the gap and create mobile charge carriers; the movement of these carriers produces current. A PV cell is a special type of photodiode. When sunlight falls on the device, it generates a photocurrent and voltage, and the cell is typically operated with a forward bias to extract power.

Photovoltaic modules, which consist of many cells connected together, have been used for decades to convert solar radiation into electrical and thermal energy. Commercial solar panels convert sunlight into electricity with efficiencies typically ranging from about 5% to 20%, depending on the cell technology. Polycrystalline silicon cells are widely used because they provide a good balance of cost, stability, and efficiency, with efficiencies of around 15% in many products. They are often assembled into dark-blue panels that are visually appealing on rooftops.

PV cell performance depends on temperature. As a module's operating temperature increases, its conversion efficiency decreases. A common rule of thumb is a loss of roughly 0.5% absolute efficiency for every 1°C rise in cell temperature. This occurs because much of the incident solar energy is absorbed as heat rather than converted into electricity, increasing the cell temperature and reducing voltage and overall output.

2. Equivalent Circuit and Mathematical Model

A current source type PV model is discussed in this section. The equivalent circuit is also shown.

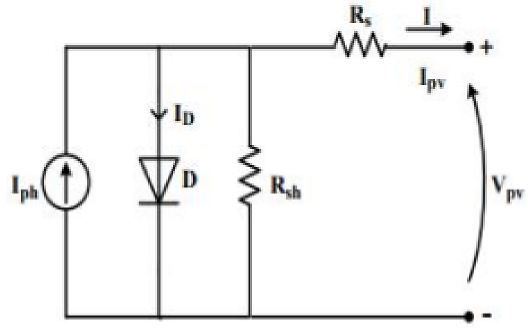

Figure 1: The equivalent circuit of a PVarray.

Where, Rs is the array series resistance in Ohm, Rp is the array parallel resistance in Ohm, I and V are the output current and voltage of the array in Ampere and Volt.

$$I = N_p \times I_{ph} - N_s \times I_{rs} [e\text{^}(q \times V / A \times K \times T) - 1] - (V + I \times R_s) / R_{sh} \quad (1)$$

Where, Iph is photo current in Amp, Irs is saturation current in Amp, Ns and Np are the number of series and parallel modules respectively, q is charge on electron in coulomb, A is diode ideality factor, T is cell Temperature with change in irradiation in degree kelvin.

Now,

$$I_{ph} = [I_{scr} + K_i \times (T - T_r)] \times S \quad (2)$$

$$I_{rs} = I_{rr} \times (T / T_r)^3 \times e\text{^}[(q \times E_9 / K \times A) \times (1/T_r - 1/T)] \quad (3)$$

Were,

Iscr is Short circuit current at reference Temperature in Amp,

Irr is reverse saturation current in Amp,

Tr is reference temperature in Kelvin,

S is solar irradiance in mW/Sq. cm,

Ki is S.C. current Temp. coefficient in (Amp/Kelvin),

K is Boltzmann's constant,

Eg is band gap energy of semiconductor used cell in joules, also,

$$E_9 = E_{90} - [(\alpha \times T^2) / (T + \beta)] \times q \quad (4)$$

Where, Ego = band gap at 0k and,

$$V_{oc} = [(A \times K \times T) / q] \times ln(I_{ph} / I_{rs}) \quad (5)$$

3. An Overview for Maximum Power Point Tracking

Solar PV systems often operate inefficiently because the power they generate doesn't always match the load. To improve overall output, systems use control techniques called maximum power point tracking (MPPT), which adjust operating conditions so the PV array produces the most power possible.

Because a PV panel's V–I characteristic is highly nonlinear, power electronics - typically a DC–DC boost converter - are used to make the panel useful to the load. MPPT works by changing the converter's duty cycle so the panel operates at its maximum power point (MPP).

