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The Maximum Power Point Tracking Efficiency Comparison on Photovoltaic Using Fuzzy Logic and Perturb & Observe Methods

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Abstract: *An analysis of the power efficiency comparison between perturb and observe (P&O) algorithm and Fuzzy Logic Control (FLC) method being implemented on a photovoltaic (PV) system's maximum power point tracking (MPPT) is presented in this paper. The main limitation of P&O algorithm is its oscillation around the maximum power point (MPP), making its implementation unstable with rapid change in atmospheric condition, such as irradiance and temperature changes. The alternative FLC method was analyzed as comparison. The MPPT simulations have been performed with equal inputs, but using two different methods, namely the P&O algorithm and FLC method. The methods implementation has been based on the common condition and parameter, which were 1000 W•m-2 radiance level and 25ºC temperature. The results show a slight advantage of the FLC method with respect to the P&O algorithm, being indicated with the power efficiency of 98.43% using the FLC method versus 98.11% using the P&O method. Another advantage is that the FLC method with a good tuning delivers smaller oscillation and better rising time.*

Keywords: *photovoltaic, maximum power point tracking, perturb and observe, fuzzy logic control, power efficiency*

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I. Introduction

As one of renewable energy sources, solar energy is one of rapid developing, thanks to its constant production cost reduction and the progress of its technology. The photovoltaic (PV) technology offers several benefits over fossil fuel, as it does not implicate fuel cost, does not contribute to pollution, requires little maintenance, emits no noise, and presents good feasibility to install in remote location. The charged particles generated by the incident radiation in PV are separated conveniently to create an electrical current by an appropriate design of the structure of the solar cell [1]. There are some PV main disadvantages, which consists of high manufacture cost, low efficiency of energy conversion, and nonlinear characteristics. The maximum power point (MPP) is a unique point on the power-voltage (P-V) curve, at which the PV array generates its maximum output power. As the MPP of a PV power generation system depends on the array temperature, received radiation, and load impedance, there is a necessity for tracking the MPP of the solar array continuously[2]. A technique to sustain the PV array operating point at its MPP, known as the maximum power point tracking (MPPT), is required.

Several MPPT methods have been known, including incremental conductance (INC) [3], perturb and observe (P&O) [4], artificial neural network (ANN) with back propagation technique [5], the fuzzy logic controller (FLC) method with DC-DC converter [6] [7], ant colony optimization (ACO), genetic algorithm (GA) method, and others.

The FLC method-based MPPT has been used in the research carried out by Sun and Han in Ref. [8]. It had been based on the improvement of the more previous research using the proportional-integral (PI) control, resulting a fuzzified-PI (FLC-PI) method [8]. The original PI method produced a rise time of 0.55 s which was improved to 0.18 s using the fuzzified-PI method.

Another MPPT technique using the FLC has been proposed in Ref. [9]by combining it with the proportional-integral-derivative (PID) control. A better performance in tracking speed has been obtained using the Fuzzy-PID control than applying conventional techniques such as P&O and ICond[9].

In the research conducted by Huang, et.al. [10], the FLC method has been integrated into artificial neural network (ANN) to find the output error signal. The proposed fuzzified ANN (FLC-ANN) approach proved to be able to reach the MPP with output signal containing less than 2% error [10].

As having been described previously, rarely a comparison between a pure FLC and other methods has been made. Another study analyzing only the application of the P&O algorithm on the PV MPPT has been conducted by Selmi, with the results show that the MPP can be tracked and almost be maintained, while the power output can be maximized [11].

The P&O technique has been widely known thanks to its ease implementation [12]. This algorithm is based on the "hill-climbing" principle, i.e. shifting the PV array point of operation in the course in which the power increases [13]. Hill-climbing performs a perturbation on the duty cycle of the boost converter, while P&O executes a shifting in the DC link operating voltage between the PV array and boost converter [14] [15] [16]. PV voltage and current inputs are used as a reference for MPPT. However, the main P&O drawback is its failure on tracking the power under rapid atmospheric condition variation. This limitation specifically reduces the MPPT efficiency of the P&O method. The P-V curve flattens out when the amount of sunlight decreases [14]. The P&O oscillates around the MPP, making this method unstable with rapid change in atmospheric conditions such as irradiance and temperature [15].

Based on this reason, an alternative MPPT technique is studied and deeply analyzed as comparison, to offer a better choice of possible MPPT techniques for a particular application. In this study, the chosen method to be compared to the P&O algorithm is the FLC method. The main problem to overcome with this alternative is that majority of the present MPPT algorithms undergo slow tracking, bringing about the reduction in their power efficiency. The lower efficiency of solar PV cells makes it difficult to determine the maximum point on the MPP path of the PV module and to give a better performance of the cell with lower oscillation during the MPPT operation. The results of comparison study is aimed to facilitate the choice among the high number of MPPT techniques available, and consequently to get a more reliable control of MPP in a PV system.

