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Analysis and Comparaison of MPPT Nonlinear Controllers for PV System using Buck Converter

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***Abstract*— This paper describes a maximum power point tracking (MPPT) approach in photovoltaic system based on sliding mode control (SMC) and fuzzy logic control (FLC). Due to the nonlinear output characteristic, fuzzy control and Sliding Mode Control are introduced to realize MPPT. The simulation is carried out based on proposed algorithm. Compared with the conventional duty cycle of perturb and observe (P&O) control method, they can track de maximum power point quickly and accurately. For simulation, a simulation model in Simulink/Matlab of a solar cell has been presented. A buck converter has been used to control the solar cell output voltage. The MPPT control the duty cycle of the buck converter.**

Keywords*— MPPT; Solar Energy; Photovoltaic; PV; DC-DC Converters; buck converter; Nonlinear Control; perturb and Observe; Fuzzy Logic Control; Sliding Mode Control Introduction

I. INTRODUCTION

Solar energy is the conversion of the energy from the sun to usable electricity. The most common source of solar energy utilizes photovoltaic cells to convert sunlight into electricity. Photovoltaic utilize a semi-conductor to absorb the radiation from the sun, when the semi-conductor absorbs this radiation it emits electrons, which are the origin of electricity.

Solar energy has extraordinary advantages when compared with other source. The field of photovoltaic (PV) solar energy has experienced a remarkable growth for past two decades. However, Maximum Power Point Tracking (MPPT) control is an essential part of a PV system to extract maximum power from the PV [1]-[3].

In recent years, a large number of techniques has been developed and implemented for tracking the Maximum Power Point (MPP) [4]-[6].

Fuzzy and sliding mode controls is two nonlinear robust MPPT approach. In this work we propose a comparison between the two controllers and Perturb and Observe (P&O) MPPT method and we will take an interest in the transitional regime.

In the second paragraph, we present a photovoltaic cell with different curve of voltage output, current output and power output for various climatic conditions.

II. PV ARRAY

A. Photovoltaic cell

Photovoltaic cell is the most basic of a PV modules. Solar cell consist of a P-N junction fabricated in a layer semiconductor. The current-voltage $(I-V)$ and power-voltage $(P-V)$ outputs characteristics of solar cell is similar to that of a diode[1]-[3]. Under sun, photons with energy greater than the bandgap energy of the semiconductor are absorbed and great an electron-hole pair and create a current proportional to the irradiation.

The performance of a photovoltaic cell is usually presented by its $I(V)$ curve and $P(V)$ which is produced for several irradiation levels and several cell temperature levels.

The variation of current versus voltage curve is shown in Fig.1 under various irradiation levels (200, 500 and 800W/m²). For each irradiation, the maximum power point (MPP) is such that the area defined by $I_{pv}V_{pv}$ is maximum.

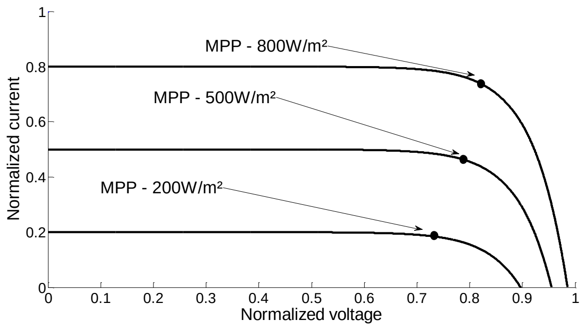

Fig. 1. Variation of normalized current vs voltage curve of PV array

The variation of power versus voltage curve is shown in Fig.2 for various irradiation levels (200, 500 and 800W/m²).

The output power has a maximum at a output voltage V_m.

When the irradiation increases the maximum power increases.

