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バージョン：

Design and development of an Artificial Neural Network-based Maximum Power Point Tracker (ANN_MPPT) for the residential solar photovoltaic

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Abstract: *In recent years, solar power generation systems have been evolving from the perspective of mitigating global warming. The Maximum Power Point Tracking (MPPT) method is a notable method garnering attention. In this study, two MPPT methods were compared using MATLAB/Simulink. One method employed the perturb and observe technique, while the other utilized Artificial Neural Networks (ANN). The comparison results revealed that the power generation system using the ANN-based approach generated more electricity than the perturb and observe method.*

Keywords: maximum power point tracking, photovoltaic system, Perturb and observe, Artificial neural network

1. INTRODUCTION

The global energy demand is continuously rising, necessitating the discovery and development of new energy sources to meet future requirements. The world's energy demand is projected to increase by 56% from 2010 to 2040 [1]. In response to this challenge, many countries are turning to renewable energy as a sustainable alternative. Although renewable energy sources are currently considered relatively expensive and less efficient, they hold great potential for the future. Renewable energy is derived from natural resources, such as sunlight, wind, rain, tides, and geothermal heat, which can be naturally replenished. Among these sources, photovoltaic (PV) energy stands out as one of the most promising options. Unlike other types of renewable energy, such as wind turbines, biomass, geothermal, and waves, PV energy is accessible in almost every location [2]. By harnessing PV energy, can tap into an abundant and widespread resource, paving the way for a greener and more sustainable energy landscape. As advancements in technology and research continue, the efficiency and cost-effectiveness of PV energy are expected to improve significantly, making it an increasingly viable choice for meeting the world's growing energy demands.

In this report, two types of Maximum Power Point Tracking (MPPT) systems were considered for PV systems, and their efficiency and power generation capabilities were compared and analyzed. The objective was to evaluate and study each method based on its performance in optimizing the PV system and maximizing power output..

2. Methods

2.1 Photovoltaic system

An ideal single diode model has been proposed for the equivalent circuit of photovoltaic converters, representing PV panels through I-V and P-V curves (see Figure 1, Fig. 2. and Fig. 3.). This model includes a current source (IL) to model the conversion of light into electricity, a diode representing the PN junction of the solar cell, a shunt resistance (Rsh) to model losses due to leakage currents, and series resistance (Rs) taking into account internal cell, metal electrodes, and contact resistances.

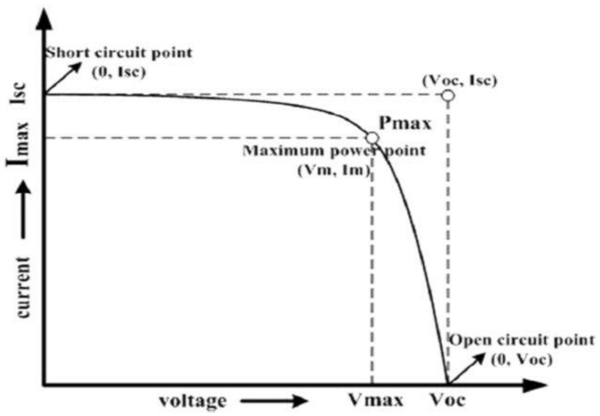

Fig. 1. I-V characteristics curve of a PV cell [3].

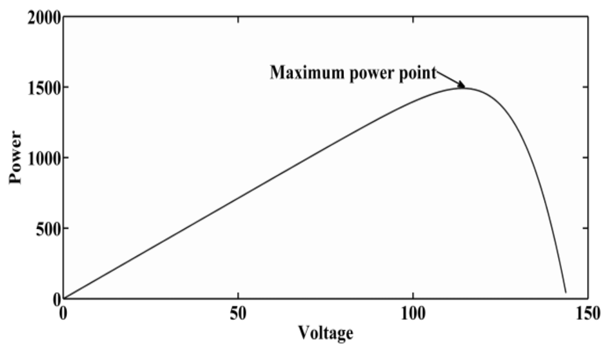

Fig. 2. P-V characteristics curve of a PV cell

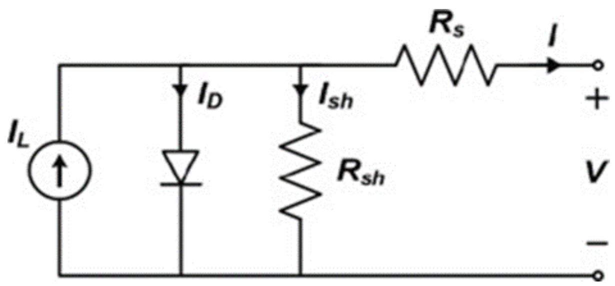

Fig. 3. Equivalent circuit of single diode model of PV cell.