II. Research Methods

Method of Comparison Study

A detail comparison between pure P&O algorithm and pure FLC method to inspect all output aspects is performed in this study, including rising time, power efficiency, and power quality (oscillation). Both P&O algorithm and FLC method parameters had been fine-tuned to display their best performance, prior to the comparison.

Several steps will be performed, which is mainly focused in the simulation using MATLAB/Simulink and the related results analysis. The first step is to determine the variables to be analysis, which consist of rise time, oscillation amplitude, and average output power. The second step is to design the model of each simulation, based on the basic principles of P&O algorithm (Fig. 1) and FLC method (Fig. 2). The step is then followed by creating common parameters in which both simulations are to be conducted, i.e. the irradiance and temperature of PV, PWM generator, boost converter, and the load. It is important to make sure that the parameters are identical for a fair comparison.

Next step is to execute the simulations in order to find the optimum output for each method. The next step is to run both simulations under common parameters prepared previously. After the results are acquired, the final step is to make a deep analysis of every outcomes and to make comparison between the two methods, as well as a general comparison with the results of other previous researches [8] [9] [10] [11] [12] [13] [14] [15].

P&O Algorithm and FLC Method as MPP Control Principles

Both P&O algorithm and FLC methods are to be implemented through simulation approach. The schemas of the MPP control using the P&O algorithm and the FLC method are given in Fig. 1 and Fig. 2 subsequently.

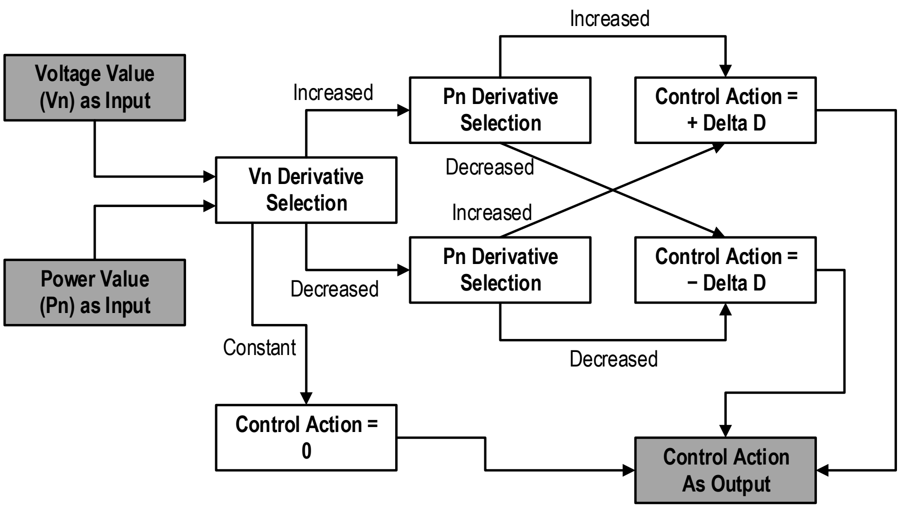

Fig. 1 The principle of MPP control using the P&O algorithm.

P&O algorithm has very simple steps. As shown in Fig. 1, voltage value (Vn) and power value (Pn) are both inputs which are then compared to their previous values, the generated derivative values. The algorithm then checks the Vn derivative value: if it has a zero value then the control action is set to zero; otherwise if it has a positive value then the control action is set to ΔD with the sign equals to the Pn derivative; otherwise if it has a negative value then the control action is set to ΔD with the sign being opposite to the Pn derivative. The value of ΔD is set constant.

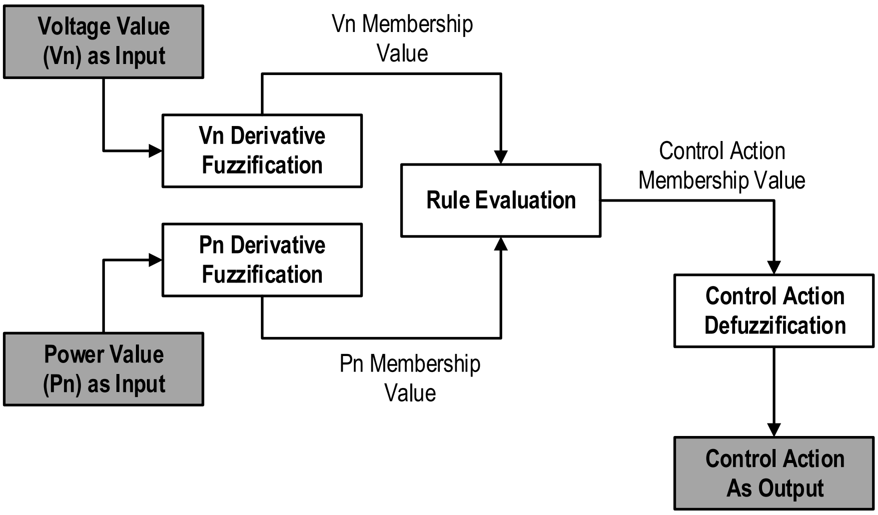

Fig. 2 The principle of MPP control using the FLC method.