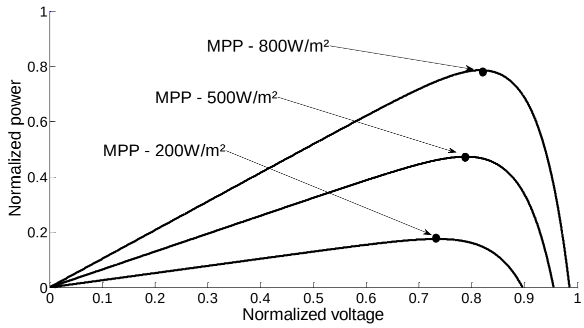

Fig. 2. Variation of normalized power vs voltage curve of PV array

The variation of current versus voltage curve under various temperature of solar cell(25-35-45°C) is shown in Fig.3. The maximum power decreases as the temperature increases.

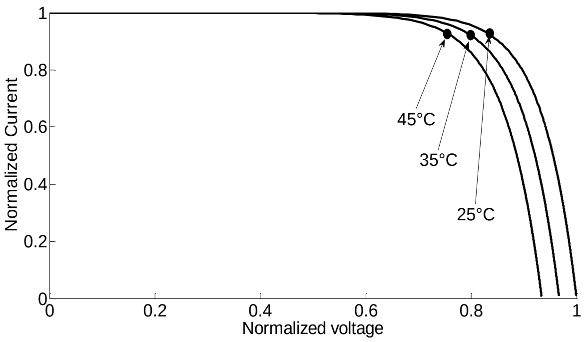

Fig. 3. Variation of normalized current vs voltage curve of PV array

The variation of power versus voltage curve is shown in Fig.4 for various solar cell temperature. The maximum power decreases when solar cell temperature increases.

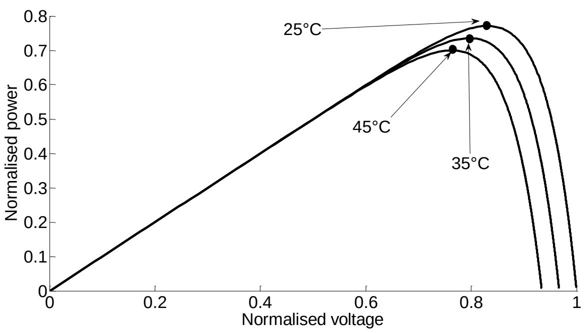

Fig. 4. Variation of normalized power vs voltage curve of PV array

We can observe that low solar irradiance and high cell temperature will reduce the power conversion capability.

B. Simulink model of the solar PV model

The above characteristics can be deduced from a mathematical model.

The general mathematical expression for the illuminated $I(V)$ curve for a solar panel is given by the following one exponential equation [1]

$$\mathrm{I_{pv}} = \mathrm{i_{pv}} - \mathrm{I_0}\left[\exp\left(\frac{\mathrm{V_{pv}}+\mathrm{I_{pv}R_s}}{\eta \mathrm{N_s V_t}}\right) - 1\right] - \frac{\mathrm{V_{pv}}+\mathrm{I_{pv}R_s}}{\mathrm{R_{sh}}} \qquad (1)$$

$$\mathrm{V_t} = \frac{\mathrm{k_b T}}{\mathrm{e}} \qquad (2)$$

Where

I_{pv} : output current of solar cell (A)

i_{pv} : photocurrent current passing P-N junction (A)

I_0 : reverse saturation current of PV (A)

V_{pv} : output voltage of solar cell (V)

N_s : number of cells

η : diode quality

R_s : series resistance (Ω)

R_{sh} : shunt resistance (Ω)

e : electron charge (C)

k_b : Boltzmann's constant ($J.K^{-1}$)

T : temperature of solar cell (K)

V_t : thermal voltage (V)

We have used Matlab/simulink to implement the model of the solar PV panel.

The equivalent circuit of equation (1) is presented schematically in Fig.5 with a DC voltage generator which models the photocurrent, a diode which models the semiconductor and two resistors which models the escape currents.

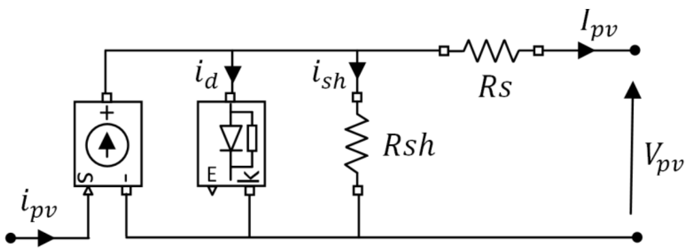

Fig. 5. Simulink model of the solar PV model

Where

i_d : diode current

R_{sh} : shunt resistance

R_s : series resistance

The key specification of PV module are shown in Table I.