Using Kirchhoff's current law (KCL), the I-V characteristic is given by:

$$I = I_L - I_D - I_{sh} \quad (1)$$

$$I = I_L - I_0 \left[exp\left(\frac{V+IR_S}{\alpha}\right) - 1\right] - \frac{V+IR_S}{R_{sh}} \quad (2)$$

$$\alpha = \frac{nkTN_S}{q} \quad (3)$$

Where:
I: PV Output current (A)
I_D: Diode current (A)
I_L: Photocurrent (A)
I_sh: Leakage current (A)
R_s:Series resistance (Ω)
R_sh: Shunt resistance (Ω)
T: Cell temperature (K)
N_s: Number of PV cells

The corresponding output power is

P=IV (4)

However, all five parameters (IL, Io, Rs, Rsh, and a) must be known in this circuit model. These parameters depend on the cell temperature and the incident solar radiation. To estimate these parameters, five equations are derived based on five conditions. The first three conditions, corresponding to short circuit, open circuit, and maximum power point, are determined from three known points on the I-V curve: (Isc, 0), (0, Voc), and (Imp, Vmp), respectively. The other two conditions are based on the operation of the model equation. Finally, optimization techniques are used to solve the obtained equations and estimate the parameters [4], [5]. A PV system encompasses the devices required for solar power generation, including solar cells and inverters. It consists of four fundamental components: power generation, current conversion, charging, and buy/sell functions. Depending on the purpose, various types of PV systems are constructed. The key performance aspects of a PV system depend on its intended use. These include the ability to generate electricity using solar cells, the inverter's capacity to convert DC to AC suitable for household appliances, the charging capability of the energy storage system, and the effectiveness of the solar cell in converting sunlight into electrical energy. PV systems effectively harness solar energy through these functions, ensuring a stable power supply.

2.2 Maximum power point tracking

In solar photovoltaic systems, the Maximum Power Point Tracking (MPPT) system is a control feature that constantly seeks electricity generation at the optimal operating voltage point to obtain the maximum power output. The maximum power point varies with changes in solar irradiance and panel temperature, and the MPPT system adapts to these variations to pursue the optimal operating point, aiming to maximize the solar panel's capability.
The maximum power point of a photovoltaic solar cell depends on both voltage and current. The machine learning algorithm helps to determine the optimal values for high efficiency. The characteristics of the cell are simplified to improve performance. The system load is also considered to ensure maximum efficiency[6].
However, the maximum power point fluctuates along the P-V curve because of the intermittent nature of solar radiation, variations in operating cell temperature, and shading effects (see Fig. 4.)[7]. The MPPT system is introduced to respond to these changing conditions effectively and actively track the optimal operating point, enabling the efficient extraction of higher power from solar energy.

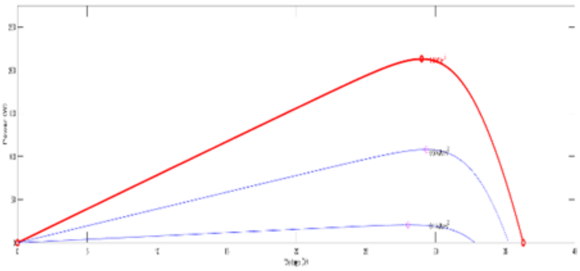

Fig. 4. PV curve showing fluctuations in the MPP

2.3 perturb and observe (P&O)