The FLC method explained in Fig. 2 comprises three main computation blocks, on the other hand. Just as in P&O, Vn and Pn are inputs in FLC and their values are converted into fuzzy memberships previously prepared, a process called fuzzification. In the rule evaluation process, the membership values are then used as lookup keys in the rule table to determine the control action membership value. Final step is to convert back the control action membership value into crisp value, an opposite process called defuzzification. The crisp value is then fed into the output as a control action. The value of ΔD in this method is basically not constant, but varies according to the current output distance from MPP. As the current state approaching MPP, the ΔD value approaches to zero.

The Model of the PV System

Fig. 3 explains the model of PV module used in this research. It is based on Ref. [17] and Ref. [18] representing the Kyocera Solar KC200GT type which has a maximum power of about 1000 W. The main parameters of the Kyocera solar module at 25 °C and 1000 W·m^{-2} comprise the open-circuit voltage V_{oc} of 32.9 V and the short-circuit current I_{sc} of 8.21 A. In the PV model, the parameters influencing the PV operation are to be known.

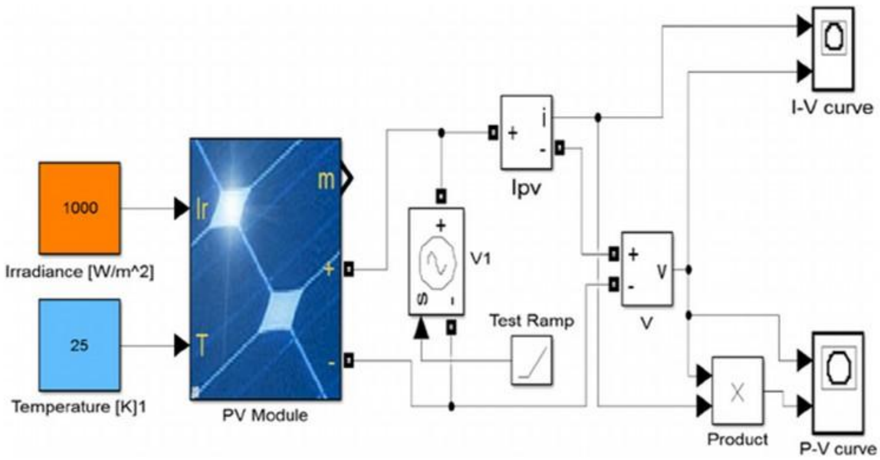

Fig. 3 Kyocera Solar KC200GT PV module modeling in Matlab/Simulink[18].

Fig. 3 shows the PV block diagram, includes the solar cell, with the positive and negative terminal connected to boost converter. The other terminal acts as feedback, is connected to the controller, whether implements P&O algorithm or FLC method. The difference between the two blocks besides receiving standard parameter signals from photovoltaic blocks (temperature and irradiation), MOSFET in the boost converter will also receive signals from P&O and FLC, then performs MPPT. At the MPP condition, the photovoltaic produces the voltage of 26.3 V and the current of 7.61 A, giving the maximum power of 200.14 W [17].

Common Simulation Parameters Determination

Simulations to perform are consisted of two types. The first one is the MPPT simulation using P&O algorithm, while the second one is the MPPT simulation using the FLC method. The simulations will be run under common parameters below:

- Irradiance level is defined to 1,000 W·m^{-2}.
- Ambient temperature of solar panel is determined as 25º C.
- PWM generator switching frequency is set to 31,000 Hz.
- Capacitor capacitance before the boost converter is set to 1,150 μF.
- Inductance in the boost converter is set to 45 μH.
- MOSFET in the boost converter has a FET resistance of 0.1 Ω, internal diode inductance of 0 H, internal diode resistance of 0.01 Ω, internal diode forward voltage of 0 V, snubber resistance of 100,000 Ω, and snubber capacitance of infinity.
- Diode in the boost converter has a resistance of 0.001 Ω, inductance of 0 H, forward voltage of 0.004 V, snubber resistance of 750 Ω, and snubber capacitance of 0.25 μF.
- Capacitor in the boost converter is set to 2,500 μF.
- Load after the boost converter has a nominal voltage of 28.5 V, nominal frequency of 50 Hz, active power of 120 W, inductive reactive power of 0 VAR, and capacitive reactive power of 0 VAR. The load flow model is set to constant current.
- Duty cycle constrains from both methods are limited to minimum of 0.02 and maximum of 0.98.

