Performance Evaluation of MPPT in a PVG with conventional and Intelligent Controllers under STC and DTC

P. Chandra Babu, B. Venkata Prasanth, P. Sujatha

Abstract: ***Maximum power point tracking (MPPT) is an essential factor to consider in photovoltaic or PV systems. Solar PV generation (PVG) systems present variable nonlinear current-voltage (I- V) as well as power- voltage (P- V) attributes, which vary with environmental problems. The optimum utilization of a PV system takes place when the system runs at the MPP in all ecological conditions. Key ecological conditions consist of the irradiance on the cell, temperature level of the cell and also any type of shading. Shading can take place because of dirt, objects and also component inequality occurring from cells damage, these leads again nonlinearity qualities in the system. In this paper gives an efficiency analysis (comparative analysis) of well-known standard MPPT algorithms-perturb-and-observe (P&O), incremental conductance (INC), improved incremental conductance (IINC) with intelligent MPPT Fuzzy logic controller (FLC) under STC and DTC. The performance comprises efficiency of PVG, rise time, accuracy, design complexity and some more, algorithms with mathematical equations additionally reviewed. The design of PVG in standalone operation with different MPPT's are done in MATLAB/SIMULINK workspace. This paper is prepared as if future scientists, as well as designers, can choose a suitable MPPT strategy without issue.***

Keywords: Maximum power point tracking (MPPT), Dynamic Test Conditions (DTC), Photovoltaic system generation (PVG), Standard Test Conditions (STC), FLC, P&O, INC.

I. INTRODUCTION

Fossil fuels are the primary resource, utilizing for electrical power generation from the past century onwards, which triggered air pollution, leads global warming and also imposed high power generation costs. In this context renewable energy resources like wind, solar are the advantage and will be no effect to the atmosphere, by virtue of their sustainable and pollution-free operation [1, 2]. The efficiency of solar cells are maximum when there are operate at their maximum power point (MPP), which happen in standard climate conditions only. As long as climatic conditions (G&T) changes, the nonlinear characteristics of solar cell also change. Consequently, the MPP also changes, which affects efficiency [3]. One essential method for obtaining the maximum possible power from a PV system in any ecological problems is known as the maximum power point tracking (MPPT). This strategy regulates the duty ratio variants from time to time to drive a DC-DC converter, which is placed amid of PV source and load. The DC-DC converter works as a coordinating device to boost or buck the input voltage or even to match the resistance in between the source and load. Within this instance, the PV source can easily produce its own maximum power successfully [4]. In the design of MPPT, many research papers are available [1-15], which can implement with fixed step and variable step sizes. The predetermined step size leads continuous oscillation around the MPP, which results in minimize the complete performance of PVG. Response time can be improve by large step sizes but oscillation will also be increased, however a small step sizes may certainly decrease the oscillation yet result in slower response times [5], in this view a lot of writers recommended various MPPT strategies like P&O, Hill Climbing, Fractional voltage(FV), Incremental conductance(InC), Modified incremental conductance (MInC) and so on, along with some smart controllers Fuzzy logic controller (FLC), Artificial neural networks (ANN), etc., also recommended [1],[12-13]. The traditional method needs manual tuning for different irradiance in PVG systems, this trouble can overcome by providing optimized step size of duty ratios, this can possible only by intelligent controllers. This paper compares the performance of PV generation with four MPPT control techniques, in that three are traditional approaches (P&O, InC and also modified InC) and other is intelligent control method (FLC). From the comparison, FLMPPT removes the disadvantages of the traditional algorithms in terms of efficiency, rise time, response time and continuous oscillation at constant and variable irradiance levels.

II. PV ARRAY MODELLING

A photovoltaic (PV) system directly converts sunlight into electricity. The fundamental unit of a solar panel is PV cell, "these are interconnected in series and parallel which is configured to a module in an array". Its equivalent circuit is shown in figure 1, which is equivalent of a current generator in parallel with a diode, the generated output current from a PV cell is directly proportional to the light falling on the cell, see figure 1(b) output current equation with an equivalent circuit.