The Perturb and Observe (P&O) controller operates by continuously adjusting the current or voltage to incrementally fluctuate or vary the duty cycle, aiming to bring the operating point (OP) in proximity to the optimal power point on the PV curve. The Perturb and Observe (P&O) method employs a constant step size, which can lead to fluctuations around the Maximum Power Point (MPP). For instance, if the P&O controller determines that the OP is on the left side of the MPP,
To reach the Maximum Power Point (MPP), the approach involves reducing the duty cycle and concurrently increasing the voltage. On the other hand, when the Operating Point (OP) lies to the right of the MPP, the controller will issue a signal to decrease the voltage of the DC-DC converter. The control direction for the next step is illustrated (see Table 1.), which is determined based on the perturbation of voltage or current and subsequent power observation[8]. The flowchart of the P&O algorithm is shown (see Fig. 5.) This approach is commonly employed because of its simplicity and cost-effectiveness.

Table 1. Direction of perturbation of P&O method.

Perturbation of Ppv or Ipv	Observation of Ppv	Direction of perturbation
positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	positive

2.4 Artificial neural network-based MPPT

The ANN consists of a three-layer neural network (see Figure 6).
The input variables to the ANN are temperature (T) and irradiance (G), while the output variable is the voltage of MPP (Vmpp). Data is collected with the PV model programmed in MATLAB to train the neural network, obtaining the necessary input and output variables, and determining the weights of neurons in different layers. The error backpropagation method is employed to train

the ANN in this study, which is one of available methods.

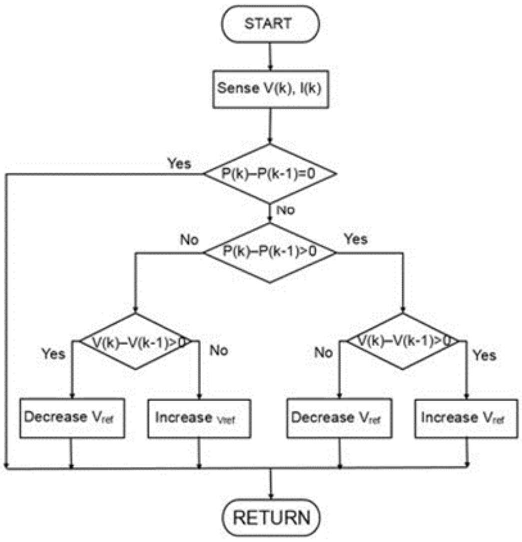

Fig. 5. Flow chart of P&O method.

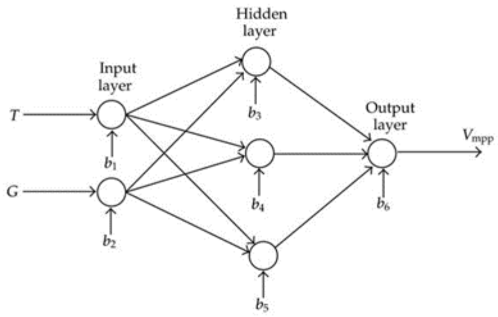

Fig. 6. Neural network structure.

After the training of the ANN and specification of neuron weights, the ANN is capable of providing the Vmpp value for any given T and G. By utilizing the V-I characteristic of the simulated PV, the current for the maximum power point (Impp) can be determined. Consequently, the maximum power (Pmax) can be attained by multiplying the Vmpp and Impp.

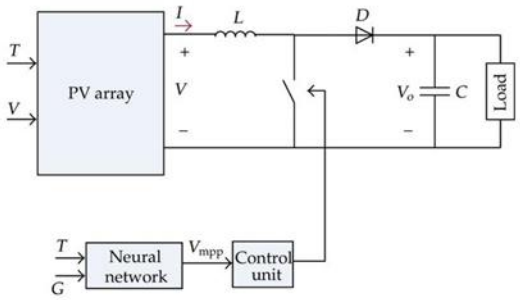

Fig. 7. DC-DC chopper includes PV as an input and its control units.