Before designing the MPPT controller, it helps to understand common PV system configurations:

- Grid-direct: PV array feeds an inverter that supplies the grid.
- Grid + storage: part of the generated power goes to the grid and part is stored in a battery bank.
- Off-grid (storage): all generated power is stored in batteries for later use.

Centralized or microinverter arrangements reduce the need for one inverter per panel and can improve system efficiency.

MPPT is implemented in the power-conversion stage because these converters can modulate the PV array's voltage or current to meet load needs. The MPP is defined by a particular voltage and current, Vmpp and Impp; their product Vmpp × Impp equals the maximum available power from the panel.

4. Incremental Conductance (INC) Algorithm

This technique of MPPT works with a simple hypothesis that "ratio of change in output conductance is equal to the negative output conductance or Instantaneous conductance"

Since we know the relation,

$$P = V I$$

The above relation is differentiated on both sides, which gives

$$\partial P/\partial V = - \partial (VI)/\partial V$$

At MPP, as $\partial P/\partial V = 0$, on substituting above value will give

$$\partial I/\partial V = - I/V$$

The LHS gives the value of instantaneous conductance of PV panel whereas right side gives instantaneous value. When LHS = RHS, MPPT is achieved. In this method both parameters are taken in to account hence the effect on error of variation of solar light is eliminated. The prime reason behind using INC method is its cost effectiveness. Hence, in this technique the duty cycle is regulated by PWM control of a dc-dc boost converter until the above condition is satisfied. The Flow chart of INC MPPT is shown below.

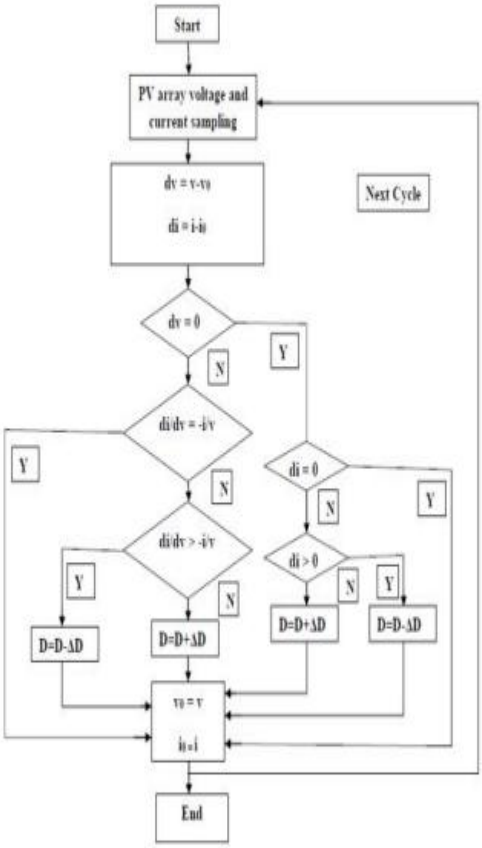

Figure 2: Incremental conductance MPPT algorithmflowchart

Genetic Algorithm

Genetic Algorithms (GAs) were introduced by John Holland at the University of Michigan in the 1970s. They draw inspiration from Darwinian evolution—“survival of the fittest”—where stronger individuals are more likely to reproduce. GAs use this idea as an optimization strategy: candidate solutions are represented as strings of bits (0s and 1s), analogous to chromosomes, and evolve over successive generations through selection, crossover, and mutation.

Each candidate (chromosome) encodes a point in the solution space. For example, a three-dimensional point (8, 5, 7) might be encoded as the concatenated binary string 1000|0101|0111, where each coordinate is represented by a 4-bit gene. How you encode variables matters: good encoding can speed up convergence and make the algorithm more effective by embedding problem knowledge into the representation.

Once a generation of candidate solutions is created, each candidate is evaluated using the objective (fitness) function. The fitness value determines how likely a candidate is to be selected for reproduction; typically, higher (more positive) fitness values are preferred. Over iterations—selecting fitter individuals, recombining their genes, and introducing random mutations—the population tends to evolve toward better solutions.