TABLE I. PV MODULE PARAMETERS

At temperature	T	25	°C
Open circuit voltage	V_{oc}	21.6	V
Short circuit current	I_{sc}	1.31	A
Voltage, maximum power	V_{pmax}	17.0	V
Current, maximum power	I_{pmax}	1.18	A
Maximum power	P_{max}	20.0	W

To properly use a PV module, it must operate in its maximum power point MPP. Next paragraph describe how tracking the maximum power point.

III. Maximum Power Point Tracking

The goal of the MPPT is to find the maximum power under different operating conditions, i.e. the different temperature and irradiation values.

Fig.6. shows the variation of normalized power versus normalized voltage curve under different irradiation (200, 400, 600, 800, 1000W.m²) and the maximum power point curve.

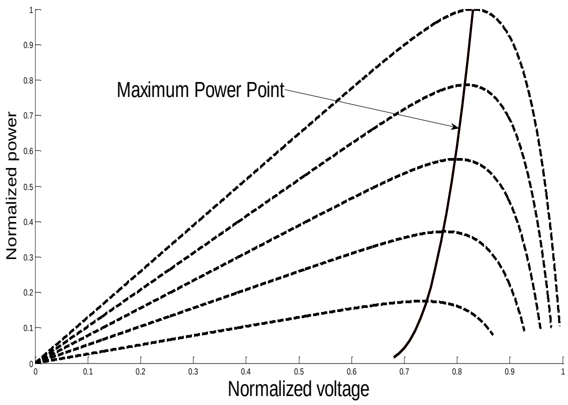

Fig. 6. Maximum power point

The problem considered by MPPT techniques is to automatically find the corresponding duty cycle D for voltage V_{pv} or current I_{pv} at which a PV array should operate to obtain the maximum power point output P_{pv} under a given irradiation and temperature [1]-[3].

Fig.7. shows MPPT system where V_{pv} is PV voltage, I_{pv} is PV current, V_L is the load voltage, I_L is the load current and D is a duty cycle.

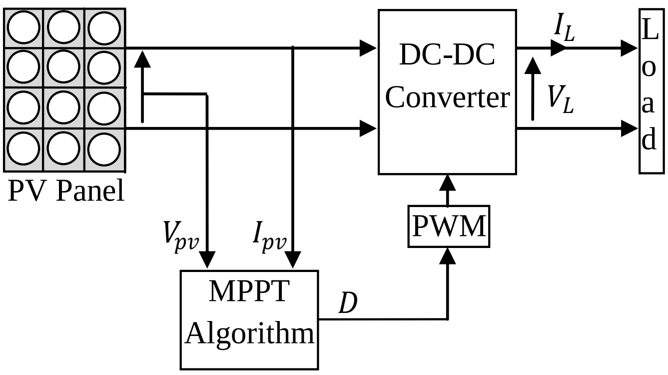

Fig. 7. MPPT system

The MPPT system contains five elements which are the PV load, DC-DC converter, load, the Pulse width Modulation (PWM) and the MPPT algorithm.

The following paragraph describing the DC-DC buck converter.

IV. DC-DC Converters Modeling

The MPPT algorithm, control the duty cycle of a buck converter[14]. Fig.8. shows a buck converter model in Simulink.

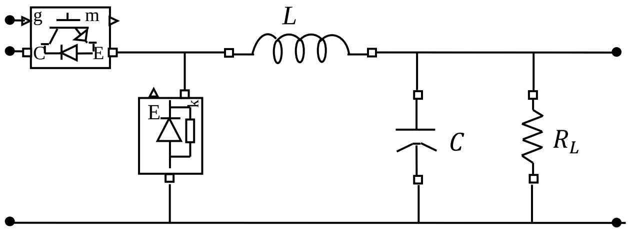

Fig. 8. Buck converter Simulink model

The buck converter can be written in two sets of state equation depends on the duty cycle D equations (8) and (9)

The buck converter operate in two state. If the IGBT is on or off, if it is on, the diode is blocked so the buck converter Simulink model is equivalent to the circuit shown in Fig.9.