  For each of the simulation performed, the period is set to 3 s, while the data sampling time of the plotting is set to 0.0001 s (100 μs).

III. Results and Discussions

P&O Algorithm Model Development for Simulation

The circuit diagram of PV MPPT using P&O algorithm in Simulink is displayed in Fig. 4, whose resulted data will be analyzed. The inputs of the function are voltage and current from the PV. Both the voltage and current can be used to compute power. All values of input and output from the previous step are stored in memory in order to generate their derivatives. This P&O has a constant change of duty cycle, which is set to 0.0025 after several attempts to achieve the fastest rising time and lowest oscillation.

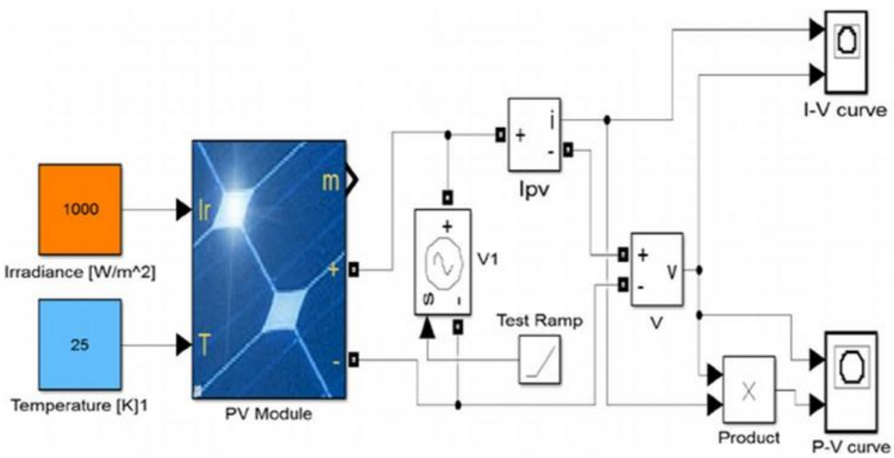

Fig. 4 Simulink PV MPPT circuit diagram for P&O algorithm.

P&O Algorithm Simulation Result on MPPT

Fig. 5 and Fig. 6, respectively, show the simulation results of P&O algorithm implementation. Fig. 5 specifies the profiles of output voltage, current, and power from simulation on PV MPPT using P&O algorithm during the first 3 seconds. Fig. 6 indicates the profile of output power from simulation on PV MPPT using P&O algorithm in the first 100 ms.

As shown in Fig. 6, P&O algorithm produces rise time at 0.0482 s. This method implementation produces the average power output value of 196.347 W, coming from the obtained minimum power of 192.573 W, and the maximum power of 200.44 W. The peak-to-peak amplitude of the oscillation is 7.867 W. The power reaches the minimum steady-state value of 192.573 W for the first time in 0.0482 s (48.2 ms).

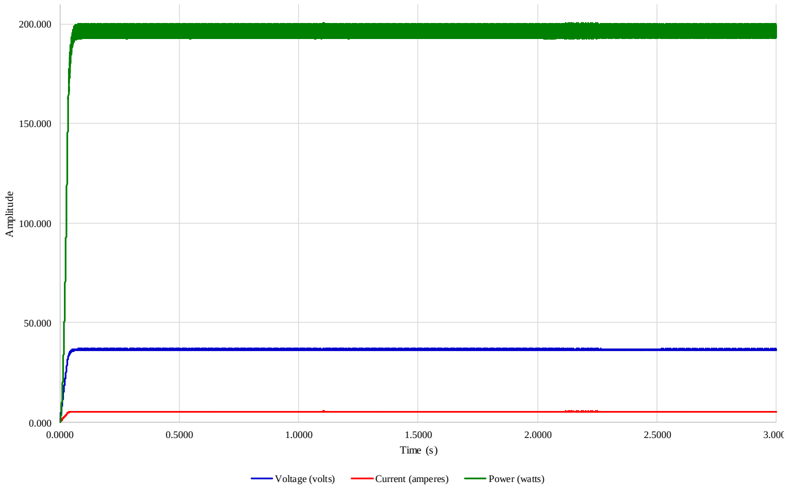

Fig. 5 The profiles of output voltage, current, and power from simulation on PV MPPT using P&O algorithm during the first 3 seconds.

FLC Method Model Development for Simulation

As shown in Fig. 7, the entire circuit diagram of PV MPPT using FLC in Simulink, whose simulation results will be analyzed. On the other side, Fig. 8 shows the detailed view of the FLC block.

