Comparison of Advanced MPPT Techniques & Introduction of Incremental Conductance MPPT Controller Based on Adaptive Neuro Fuzzy Inference Systems (ANFIS) for PV system

1st Ganesh G. Mhatre,

Ph.D. Research Scholar, Department of Electrical Engineering,

RKDF IST, SRK University, Bhopal, M.P., India,

E-mail – ganeshmha@gmail.com

2nd Dr. E. Vijaykumar

Professor & HOD, Department of Electrical Engineering,

RKDF IST, SRK University, Bhopal, M.P., India,

E-mail – drvijaykumareda03@gmail.com

Abstract : Efficient usage of renewable energy systems like photovoltaic (PV) and wind energy systems greatly benefit from Maximum Power Point Tracking (MPPT) techniques. The primary objectives of these advanced MPPT algorithms are addressing slow response times, inefficiency in partial shading, and other issues such as undulated behavior around the Maximum Power Point (MPP). This paper provides a comparative analysis of various advanced MPPT techniques, namely P&O with adaptive step size, fuzzy logic based Incremental Conductance (INC), Artificial Neural Networks (AAN), Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and Sliding Mode Control (SMC) techniques. Key metrics considered for evaluating the techniques included tracking speed, overall efficiency, the complexity of the algorithms, and performance under varying conditions. The study showed that higher utilization of fuzzy logic in conjunction with hybrid integrated intelligent control mechanisms was more effective. The proposed method will demonstrate that the strategy performs noticeably better than conventional techniques in terms of responsiveness, stability, and efficiency.

Keywords: photovoltaic (PV), MPPT, Incremental Conductance (INC), fuzzy logic based Incremental Conductance (INC), Artificial Neural Networks (AAN), Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and Sliding Mode Control (SMC), ANFIS

1. Introduction

Renewable energy sources, particularly in the domain of solar and wind resources, require efficient MPPT techniques to maximize energy extraction. Conventional P&O and INC MPPT techniques face challenges under dynamic weather conditions. Therefore, advanced MPPT techniques have been proposed incorporating intelligent algorithms and optimization strategies. This paper highlights a comparative study of such techniques based on their advantages, limitations, and practical applications.