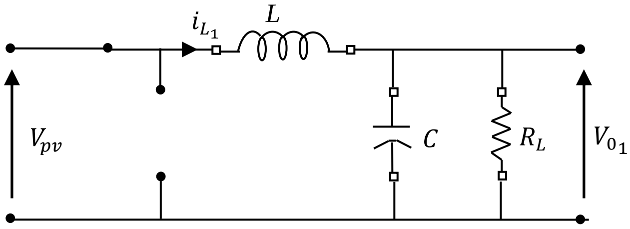

Fig. 9. Buck converter equivalent circuit when IGBT is on.

The system can be written in two equations :

$$\frac{dV_{0_1}}{dt} = \frac{i_{L_1}}{C} - \frac{V_{0_1}}{CR_L} \qquad (3)$$

And

$$\frac{di_{L_1}}{dt} = \frac{V_{pv}}{L} - \frac{V_{0_1}}{L} \qquad (4)$$

If the IGBT is off, the diode is conducting so the buck converter Simulink model is equivalent to the circuit shown in Fig.10.

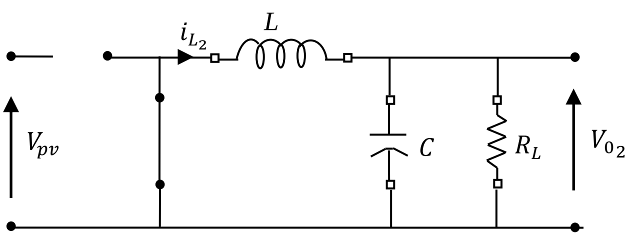

Fig. 10. Buck converter equivalent circuit when IGBT is of.

The system can be written in to two equation :

$$\frac{dV_{0_2}}{dt} = \frac{i_{L_2}}{C} - \frac{V_{0_2}}{CR_L} \qquad (5)$$

And

$$\frac{di_{L_1}}{dt} = -\frac{V_{0_1}}{L} \tag{6}$$

The buck converter can be written in two sets of state equation depends on the duty cycle :

$$\frac{dV_0}{dt} = \frac{i_L}{C} - \frac{V_L}{CR_L} \tag{7}$$

And

$$\frac{di_L}{dt} = \frac{V_{pv}}{L}D - \frac{V_0}{L} \tag{8}$$

If the IGBT is on $D = 1$, and if it is of $D = 1$

V. MPPT ALGORITHMS

This paragraph describing three MPPT algorithms which are the Fuzzy logic , sliding mode and perturb and observe controls.

A. Fuzzy logic control

Fuzzy logic controller have the advantage to working with imprecise inputs, not needing an accurate mathematical model, and handling nonlinearity[7]-[10].

Fuzzy logic controller generally consists of three stages: fuzzification, rules base table lookup, and defuzzification. During fuzzification, numerical input variables are converted into linguistic based on membership function similar to Fig.11. In this case five fuzzy levels are used : NB (Negative Big), NS (Negative Small), ZE(Zero), PS (Positive Small) and PB (Positive Big).

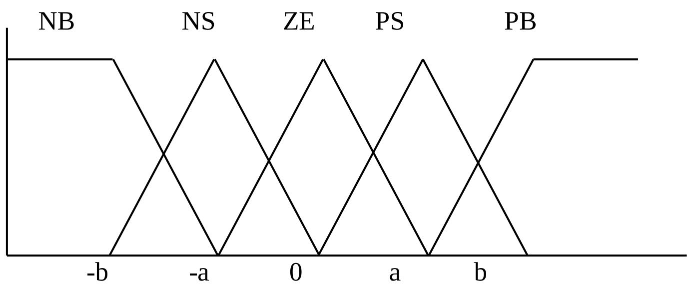

Fig. 11. Membership function for inputs and output of fuzzy controller

The inputs to a MPPT fuzzy logic controller are usually an error E and a change error CE.