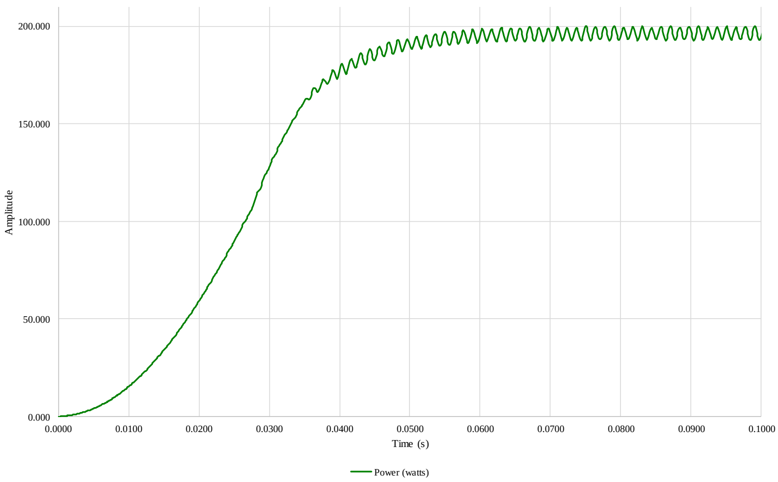

Fig. 6 The profile of output power from simulation on PV MPPT using P&O algorithm during the first 100 milliseconds.

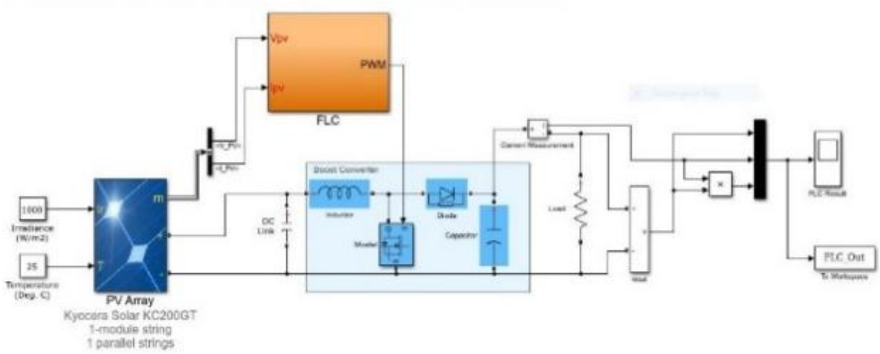

Fig. 7 Simulink PV MPPT entire circuit diagram for FLC method.

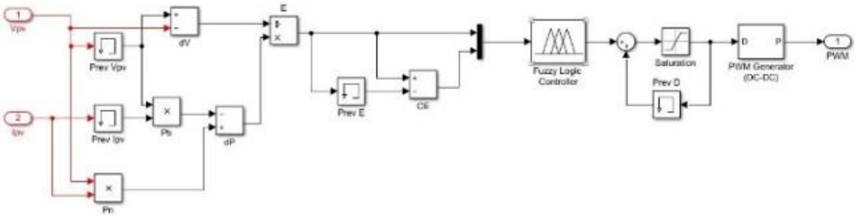

Fig. 8 Simulink PV MPPT detailed circuit diagram for FLC method.

The method implementation covers the process of fuzzification, implementation of rules, and defuzzification which determines the duty cycle value for the PWM generator. The fuzzification of voltage derivative (Vn) is shown by the membership functions given in Fig. 9, while for the power derivative (Pn) is shown in Fig. 10.

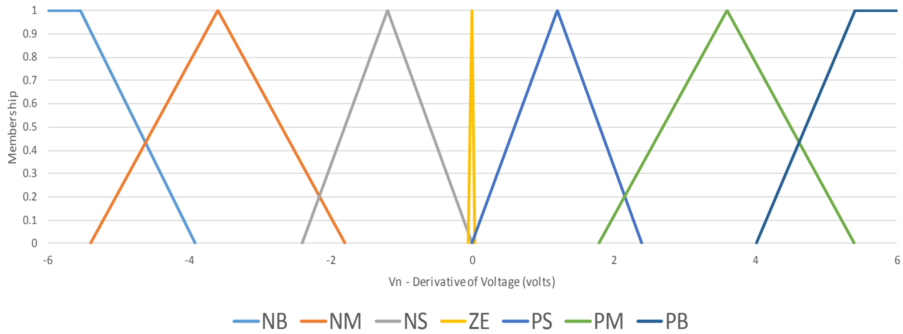

Fig. 9 Membership functions of voltage derivative.