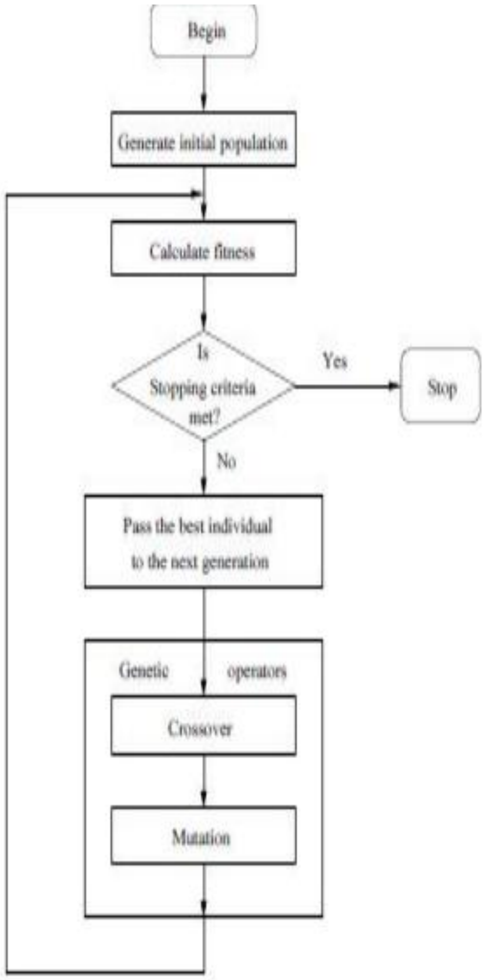

Figure 3: GA algorithm flowchart

Result and Discussion

In this work we present a Simulink model of a solar PV system developed in MATLAB and analyze ways to improve its efficiency using two MPPT techniques: incremental conductance (INC) and a genetic algorithm (GA). Simulations cover variable irradiation from 1000 to 225 W/m^2 and temperatures from 25 °C to 50 °C.

The INC-based PV system model is described and discussed in this section. Irradiance is varied to simulate cloud shading, with the pattern 1000 → 225 → 1000 W/m^2. These changes alter the PV array's output and shift the maximum power point (MPP), which the MPPT algorithm must track. The simulation examines both steady-state and dynamic responses to sudden irradiance changes. To achieve the required voltage level, the modeled array uses 66 parallel strings, each string containing 5 modules in series.

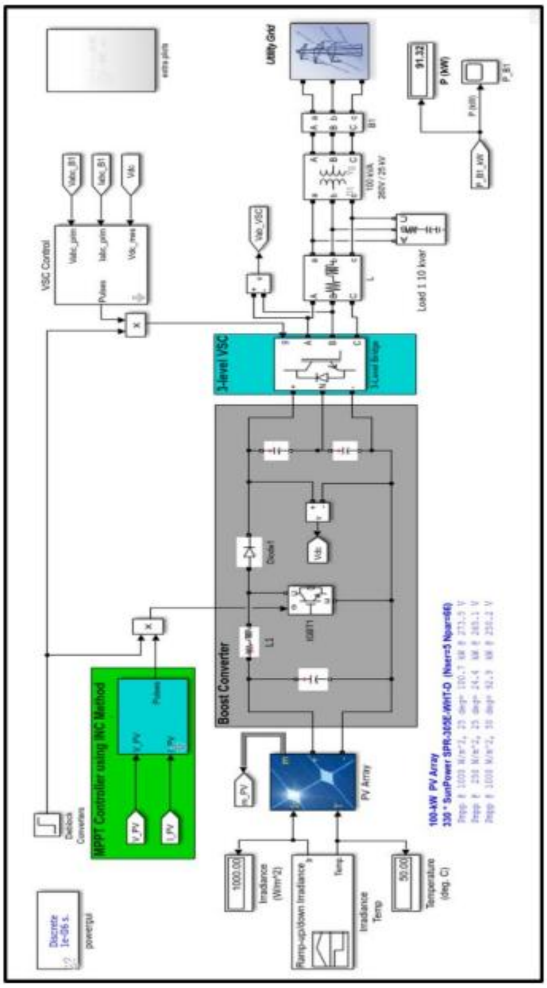

Figure 4: Simulation model of system with INC MPPT method

On simulating the model, it is observed that there are certain transients are generated in the system at the starting of simulation while converter is drawing system to MPP. The results were summarized and compared in table 1.