$$E(n) = \frac{P(n)-P(n-1)}{V(n)-V(n-1)} \tag{9}$$

$$CE(n) = E(n) - E(n-1) \tag{10}$$

Where

$P(n)$: actual output power

$V(n)$: actual output voltage

$E(n)$: actual error

$CE(n)$: actual change error

$P(n-1)$: previous output power

$V(n-1)$: previous output voltage

$E(n-1)$: previous error

$CE(n-1)$: previous change error

Table II shows the rule table of fuzzy controller, where all the entries of matrix are fuzzy sets of error E, change of error CE and duty cycle D [9].

TABLE II. FUZZY RULE BASE TABLE

E\CE	NB	NS	ZE	PS	PB
NB	ZE	ZE	NB	NB	NB
NS	ZE	ZE	NS	NS	NS
ZE	NS	ZE	ZE	ZE	PS
PS	PS	PS	PS	ZE	ZE
PB	PB	PB	PB	ZE	ZE

If, for example, the operating point is far to the left to the maximum power point (MPP) that is E is PB and CE is ZE, then we need to largely increase the duty cycle, that D should be PB to reach the MPP.

To explain the steps to follow to determine how the fuzzy logic controller operate, we take an example of an operating point. Which the membership of error and changing error is shown in Fig.12. and Fig.13.

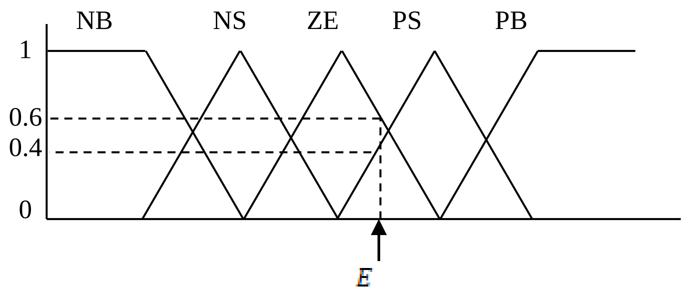

Fig. 12. Membership function for error E

We read, the error E is sixty percent ZE and forty percent PS.

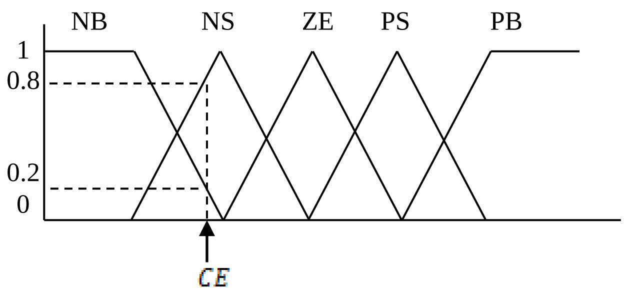

Fig. 13. Membership function for changing error CE

In this example changing error CE is 80% NS and 20% NB.

From fuzzy rules base table, we have :

E is 60% ZE and CE is 80% NS, D is 60% ZE

E is 60% ZE and CE is 20% NB, D is 20% NS

E is 40% PS and CE is 80% NS, D is 40% PS

E is 40% PS and CE is 20% NB, D is 20% PS

In result,

D is 60% ZE, 20% NS and 40% PS

Then the membership function for duty cycle D is shown in Fig.14.

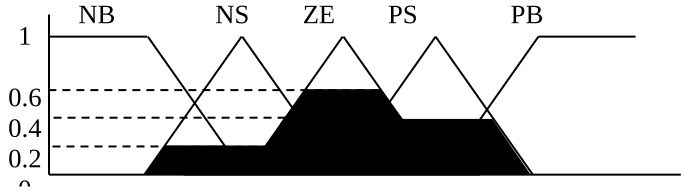

Fig. 14. Membership function for duty cycle D

The last stage of fuzzy logic controller is the defuzzification that converts the fuzzy duty cycle into numerical duty cycle proportional to the black area in fig.14.