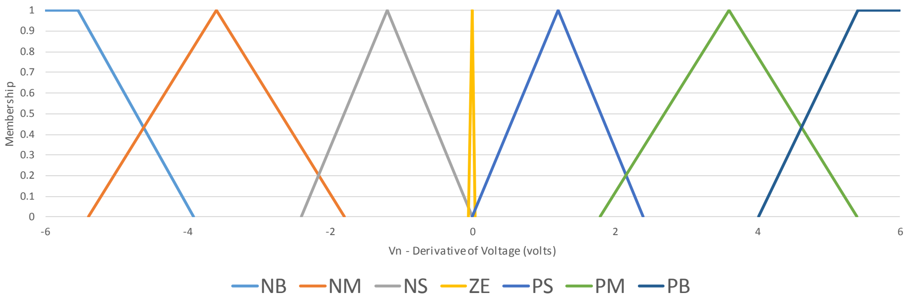

Fig. 10 Membership functions of power derivative.

After the membership of voltage derivative and power derivative are determined, the FLC process goes into the rule evaluation to decide the control action to be taken. The FLC rule is set into table type as in Table 1.

TABLE I
FLC RULE FOR MPPT

Vn \ Pn	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	PB	PM	PS	NS	NS	NM	NB
NM	PM	PS	PS	NS	NS	NM	NB
NS	PS	PS	PS	PS	NS	NS	NM
ZE	NS	NS	NS	ZE	PS	PS	PS
PS	NS	NS	NS	ZE	PS	PS	PS
PM	NM	NS	NS	NS	PS	PS	PM
PB	NB	NM	NS	NS	PS	PS	PB

Under the rule table at Table 1, the control action can be decided. Fig. 11 shows the surface control for MPPT. The action taken can be fallen into more than one membership of the control action. The inference engine chooses minimum membership value between power derivative and voltage derivative, and gives the value to the action membership as weight.

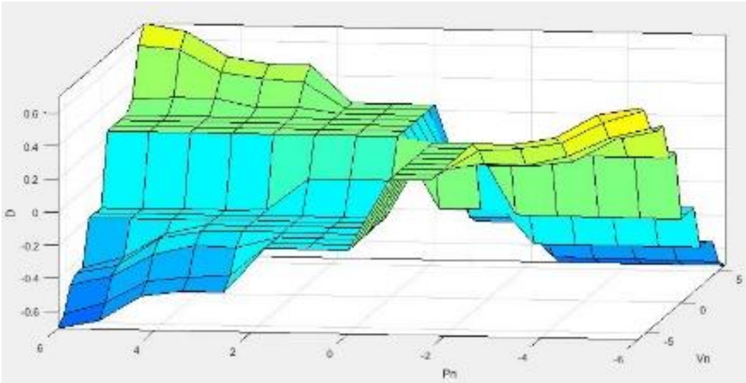

Fig. 11 Surface view of FLC rules for MPPT.

The membership functions of duty cycle as the control action is given in Fig. 12. Next, in the Fig. 12, the action is given in Fig. 12. The membership functions are the defuzzification to generate level of increasing or decreasing value of duty cycle. After the centering process, the membership of control action are determined, and finally the value of duty cycle can be updated by the defuzzification value and constrained within the value of 0.02 to 0.98.

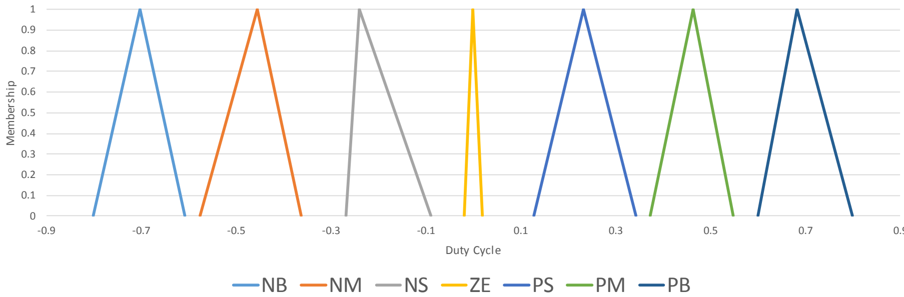

Fig. 12 Membership functions of duty cycle as the control action.

FLC Method Simulation Result on MPPT

The profiles of output voltage, current, and power from simulation on PV MPPT using FLC method during the first 3 seconds is indicated by Fig. 13. On the other side, Fig. 14 shows the profile of output power from simulation on PV MPPT using FLC method during the first 100 milliseconds.