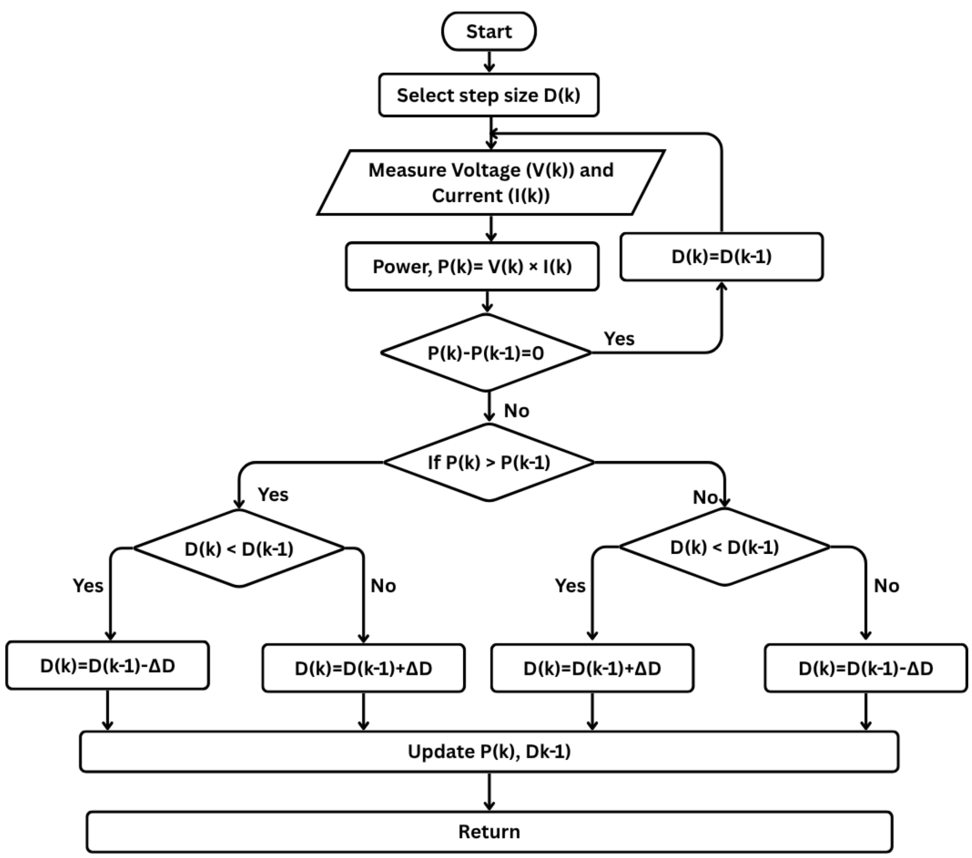
2. Advanced MPPT Techniques

2.1 Perturb and Observe (P&O) with Adaptive Step Size [8]

For maximum power point tracking in solar energy systems, the Perturb and Observe method with Adaptive Step Size performs comparably better than the traditional P&O algorithm. The primary objective of this modification is to drastically reduce dc oscillation under steady-state settings while offering a dynamic perturbation step size for faster convergence.

Algorithm

1. **Start**
2. Measure **Voltage (V) and Current (I)**
3. Calculate **Power, P = V × I**
4. Compare **current power, P(k)** with **previous power, P(k-1)**:
    - If **P(k) > P(k-1)**, continue in the **same direction** and **increase/decrease step size adaptively**
    - If **P(k)< P(k-1)**, **reverse the perturbation direction** and reduce step size
5. Update **voltage, V(k-1) = V(k)** and **power P(k-1) = P(k)**
6. Repeat until Maximum Power Point (MPP) is reached



Flowchart:

Fig.1: Perturb and Observe (P&O) with Adaptive Step Size Flow chart

2.2 Incremental Conductance (INC) with Fuzzy Logic [12,13,19,29,30]

Incremental Conductance (INC) is an advanced Maximum Power Point Tracking technique and is characterized by disadvantages of Perturb and Observe (P&O) in explicitly identifying the MPP without steady state oscillations. Fuzzy Logic Control enhances INC technique having the feasibility of changing the step based on the system conditions. Hence, it can improve the performance, both in rapidity and efficiency.

Algorithm

1. **Start**
2. Measure **Voltage (V) and Current (I)**
3. Find out **Change in Voltage (ΔV) and Change in Current (ΔI)**
4. Calculate **Incremental Conductance (ΔI/ΔV)**
5. Compare **Incremental Conductance (ΔI/ΔV) with Conductance (I/V)**:
    - If **ΔI/ΔV = -I/V**, the Maximum Power Point (MPP) is reached → Maintain current voltage.
    - If **ΔI/ΔV > -I/V**, increase voltage.
    - If **ΔI/ΔV < -I/V**, decrease voltage.
6. Apply **Fuzzy Logic Controller (FLC)** to adjust step size dynamically based on system conditions.
7. Update **previous values (V_k-1 = V_k, I_k-1 = I_k)**
8. Repeat until **MPP is reached**.

Flowchart:

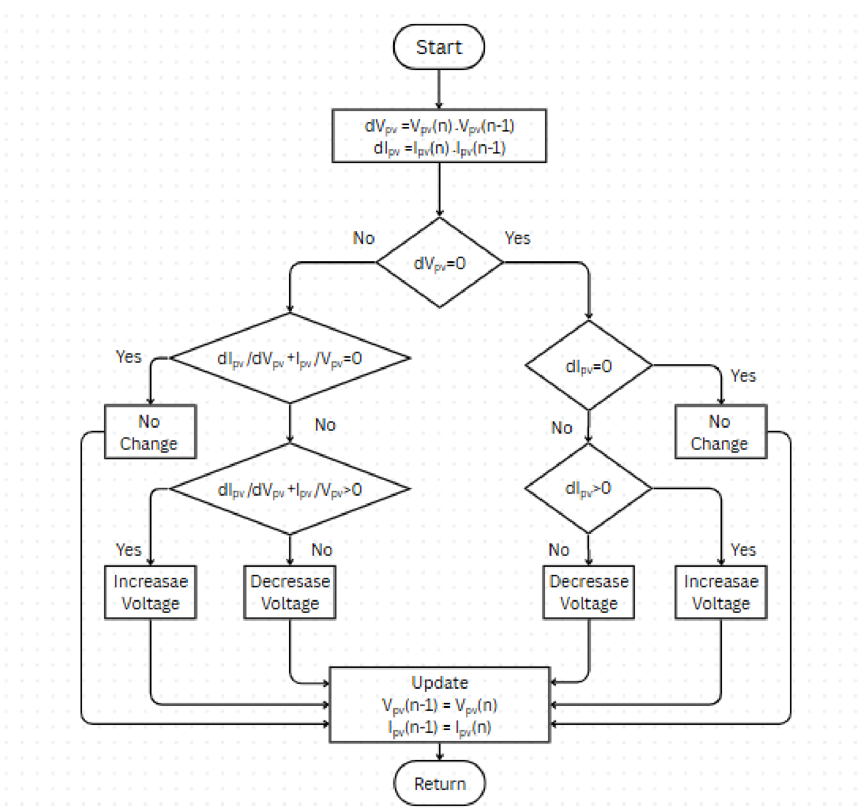


Fig.2: Incremental Conductance (INC) with Fuzzy Logic Flow chart

2.3 **Artificial Neural Network (ANN)-Based MPPT [20,22,26]**

Artificial Neural Networks (ANNs) provide a highly intelligent and powerful approach that may be used to Maximum Power Point Tracking (MPPT) on Photovoltaic (PV) systems. While conventional approaches such as the P&O and INC may fail to track the optimal operating point during sudden fluctuations in irradiance or temperature, established ANN-based MPPT are capable of doing so.

Algorithm

1. **Start**
2. Measure **Input Parameters (Voltage, Current, Temperature, Irradiance, etc.)**
3. Preprocess the data (Normalization & Feature Scaling)
4. Feed the input parameters into the **Trained ANN Model**
5. ANN **Predicts the Optimal Duty Cycle or Reference Voltage**
6. Apply the predicted value to the **DC-DC Converter** (e.g., Boost Converter)
7. Measure the new **Power Output (P = V × I)**
8. Check for **Convergence to MPP**:
    - If **MPP is reached**, maintain current operation.
    - If **MPP is not reached**, update weights (if online learning is enabled) and adjust control parameters.
9. Repeat the process continuously for real-time tracking.

Flowchart:

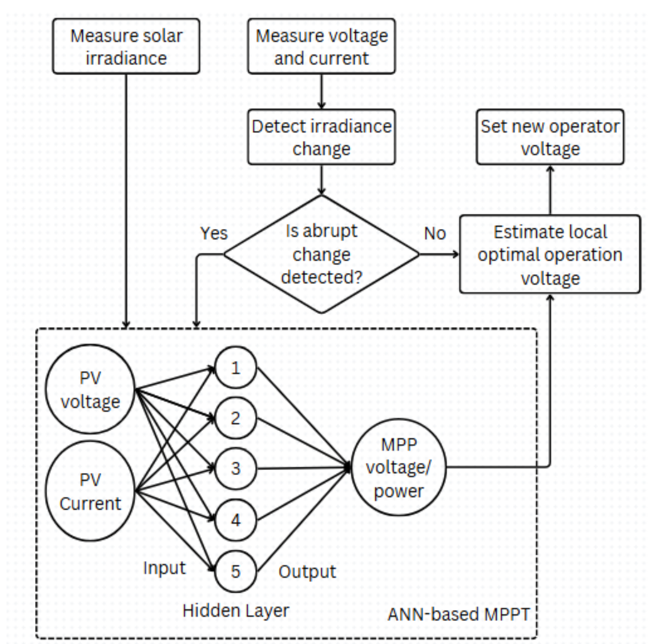


Fig.3: Artificial Neural Network (ANN)-Based MPPT Flowchart

2.4 Particle Swarm Optimization (PSO)-Based MPPT [25]

Particle Swarm Optimization (PSO) is a smart, metaheuristic technique that takes inspiration from how birds or fish groups move together. It is commonly used for Maximum Power Point Tracking (MPPT) in photovoltaic (PV) systems, particularly in tough situations like partial shading and quick changes in sunlight. PSO improves the duty cycle of a DC-DC converter (such as a boost converter) so that the PV system works at the Global Maximum Power Point rather than local maxima where it often gets trapped—a problem for many traditional MPPT techniques.