The algorithm of the fuzzy logic controller is as follows. The actual voltage and current of PV array can be measured continuously and the power can be deduced by calculation, then, the error and changing error can be calculated and converted into linguistic variables based on membership function, so, the linguistic duty cycle can be converted into numerical variables based on fuzzy rules then, the duty cycle can be converted by defuzzification. Fig.15. shows the fuzzy logic controller algorithm.

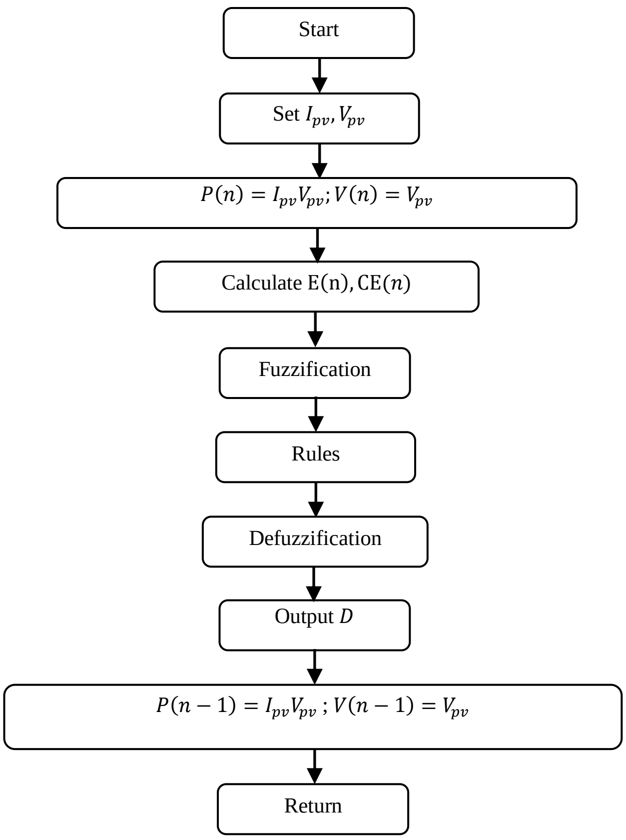

Fig. 15. Algorithm for fuzzy logic controller

In Simulink we use the bloc shown in Fig.16.[10]

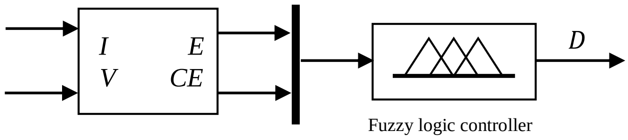

Fig. 16. Simulink bloc for fuzzy logic controller

B. Sliding mode control

The advantage of sliding mode controller are various and important : high precision, good stability, simplicity, invariance, robustness [11],[13], [14].

A typical sliding mode control has two modes of operation. One is called the approaching mode, where the system state converges to a pre-defined manifold named sliding function in finite time. The other mode is called the sliding mode, where the system state is confined on the sliding surface and is driven to the origin. In this study, we introduce the concept of the approaching control approach. By selecting the sliding surface as $\frac{\partial P_{pv}}{\partial I_{pv}} = 0$, it is guaranteed that the system state will hit the surface produce maximum power output persistently [11],[13].

The expression of sliding surface is :

$$\frac{\partial \mathrm{P_{pv}}}{\partial \mathrm{I_{pv}}} = \frac{\partial \mathrm{I_{pv}^2 R_{pv}}}{\partial \mathrm{I_{pv}}} = \mathrm{I_{pv}}\left(2\mathrm{R_{pv}} + \mathrm{I_{pv}}\frac{\partial \mathrm{R_{pv}}}{\partial \mathrm{I_{pv}}}\right) = 0 \qquad (11)$$

Where $R_{pv} = \frac{V_{pv}}{I_{pv}}$ is the equivalent load connect to the PV.