Table 1: Output Parameters with INC MPPT Method

S.No.	Parameters	INC Method
1.	Panel Voltage Vpv (V)	251.71
2.	Panel Current Ipv (A)	268.07
3.	Irradiation (W/m2)	2000
4.	Temperature (0C)	50
5.	PV Maximum Power/MPPT (KW)	90.41
6.	Boost Converter Output Voltage (V)	501.50
7.	Boost Converter Output current (A)	260.89

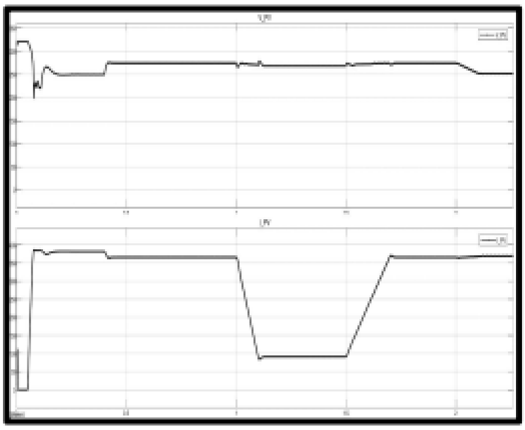

Figure 5: PV array voltage and current with INC Method

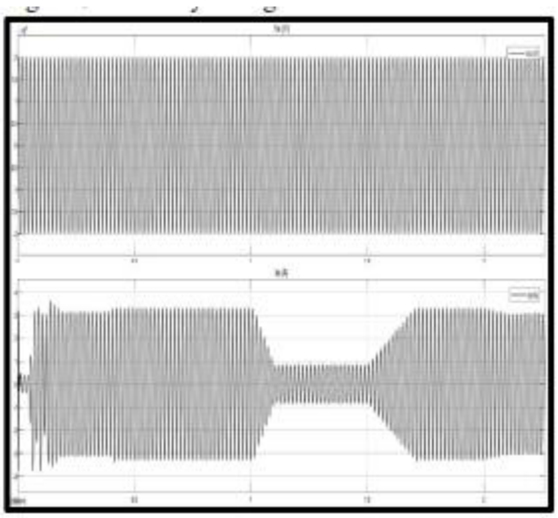

Figure 6: Utility grid voltage and current for INC MPPT method

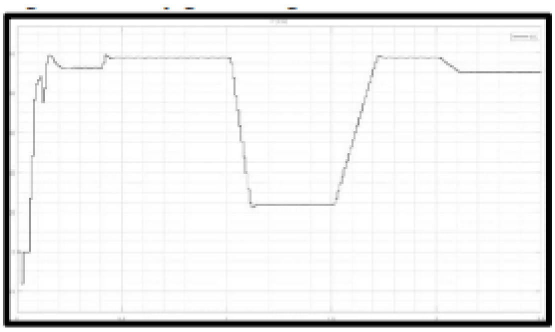

Figure 7: PV array maximum power with INC Method

Simulation Modeling and Result Analysis of

GA-MPPT Method

In this section, the simulation model of the PV system developed for the GA-based MPPT technique in MATLAB/Simulink is presented and analysed. The solar irradiation level was intentionally varied to replicate the effect of passing clouds, which obstruct the direct sunlight incident on the PV array. Due to this variation in irradiation, the maximum power point shifts to a new operating point that must be tracked continuously by the MPPT controller. The simulation study evaluates both the steady-state and dynamic performance of the system under sudden changes in solar irradiation conditions. After implementing the control system integrated with the GA-based MPPT technique, the behaviour of important output parameters such as power, voltage, and current was observed and analysed..