Revised Manuscript Received on 30 July 2019.
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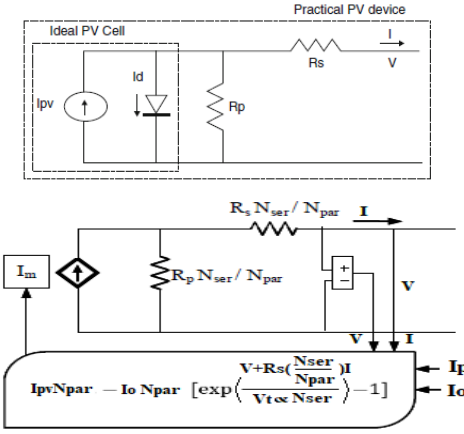
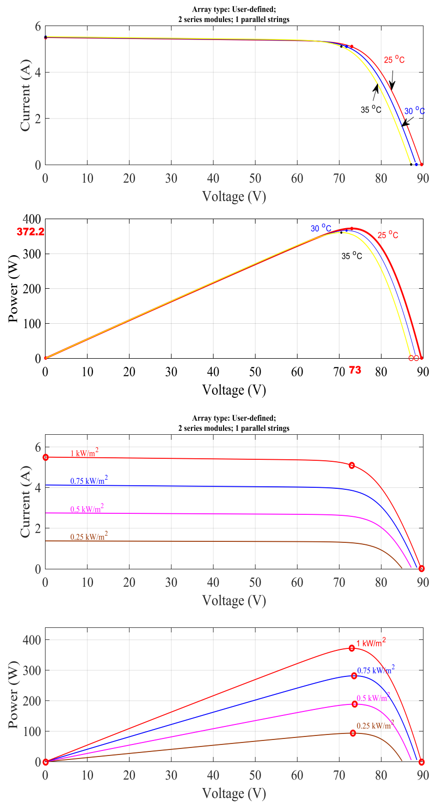
The characteristics of a PV array under STC, different solar insolation and temperature conditions are shown in figure 2 (a) and (b).



(a) (b)

Fig.1 (a) PV cell single-diode theoretical & practical equivalent circuit Fig.1(b) Circuit diagram of a PV array



(a) (b)

Fig.2 SPV characteristic curves (a) at different Temperature and STC irradiances (b) at different irradiances and STC Temperature

In designed SPV standalone mode the input PV temperature (T) and irradiations (G) are considered as variable one and which are dynamically changed with respect to time, temperatures variation considered as 25°C, 30°C and 35°C and irradiation variation considered as 250 w/m^2, 500 w/m^2,750 w/m^2,1000 w/m^2 . Figure 2(a) shows the P-V, I-V curves under fixed G of 1000 w/m^2 with different T of 25°C, 30°C, and 35°C. Figure 2(b) shows the P-V, I-V curves under fixed T of 25°C with different G of 250 w/m^2, 500 w/m^2,750 w/m^2,1000 w/m^2 , in mat lab simulation SPV system tested under dynamic test conditions , which means both PV inputs are varied suddenly at specified time intervals.

From fig 1 (a) output current from a single PV cell is

$$I = Ipv - Id \qquad (1)$$

$$I_d = I_o\left[e^{\left(\frac{V_d}{V_T}\right)} - 1\right] \qquad (2)$$

$$V_T = \frac{kT}{q}\left(n \times N_{Cells}\right) \qquad (3)$$

Ware n is diode ideality factor (≈ 1), k is Boltzman constant ($1.3806e^{-23} j.k^{-1}$), $N_{Cells} = 1,$ the output current of the cell can be written as

$$I = I_{PV} - I_o\left[e^{\left(\frac{qV_d}{knT}\right)} - 1\right] \qquad (4)$$