Algorithm

1. **Start**
2. Initialize **Particles** (each representing a potential duty cycle or voltage)
3. Measure **Voltage (V) and Current (I) from PV Panel**
4. Calculate **Power (P = V × I) for Each Particle**
5. Update **Personal Best (P_best) and Global Best (G_best) Values**
6. Adjust **Velocity and Position** of Particles Using PSO Equations
7. Update **Duty Cycle or Reference Voltage**
8. Apply the Updated Value to the **DC-DC Converter**
9. Measure the New **Power Output (P_new = V × I)**
10. Check **Convergence to MPP**:
    - If **MPP is reached**, maintain operation.
    - If **not**, return to Step 5 and continue updating particles.
11. Repeat the process continuously for real-time MPPT.

Flowchart:

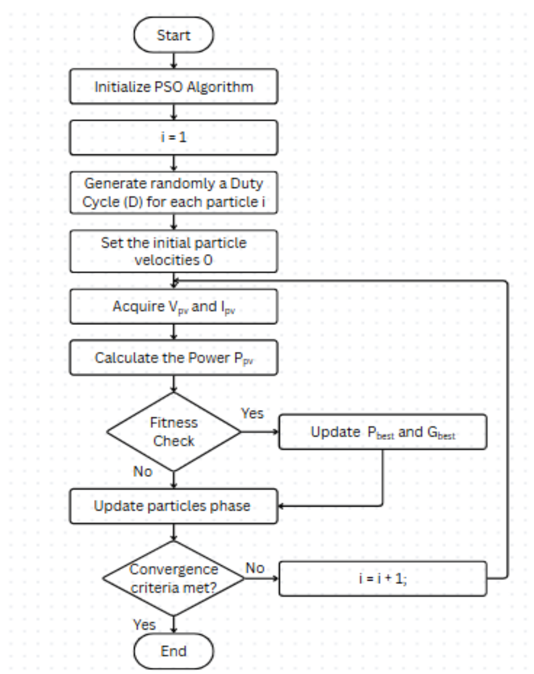


Fig.4: Particle Swarm Optimization (PSO)-Based MPPT Flowchart

2.5 Genetic Algorithm (GA)-Based MPPT [10]

Genetic Algorithm (GA) is a natural selection and genetic evolution-inspired optimization method. It is commonly utilized for Maximum Power Point Tracking (MPPT) in photovoltaic (PV) systems, particularly under partial shading and rapid weather conditions.Unlike conventional MPPT techniques (P&O, INC), GA searches for many solutions at the same time and improves the best solution over generations to converge to the Global Maximum Power Point (GMPP) rather than being trapped in local maxima.

Algorithm

1. **Start**
2. Initialize **Population of Duty Cycles (Chromosomes)**
3. Measure **Voltage (V) and Current (I) from PV Panel**
4. Compute **Power (P = V × I) for Each Chromosome**
5. Evaluate **Fitness Function** (Power Maximization)
6. **Selection**: Choose the Best Individuals (Higher Power Output)
7. **Crossover**: Generate New Offspring by Combining Parent Chromosomes
8. **Mutation**: Introduce Small Random Changes for Diversity
9. Generate **New Population** Based on Selected and Mutated Offspring
10. Apply the **Best Duty Cycle to the DC-DC Converter**
11. Measure **New Power Output (P_new = V × I)**
12. Check **Convergence to MPP**:
    - If **MPP is reached**, maintain operation.
    - If **not**, go back to Step 5 and continue evolution.