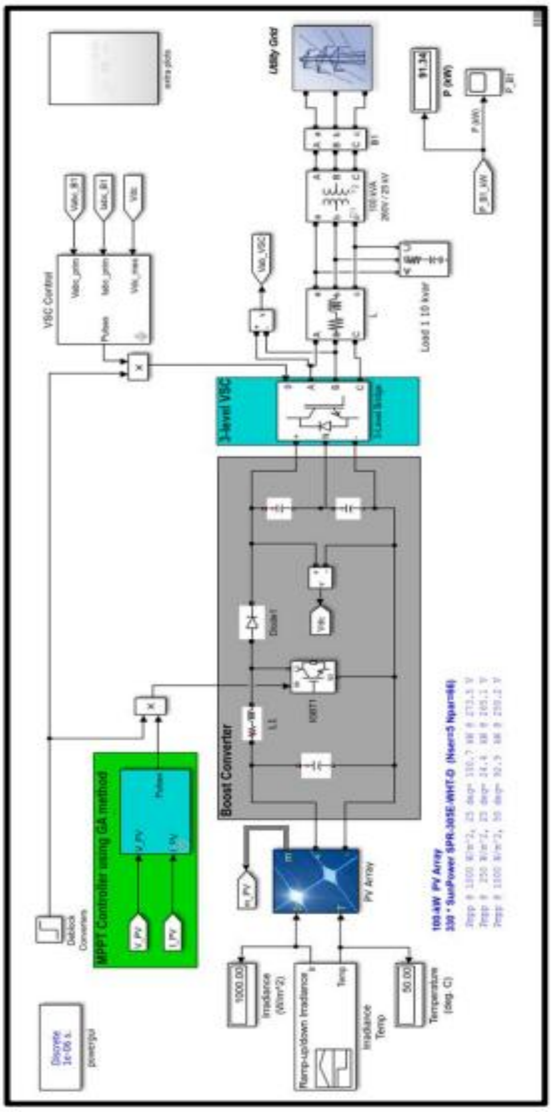

Figure 8: Simulation model of system with GA MPPT method

On simulating the model, it is observed that there are certain transients are generated in the system at the starting of simulation while converter is drawing system to MPP. The results were summarized and compared in table 2.

Table 2: Output Parameters with GA MPPT Method

S. No.	Parameters	GA Method
1.	Panel Voltage Vpv (V)	251.81
2.	Panel Current Ipv (A)	268.91
3.	Irradiation (W/m2)	2000
4.	Temperature (0C)	50
5.	PV Maximum Power/MPPT (KW)	92.26
6.	Boost Converter Output Voltage (V)	502.13
7.	Boost Converter Output current (A)	260.82