From equation 4, the output current depends on cell current (Ipv) corresponding to the incident of light and cell temperature (T). Hence we can write Voc equation as a function of temperature

$$Voc(T) = Voc\,(1 + \beta\_Voc\,(T-25)) \qquad (5)$$

Variation of Isc as a function of temperature

$$Isc(T) = Isc\,(1 + \alpha\_Isc\,(T-25)) \qquad (6)$$

Similarly, the output current from a PV Array is shown in figure 1 (b) can we write in equation (7)

$$I = I_{PV}\,N_{par} - I_O N_{par}\left[exp^{\left(\frac{V+Rs\left(\frac{N_{ser}}{N_{par}}\right)I}{V_T N_{ser}}\right)} - 1\right] - \frac{V+Rs\left(\frac{N_{ser}}{N_{par}}\right)I}{Rp\left(\frac{N_{ser}}{N_{par}}\right)} \qquad (7)$$

Above equations (1) to (7) are for a single diode model, there are sophisticated two and three diode PV models also proposed in 1999 and 2013 [7-8] to include the effect of the recombination of carriers and other influenced effects, but in view of simplicity and negligible error [9] this model only considers in this paper and so many authors also used has been used in present, previous works. In this paper, a single SPV system is implemented in all cases, whose design parameters are shown in Table-I.

Table-I: SPV module parameters of the designed system datasheet

SPV Module Parameters	Values
No of series modules	**2**
No of Strings	**1**
Maximum Power of a Module	**186.15 W**
O.C Voltage	**44.8 V**
S.C Current	**5.5 A**
Current at MPP	**5.1 A**
Voltage at MPP	**36.5 V**

Cells Per Module	**96**
Temperature Coefficient of Voc and Isc	**-0.27269 &0.0617 (%/deg.C)**
Shunt and Series Resistance	**230.16 &0.6429 ohm**
Diode Ideality factor	**0.65918**

III. MPPT STRATEGIES

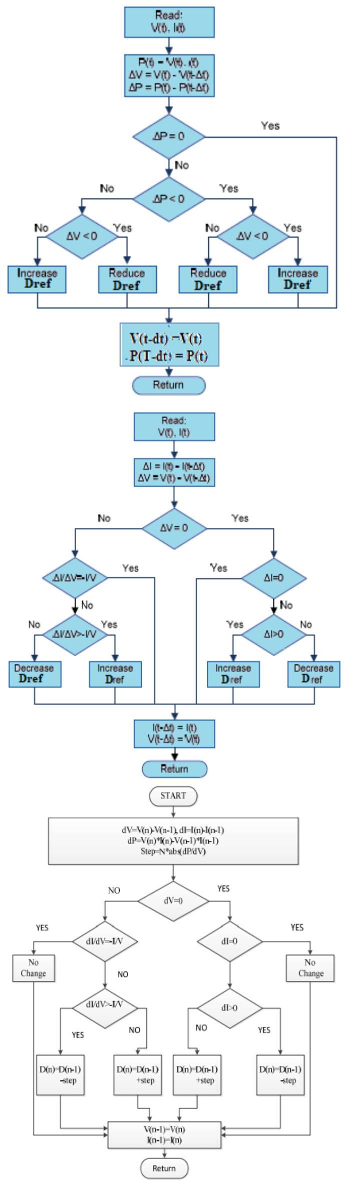
a) Popular Conventional MPPT Techniques

An SPV Array cannot deliver always its maximum power to a load directly due to the mismatch between source impedance and load impedance, so we cannot achieve maximum efficiency. The impedance mismatch happens by two cases, i.e. either load fluctuates or continuous changing of ecological conditions (T, G). Hence to achieve maximum power need MPP tracker, it is a combination of the DC-DC converter and an MPPT controller placed in between SPV and load [6]. Bidyadhar Subudhi et. al. 2013 & B. Subudhi et. al. 2011 reviewed a Comparative Study on basic MPPT strategies like Hill Climbing formula, Incremental Conductance, short circuit current, open circuit voltage, and also ripple correlation algorithm methods, which are not appropriate for non-uniform irradiance problems [12-14] Despite the fact that these strategies are simple as well as basic to apply, they cannot be utilized under partial shading problems (PSC) [12] because of slow down tracking and low utilization efficiency. The role of intelligent controllers to extract the Maximum Power at DTC and PSC are prominent. Present day research on Intelligent Controllers carried on Fuzzy, ANN, AP-AI controllers, etc. [15] Conventional MPPT Controller such as P&O, INC, IINC are replaced by these Intelligent controllers for obtaining the accurate MPP.