The equations for Impp and Vmpp can be expressed as follows:

$$I_{mpp} = IMPS \times \frac{G}{G_s} \times \left(1 + \left(\alpha + (T - T_s)\right)\right) \qquad (5)$$

$$V_{mpp} = VMPS + \left(\beta \times (T - T_s)\right) \qquad (6)$$

Where:
IMPS : maximum current at from PV panel
VMPS : maximum voltage at from PV panel
α : current temperature coefficient
β : voltage temperature coefficient
G_s : standard irradiance
T_s : standard temperature

The PV and Maximum Power Point Tracker system, depicted (see Fig. 7.), comprises a DC-DC boost converter and a control unit based on the neural network. At each moment, to control the chopper with the specified Vmpp and Impp, the duty cycle of the chopper is calculated using the provided equation[9]:

$$D = 1 - \sqrt{\frac{V_{mpp}}{I_{mpp}} \times \frac{I_{out}}{V_{out}}} \qquad (7)$$

3. Simulation

3.1 Simulation model

For the purpose of modeling and simulating a solar panel, the JAP6-72-320/4BB solar PV module has been chosen, and it is presented (see Table 2.). This PV module comprises 72 polycrystalline silicon solar cells connected in a series configuration. Utilizing back-to-back cell interconnectors, the module effectively minimizes series resistance between cells, resulting in elevated conversion efficiency.

Table 2. Electrical parameters of the PV module [10]

Parameters	Values
Maximum output power at STC (Pm)	320W
Maximum output voltage (Vmp)	37.38V
Maximum output current (Imp)	8.56A
Short-circuit current (Isc)	9.06A
Open circuit voltage (Voc)	46.22V
Number of cells in series	72
Number of cells in parallel	1
Diode ideality factor	1.3
Cell short circuit current temperature coefficient	0.058%/°C
Reference temperature	1000 at STC
Reference temperature	25°C

A comprehensive simulation model was developed in MATLAB Simulink to evaluate the effectiveness of various MPPT (Maximum Power Point Tracking) techniques. The model encompasses a PV panel, a buck converter, a load, a battery, and the MPPT algorithm (see Fig. 8.).
Within the simulation model, the MPPT algorithm is responsible for dynamically adjusting the PV panel's operating point to harness the maximum power from the solar irradiance and temperature inputs. The buck converter is tasked with converting the PV panel's output voltage to the desired voltage level required by both the load and battery. The load represents the electrical consumption connected to the PV system, while the battery is an energy storage unit. By running the

simulation, it is possible to carefully compare and analyze the performance of different MPPT techniques under varying environmental conditions, including solar irradiance and cell temperature changes. This meticulous evaluation will facilitate the identification of the most efficient and effective MPPT method suitable for the specific PV system.

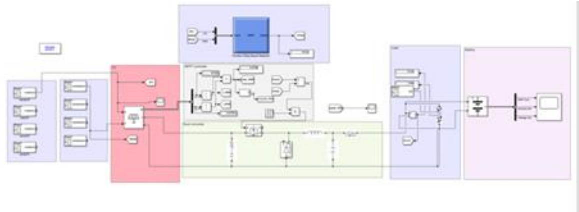

Fig. 8. Structure of the PV system

3.2 Simulation scenarios

To conduct a comprehensive performance analysis under extreme conditions, the simulation model was subjected to four distinct climatic scenarios in the same location of Fukuoka, Japan: cloudy, sunny, rainy, and windy, with each condition simulated 3 days.

Weather conditions for the four scenarios are shown in the following figures(see Fig. 9 – Fig. 12.), based on data from the Japan Meteorological Agency.

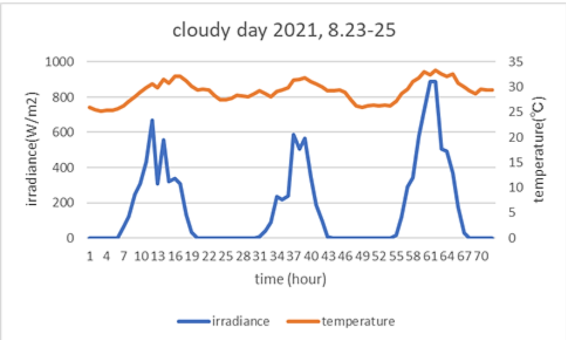

Fig. 9. Irradiance and temperature of cloudy day(2021, August 23~25).