13. Repeat Until **Optimal MPP is AchievedFlowchart:**

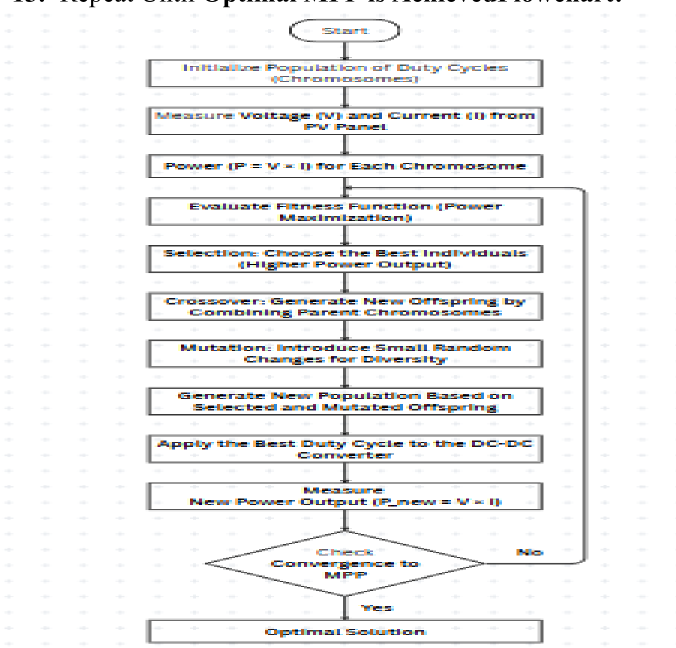


Fig.5: Genetic Algorithm (GA)-Based MPPT Flowchart

2.6 Sliding Mode Control (SMC)-Based MPPT [1]

Sliding Mode Control (SMC)-Based Maximum Power Point Tracking (MPPT) is a sophisticated nonlinear control method employed in photovoltaic (PV) systems for maximum power extraction from solar panels. SMC is renowned for its robustness, quick dynamic response, and capacity to counteract uncertainties and disturbances in the system.

Algorithm

1. **Start**
2. Measure **Voltage (V) and Current (I) from the PV panel**
3. Compute **Power (P = V × I)**
4. Compute **Error Signal (Sliding Surface, S):** S=dP/dV=d(VI)/dV
5. **Check the Sliding Surface Condition (S = 0)?**
   - **If S ≠ 0:** Continue sliding mode adjustments
   - **If S = 0:** System is at MPP → Maintain current operation
6. Apply **Sliding Mode Controller (SMC) Switching Law:**
   - If S>0, **Increase Duty Cycle (D)**
   - If S<0, **Decrease Duty Cycle (D)**
7. Update **Duty Cycle of DC-DC Converter**
8. Check for **Steady-State Condition (Convergence to MPP)**
   - **If MPP is not reached**, go back to Step 2
   - **If MPP is reached**, maintain operation
9. **Repeat the process continuously for real-time MPPT**

Flowchart:

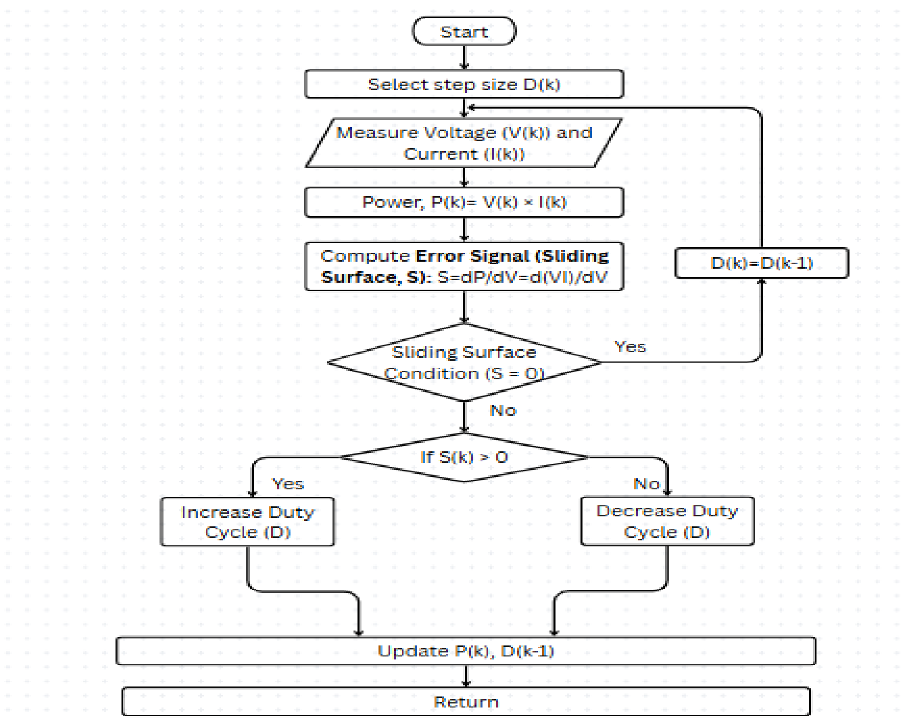


Fig.6: Sliding Mode Control (SMC)-Based MPPT Flowchart

2.7 Proposed Incremental Conductance (Inc)- MPPT Controller Based on Adaptive Neuro Fuzzy Inference Systems (ANFIS) [12,13,21,28,31,32]