The non-trivial solution of Eq (11) is :

$$2\mathrm{R_{pv}} + \mathrm{I_{pv}}\frac{\partial \mathrm{R_{pv}}}{\partial \mathrm{I_{pv}}} = 0 \qquad (12)$$

The sliding surface is defined as :

$$\sigma = 2\mathrm{R_{pv}} + \mathrm{I_{pv}}\frac{\partial \mathrm{R_{pv}}}{\partial \mathrm{I_{pv}}} \qquad (13)$$

The buck converter can be written in two sets of state equation depends on the duty cycle D : (7) and (8). Which can be combined into one set of state equation to represent the dynamic of system :

$$\dot{X} = (1-\mathrm{D})\dot{\mathrm{X}}_1 + \mathrm{D}\dot{\mathrm{X}}_2 \qquad (14)$$

Based on the observation of duty cycle versus operation region as depicted, the duty cycle output control can be chosen as :

$$D_{update} = \begin{cases} D + \Delta D \; si \; \sigma > 0 \\ D - \Delta D \; si \; \sigma < 0 \end{cases} \qquad (15)$$

Equivalent control D_{eq} is determined by condition

$$\dot{\sigma} = \left[\frac{d\sigma}{dx}\right]^T \frac{\mathrm{di_{pv}}}{\mathrm{dt}} = 0 \qquad (16)$$

The equivalent control is derived :

$$D_{eq} = -\frac{\left[\frac{\partial\sigma}{dX}\right]^T f(X)}{\left[\frac{\partial\sigma}{dX}\right]^T g(X)} = \frac{V_{PV}}{V_L} \qquad (17)$$

Finally The control is given by :

$$D = \begin{cases} 1 & si \quad D_{eq} + k\sigma \geq 1 \\ D_{eq} + k\sigma & si \quad 0 \leq D_{eq} + k\sigma \leq 1 \\ 0 & si \quad D_{eq} + k\sigma \leq 0 \end{cases} \qquad (18)$$

where k is a positive constant

The duty cycle of sliding mode controller is determined by the operating point. As the operating point is to the left of maximum power point (MPP), the sliding surface is negative so the duty cycle decrease. The same the duty cycle increase if the operating point is in the right of MPP.Fig.17.

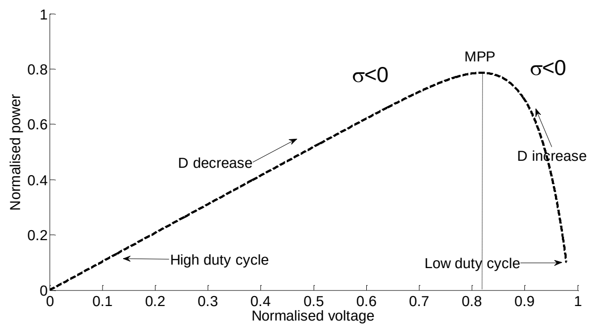

Fig. 17. Duty cycle versus operation region

C. *Perturb and observe (P&O) control*

There have been extensive applications of the P&O MPPT algorithm in various types of PV system. This is because P&O algorithm has a simple control structure and few measured parameters are required for the power tracking. Moreover, it has an advantage of not relying on the PV module characteristics in the MPPT process and so can be easily applied to any PV panel. The name of algorithm itself reveals that it operates by periodically perturbing the control variable and comparing the instantaneous PV output power after perturbation with that before. The outcome of the PV power comparison together with the PV voltage condition determines the direction of the next perturbation that should be used.

The simplicity of perturb and observe method make it the most commonly used MPPT algorithm in commercial PV products. It is easy to implement.

This is essentially a 'trial and error' method. The PV controller increase the reference for the inverter output power by a small amount, and then detect the actual output power. If the output power is indeed increased, it will increase again until the output starts to decrease, at which the controller decreases the reference avoid collapse of the PV output due to the highly non-linear PV characteristic [4],[5],[12].

Fig.18. shows the P&O algorithm [15].