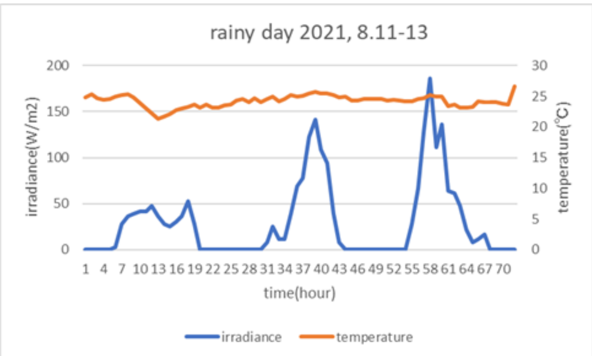

Fig. 10. Irradiance and temperature of rainy day(2021, August 11~13).

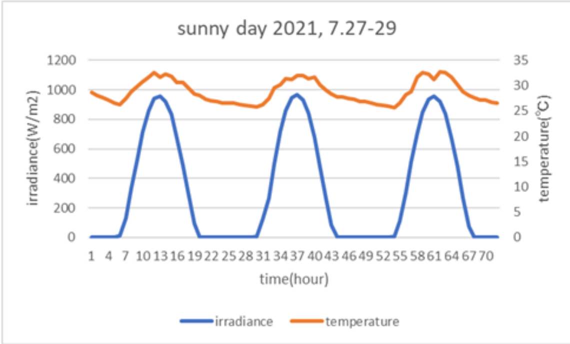

Fig. 11. Irradiance and temperature of sunny day(2021, July 27~29).

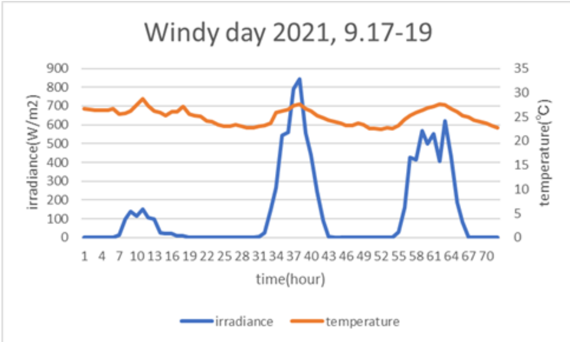

Fig. 12. Irradiance and temperature of windy day(2021, September 17~19).

4. Result

Based on the results obtained from conducting simulations for different scenarios (as shown in Fig. 13 to Fig. 16), a comparison was made between the Perturb and Observe (P&O) method and the Artificial Neural Network (ANN) in the context of Maximum Power Point Tracking (MPPT) system performance.

Under conditions of low solar irradiance, it was observed that the P&O method could accurately track the maximum power point. The P&O method demonstrates the capability to swiftly identify the optimal operating point even under low-light conditions, efficiently controlling the solar panel to generate maximum power.

Conversely, as solar irradiance levels increased, the accuracy of the ANN improved. The ANN employs a more complex model to predict the behavior of the photovoltaic system and adaptively tracks the optimal operating point. In situations with high solar irradiance, the ANN showed superior predictive accuracy and maintained the optimal power generation conditions.

Overall, it was confirmed that the power generation achieved by the ANN was higher than that of the P&O method. The ANN's utilization of advanced control algorithms enables it to exhibit excellent performance and adaptability to various environmental conditions.

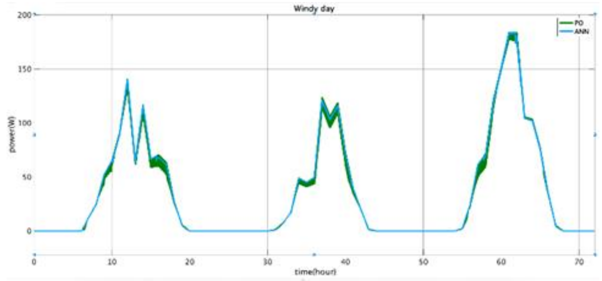

Fig. 13. Comparison of output power with P&O and ANN(cloudy day).