In the selected conventional controllers following step sizes are considered

- P&O: Fixed step size
- INC: Fixed Step size
- IINC: Fixed & Variable Step size

Due to the fixed step size algorithm, P&O and INC controller are not effective under DTC. In this contrast, a variable step integrator is added in IINC to perform well in the DTC, but the cannot achieve accurate MPP, The step is varied in accordance with the power, see mathematical equations in table-II, from this we can understand how the duty cycle produce from each MPPT controller. D(n) corresponds to the duty cycle and K is a scaling factor, which has been adjusted properly to get better tracking performance. Algorithms of three popular conventional and intelligent MPPT control techniques are shown in figure 3 and 4. In four cases the output of MPPT is in terms of duty cycle (D).



(a) (b)

(c)

Fig. 3 Flowchart of the different MPPT methods (a) P&O method (b) Inc Method (c) Modified Inc Method

The relationships applicable in 4 techniques are given in Table -II

P&O method	Incremental conductance
$\frac{dP}{dV} > 0 \rightarrow$ left of MPP $\frac{dP}{dV} = 0 \rightarrow$ at MPP $\frac{dP}{dV} < 0 \rightarrow$ right of MPP	$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V.\frac{dI}{dV} \approx I + V.\frac{\Delta I}{\Delta V}$ $\frac{\Delta I}{\Delta V} > -\frac{I}{V} \rightarrow$ left of MPP $\frac{\Delta I}{\Delta V} = -\frac{I}{V} \rightarrow$ at MPP $\frac{\Delta I}{\Delta V} < -\frac{I}{V} \rightarrow$ right of MPP

Modified incremental conductance	Fuzzy logic control
$D(n) = D(n-1) \pm \text{Step}$ $\text{Step} = K * \left\lvert \frac{dP}{dV} \right\rvert$ A variable step is added always to obtained duty cycle, unlike the INC method.	**1.Fuzzification** **2.Rule Inference** **3.Defuzzification** $E(k) = \frac{P_{pv}(k) - P_{pv}(k-1)}{V_{pv}(k) - V_{pv}(k-1)}$ $\Delta E(k) = E(k) - E(k-1)$

b) Intelligent MPPT Technique (FLC)

The FLCMPPT designed with two inputs (output of PV voltage & current) and one output (change in the duty cycle ΔD), Mamdani approach is utilized for fuzzy inference and center of gravity approach for defuzzification to compute the duty ratio. In order to conquer the nonlinearity attributes of PV cell, this method was implemented. In general, the fuzzy input variables are the slop of the PV curve (E (k)) and also a variant of slop (ΔE (k)) as 2 inputs. These variables equations are shown in Table-II, designed model fuzzy rules database is shown in Table –III. The FLC having 3 functional blocks namely fuzzification, rule inference and defuzzification. In fuzzification procedure, mathematical input variables V & I are changed into membership functions see fig. 7 designed block representation, error, and change in error values are computed from that two numerical inputs. Whose formulas displayed in the above table, then after which are converted into 'linguistic variables' conveying membership function (MF). These variables are expressed in different fuzzy levels: LV (low voltage), MV (medium voltage), HV (high voltage), likewise for current and duty cycle. In this work trapezoidal membership functions are considered which assumes that for any particular input there is just one leading fuzzy subset. Layout factors as well as performance of the fuzzy MPPT algorithm rely on the picked input and produced output variable, view the flow chart of FLMPPT in fig.4. The fuzzy rules are associated with "if-then rules" that are actually made use of for fuzzified inputs as well as could be discovered based upon experimental knowledge in difficulty or even attributes of the PV system. Fuzzy inference device does make-up procedure that creates a sensible selection based upon fuzzy regulations through which a control ouput is actually produced. Mamdani fuzzy inference strategy has actually been used in this controller with Max-Min structure procedure.