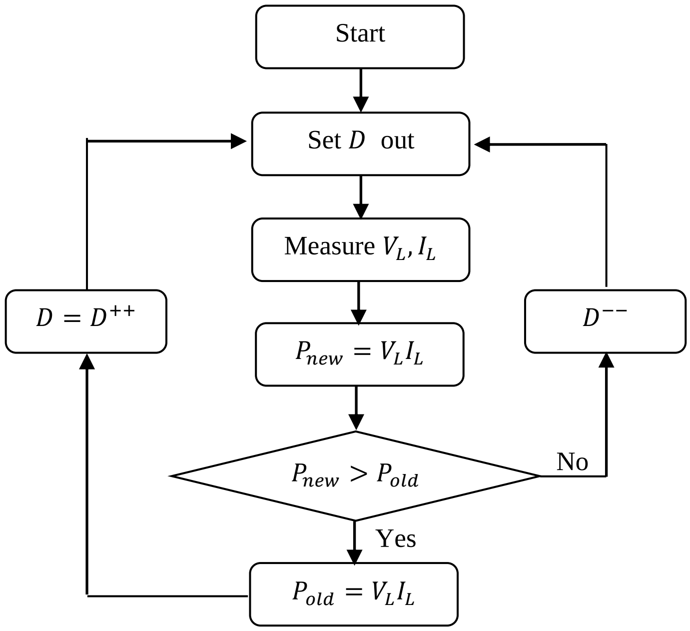

Fig. 18. Algorithm for P&O controller

VI. SIMULATION RESULTS

The MPPT simulation results present the response of a PV array with different MPPT approach : fuzzy logic, sliding mode and P&O controllers.

Fig.19 shows the power response obtained using Fuzzy logic(FL) and Sliding mode(SM) controllers based MPPT and Perturb & Observe algorithm. From the above results it seems that the PV power which is controlled by the proposed SM Controller is more stable than FL and P&O MPPT techniques. The power curve obtained with SM is smoother when compared to FL and P&O algorithms. Fig.20 shows the output voltage of buck converter using Fuzzy Logic, SM, FL and P&O Controllers.

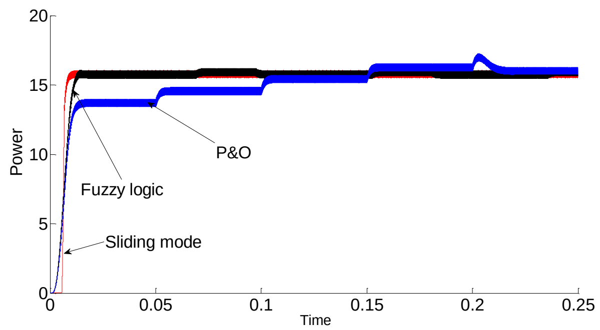

Fig. 19. Power output under step changing irradiation for P&O, Fuzzy and Sliding mode MPPT methods

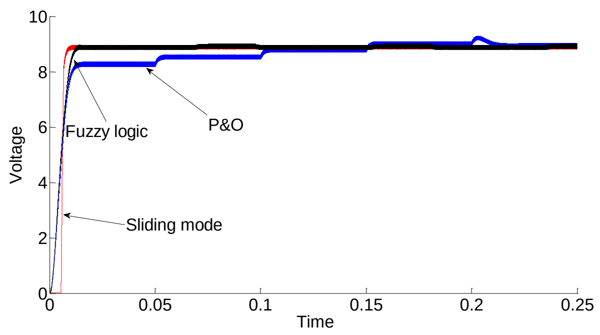

Fig. 20. Voltage output under step changing irradiation for P&O, Fuzzy and Sliding mode MPPT methods

VII. CONCLUSIONS

In this paper, three method for MPPT (Fuzzy logic, Sliding mode and P&O). Three of them have been applied to an energy conversion chain by DC-DC buck converter. We compared the simulation results obtained by subjecting the system to the same controlled environmental conditions.

It is concluded that the overall model in Simulink/Matlab is satisfactory for simulation purposes.

Even if, in transitional regime, the sliding mode present a delay due to the calculation step, it respond quickly.

All this algorithm converge to desirable output. Sliding mode controller exhibits fast dynamic performance and stable response, response of fuzzy logic controller is fast and stable than P&O controller but is slow and not as stable as sliding mode controller.

The response of sliding mode controller is better than fuzzy logic and Perturb and observe controllers, but it requires too many calculation and system equations. In contrast, the fuzzy logic controllers is easy to introduce, it does not require the system equations. Both of them is fast than P&O controllers.

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