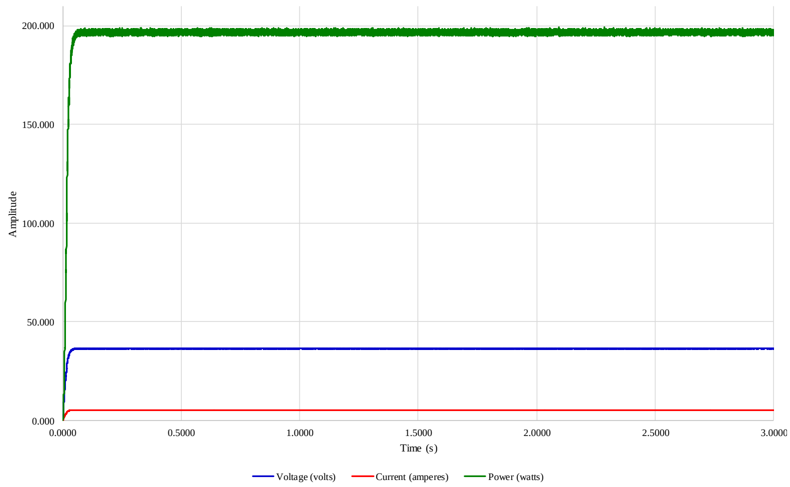

Fig. 13 The profiles of output voltage, current, and power from simulation on PV MPPT using FLC method during the first 3 seconds.

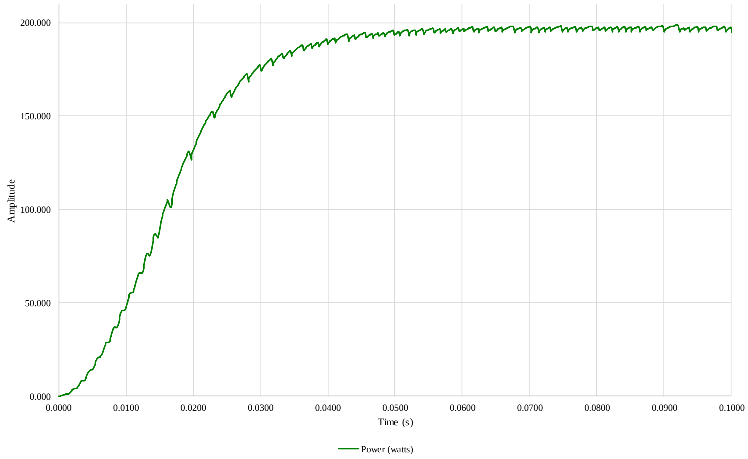

Fig. 14 The profile of output power from simulation on PV MPPT using FLC method during the first 100 milliseconds.

Visually, the power profile is analogue to both the voltage and current profiles, as seen in the FLC method implementation result. As indicated in Fig. 14, the FLC method implementation produces the rise time of 0.0454 s. The implementation of FLC method delivers the average power output value of 196.996 W, with minimum power of 194.545 W, and maximum power of 199.091 W. The oscillation has the peak-to-peak amplitude of 4.546 W. The power reaches minimum steady-state value of 194.545 W for the first time in 0.0454 s (45.4 ms).

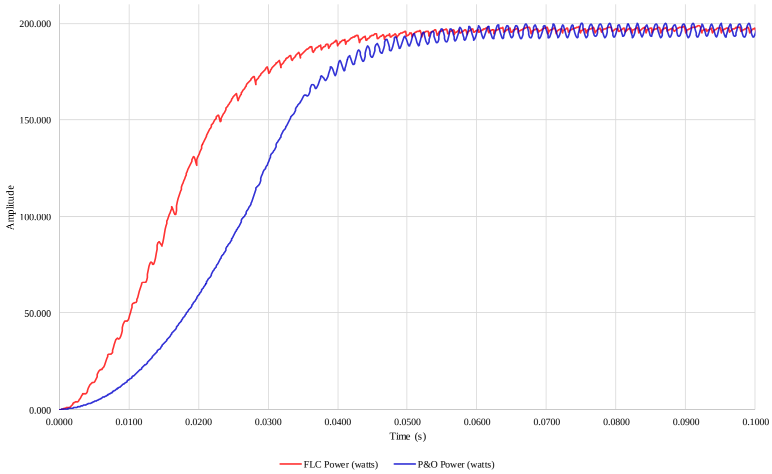

Fig. 15 Comparison between MPPT power profile using P&O algorithm and FLC method during the first 100 milliseconds.

P&O Algorithm and FLC Method Implementation Results Comparison Analysis

The comparison results between the implementation of P&O algorithm and FLC method for MPPT are shown in Fig. 15 and Fig. 16, respectively. Fig. 15 shows the comparison between MPPT power profiles using P&O algorithm and FLC method during the first 100 milliseconds. Fig. 16 indicates those profiles during the time between 100 ms to 200 ms.

During the first 100 milliseconds, the P&O algorithm takes a bit longer rising time from zero to reach the stability point, while the FLC method gives the rapid one, as seen on Fig. 15.