Traditional INC methods use a fixed step size to adjust the duty cycle, which can lead to slower tracking of the MPP and increased oscillations near the MPP. In the proposed method, ANFIS calculates a variable step size d by measuring real-time temperature and irradiance. This step size is then passed to the INC algorithm, which adjusts the duty cycle by either increasing or decreasing it based on. The use of variable step size d in this approach effectively overcomes the limitations of the conventional INC method. The traditional INC method uses a fixed step size to adjust the duty cycle, which often leads to oscillations around the MPP and slower detection of the current MPP. In the proposed approach, ANFIS generates variable step sizes based on changes in temperature and irradiance to address the limitations of traditional methods. The INC MPPT algorithm then uses these step sizes to calculate a new duty cycle, which is applied by the Boost Converter to adjust the switching frequency accordingly. Figure 7 shows the Proposed ANFIS-based INC algorithm.

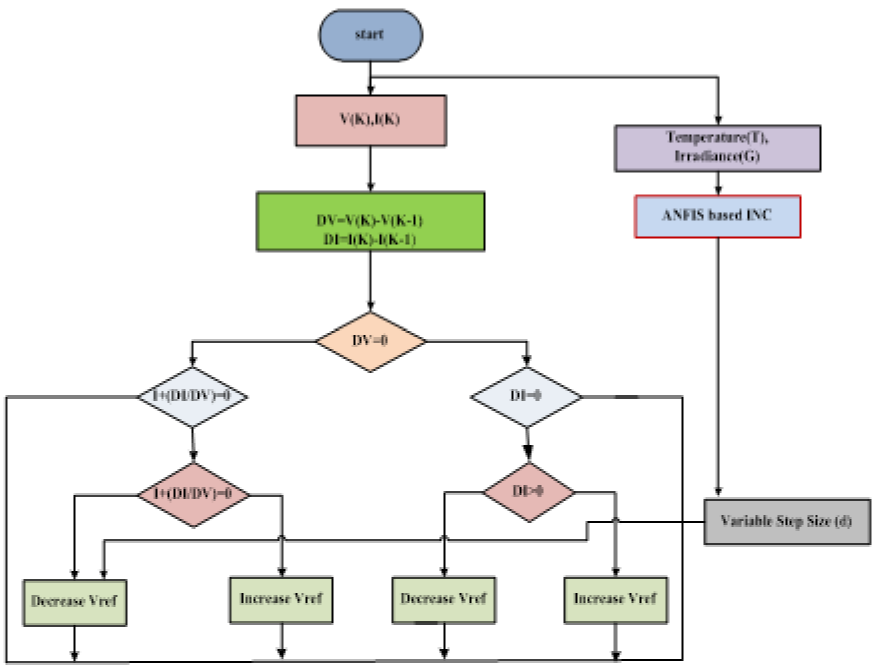


Fig. 7 Proposed ANFIS based INC Flow chart

3. Comparative Analysis

Table 1: Comparison of advanced MPPT Methods

Technique	Accuracy	Speed	Complexity	Suitability for Partial Shading	Stability
P&O Adaptive	Medium	Medium	Low	Poor	Moderate

INC with Fuzzy	High	Medium	Medium	Moderate	High
ANN-Based	High	High	High	Good	High
PSO-Based	Very High	Medium	High	Excellent	Moderate
GA-Based	Very High	Medium	High	Excellent	Moderate
SMC-Based	High	Very High	High	Good	Excellent

4. Conclusion

Newer MPPT methods ensure much enhanced energy harvesting effectiveness in renewable energy systems. ANN-based and PSO-based schemes have better tracking performance under dynamic conditions, while GA-based and SMC-based systems work well in partial shading cases. Combination of conventional and intelligent control methods using hybrid approaches results in the best overall performance. Future work should include minimizing computational complexity and enhancing real-time adaptability.

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