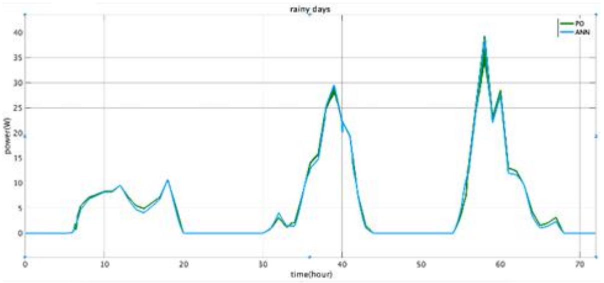

Fig. 14. Comparison of output power with P&O and ANN(rainy day).

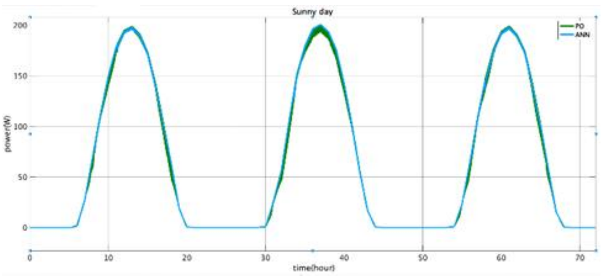

Fig. 15. Comparison of output power with P&O and ANN(sunny day).

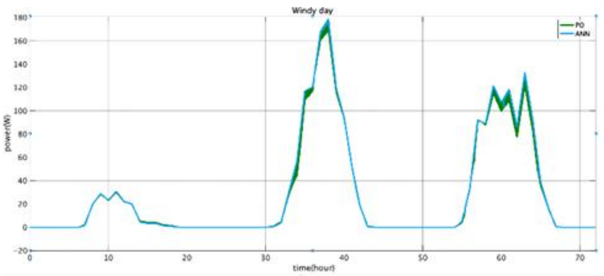

Fig. 16. Comparison of output power with P&O and ANN(windy day)

The power balance between P&O and ANN is shown (see Table 3.)."Improve" represents the percentage by which ANN generated more electrical power compared to P&O. The four simulations conducted found that ANN generated more power than P&O, except on rainy days.

Table 3. Generated power from P&O and ANN for different scenarios

	ANN(W)	P&O(W)	Excess electricity	&improve
Cloudy	2542.44	2522.46	19.97	0.79
Rainy	407.86	420.50	-12.64	-3.01
Sunny	4782.37	4766.46	15.91	0.33
Windy	2050.10	2024.94	25.17	1.24

Considering these results, the selection of the MPPT system should be made based on specific environmental conditions. The P&O method is a favorable choice for scenarios with low solar irradiance, while the ANN demonstrates its advantages in situations with higher irradiance levels. By appropriately selecting the MPPT method, solar photovoltaic systems can achieve greater power generation efficiency under diverse environmental conditions.

5. conclusion

The comparison of simulations between the Perturb and Observe (P&O) method and the Artificial Neural Network (ANN) for Maximum Power Point Tracking (MPPT) systems has revealed that the amount of solar irradiation significantly influences the power generation of solar panels. As solar irradiation increases, the solar photovoltaic system generates more power. Notably, in conditions with relatively high solar irradiation, an MPPT system utilizing ANN is expected to be more efficient in obtaining more power.

These findings provide valuable insights for designing and operating solar photovoltaic systems. For instance, selecting an ANN-based MPPT system can achieve higher power generation efficiency in regions or seasons with abundant sunlight. On the other hand, in areas or times with lower solar irradiation, the P&O method may be a more suitable choice. The selection of the MPPT system should consider specific environmental conditions, such as the local climate and seasonal variations, to ensure optimal performance.

Furthermore, the ANN, employing a more complex model, exhibits greater adaptability to changes in solar irradiation. As a result, it is expected to perform effectively under various weather conditions. The P&O method, while having a relatively simple algorithm, may be more susceptible to fluctuations in solar irradiation. However, the P&O method can also achieve sufficient power generation under stable solar irradiation conditions.

In conclusion, the selection of the MPPT system plays a crucial role in improving the performance of solar photovoltaic systems, and it should be based on the specific environmental conditions of the installation site. An appropriately chosen MPPT system enhances solar energy generation efficiency and promotes the sustainable supply of clean energy.

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