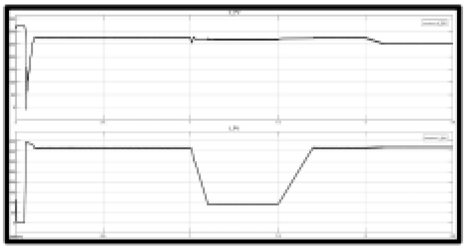

Figure 9: PV array voltage and current with GA Method

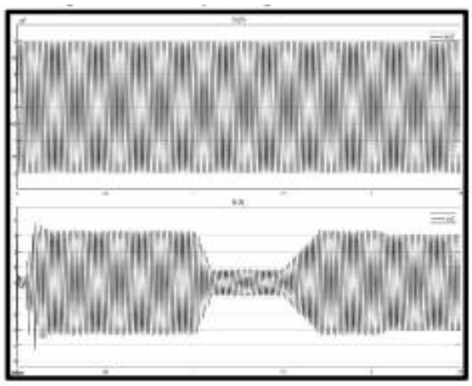

Figure 10: Utility grid voltage and current for GA MPPT method

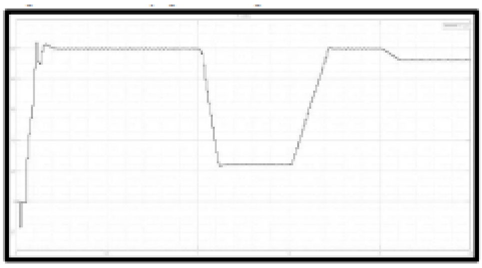

Figure 11: PV array maximum power with GA Method

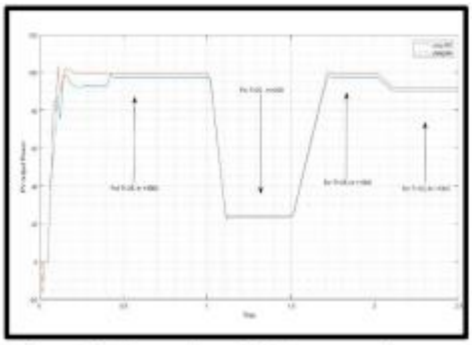

Figure 12: Comparison of PV array maximum power with GA Method

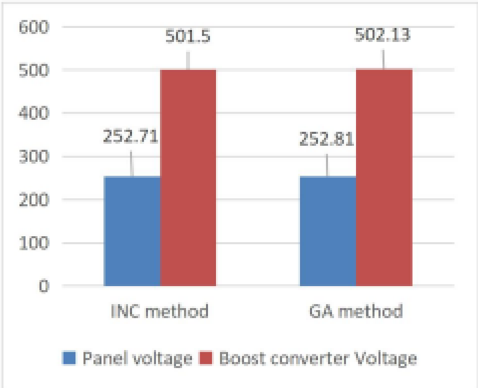

Figure 13: Comparison of PV voltage and converter output voltage with INC and GA Method

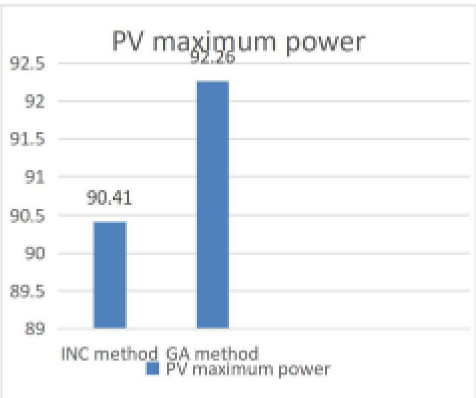

Figure 14: Comparison of PV max power and converter output power with INC and GA Method

In this section, results were evaluated from both INC and GA methods for both cases under consideration and values and plot were displayed through various figures and tables. Values were calculated at both panel end and Boost converter end.

Conclusion

As discussed in the previous section, the PV system model was successfully developed and simulated using MATLAB/Simulink software. To enhance the overall output power generation of the PV system, two MPPT techniques were implemented and analysed, namely the Genetic Algorithm (GA) and Incremental Conductance (INC) methods.

Under varying solar irradiation and temperature conditions, the boost converter output voltage obtained using the GA and INC techniques was observed to be 502.13 V and 501.50 V, respectively. Similarly, the corresponding output power values under constant irradiation conditions were found to be 92.26 kW for the GA method and 90.41 kW for the INC method. These results indicate that the GA-based MPPT technique provides better performance compared to the INC method under constant irradiation conditions.

The performance analysis was also carried out under variable irradiation and temperature conditions to evaluate the dynamic response of both techniques. Simulation results showed that the boost converter maintained an output voltage of 502.13 V using the GA-based MPPT method, whereas the INC method produced 501.50 V. In addition, the output power achieved under variable irradiation conditions was 92.26 kW for the GA technique and 90.41 kW for the INC technique. From the comparative analysis, it is evident that the GA-based MPPT method demonstrates superior tracking capability and overall performance when compared with the INC approach.

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