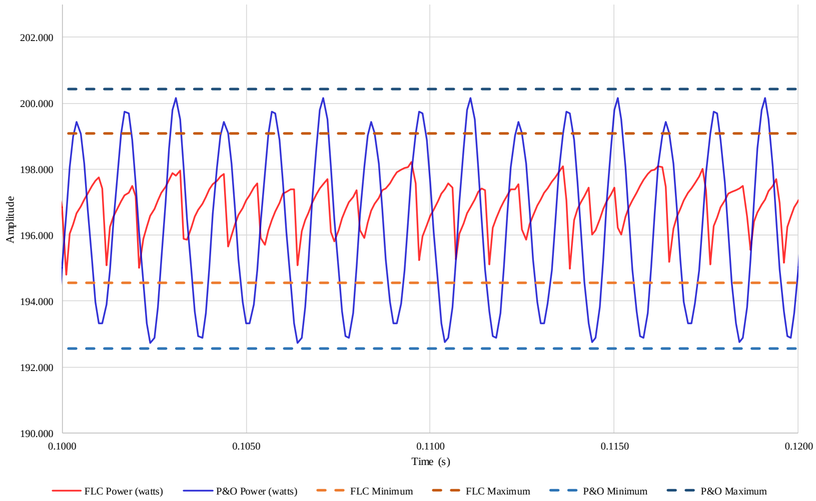

Fig. 16 Comparison between MPPT power profile using P&O algorithm and FLC method between 100 ms to 200 milliseconds.

The ΔD of P&O algorithm plays a special role in rising time and oscillation near the maximum power point. If a large ΔD value is chosen, a rapid rising time will be achieved, with a consequence of a large oscillation around MPP. In the other case, if a small ΔD value is chosen, the oscillation around MPP will be suppressed while it needs longer time of rise time. In this simulation case, the value of ΔD has been chosen as 0.0025. The P&O algorithm uses constant ΔD, therefore the increasing or decreasing value of duty cycle during one step of the function is fixed at 0.0025.

In contrary to P&O approach, FLC method uses various value of ΔD, based on input. Voltage and power change as inputs are converted into fuzzy value membership, and based on the rule table the output of ΔD is then determined through the defuzzification. Therefore, the wildness of duty cycle changing depends on the voltage distance from maximum power point.

Table II: Summary of P&O Algorithm and FLC Method on Photovoltaic MPPT

Description	P&O Algorithm	FLC Method
Rising time	0.0482 s	0.0454 s
Minimum power on oscillation after 100 ms	192.573 W	194.545 W
Maximum power on oscillation after 100 ms	200.44 W	199.091 W
Average power after 100 ms	196.347 W	196.996 W
Peak-to-peak oscillation after 100 ms	7.867 W	4.546 W
Method efficiency (compared to 200.14 W in datasheet)	98.105%	98.429%

Constant duty cycle changing in P&O algorithm is its nature, while it tends to oscillate larger than FLC method ones. Based on the theory, FLC method can achieve zero oscillation. However, The nature of boost converter and PWM generator produces a slight oscillation. The oscillation in the simulations shows the peak-to-peak ripple of 7.867 W under P&O algorithm and 4.546 W under the FLC method.
Table 2 shows the summary of both methods results, which displays the difference between FLC method and P&O algorithm implementation.

The summary on Table 2 gives the conclusion that the FLC method produces efficiency reaches 98.429%; a slightly better than the value obtained using the P&O algorithm, which is 98.105%. The FLC method also has a slightly better rising time of 45.4 ms, compared to 48.2 ms using P&O algorithm. The oscillation generated by FLC method is also lower in just 4.546 W peak-to-peak, compared to the 7.867 W peak-to-peak using P&O algorithm. It concludes that in those three aspects, which are the effective power, rising time, and oscillation, the FLC method generates better performance over P&O algorithm.

Some previous studies results are given as comparable values: Sun and Han achieved 0.18 s of rise time in FLC-PI method [8], while this study can make 0.0454 s of rise time in the pure FLC method. A research by Huang achieved less than 2% of signal error, which corresponds to at least 98% power efficiency in the implementation of FLC-ANN into MPPT [10], while this research delivers 98.429% power efficiency in pure FLC method. Those better results in this study have been reached because of a fine-tuning procedure to find optimum performance of each method before conducting simulation for comparison.

IV. Conclusions

After a deep analysis undertaken of the results in this study, some conclusions can be taken as following:

- Two types of PV MPPT simulations have been successfully built using Simulink, implemented the P&O algorithm and the FLC method.
- When the PV MPPT method performed under 1,000 $W \cdot m^{-2}$ irradiance and 25º C temperature, P&O algorithm implementation produced 98.105% of efficiency, while the FLC method delivered 98.429% of efficiency.
- The efficiency, rising time, and oscillation of FLC method are better than P&O algorithm in PV MPPT.

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