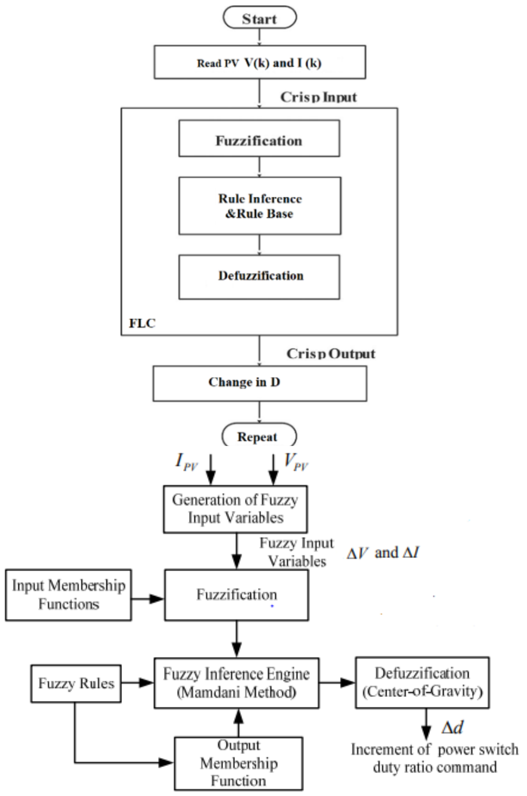


Fig. 4 Flow chart of FLMPPT and its internal operation

c) DC-DC Boost converter

To boost up the voltage several DC-DC converters are actually made use of. In this article, a DC-DC boost converter is actually looked at to attach the SPV and also load. DC-DC boost converters work as step-up choppers of the PV input voltage in order that it is actually consistently higher on the outputside. This coordinating converter is actually driven with the help of MPPT operator, which regularly sampled the input information of the PV source and produces suitable duty ratio (D) to the boost converter. Formula (8) exposes exactly how the boost converter boost the output voltage, which depending upon D varieties, where Vi and Vo, are actually the input, output voltages. Fig. 5 listed below equivalent circuit of boost converter. The input voltage is actually charge the inductor, whenever mosfet is on, at that instant the load is actually provided by the capacitor voltage. When the mosfet is actually open-circuited, the inductor current is actually discharged to the load, at that instant capacitor start charging.

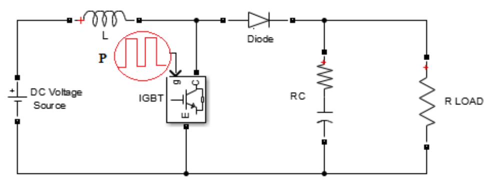


Fig. 5 Connection diagram of the boost converter

International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-8 Issue-2, July 2019

$$\frac{Vo}{Vi} = \frac{1}{1-D} \quad (8)$$

The power coming from the PV system will be actually write as

$$P_{pv} = \left(\frac{D}{1-D}\right)^2 \frac{V^2}{R_L} \quad (9)$$

From the equation 8and 9, we can easily understood that the operating point on PV curve can be control by only with D of a boost converter, if we adjust D perfectly then we can operate PV system at maximum power point.

IV. RESULTS AND DISCUSSION

A MATLAB/Simulink environment was used to model and simulate the PV system and MPPT controllers, as it is shown in Figure 6. The designed PVG module with 4 different MPPT controllers performance was tested under DTC conditions, it means dynamic test condition. In general, the sun insolation (G) and temperature (T) values are changes suddenly in a day, some test values range from 25 to 35°C temperature and 200 to 1000 W/m^2 irradiation are selected and implemented as an input block to SPV standalone system in MATLAB/Simulink workspace, see figure 8. The designed SPVG supplied the output power of 300 W at 1,000 W/m^2. The module datasheet is shown in Table-I. The boost converter was the other important part of the PV system for which the input voltage was 73V, and the output voltage was almost 120 V. The parameters of the boost converter included C_{in} and C_{out} selected as 220uF and 220uF, the inductor was chosen to be 15m H and the load was determined to be 40 Ohms. The main part of the system is MPPT, which is proposed with FLC and compare with popular conventional P&O, INC, IINC MPPT algorithms that modulate the duty ratio variations for appropriate switching of the IGBT. The proposed FLC and conventional algorithms were designed and developed, and their performance was tested and compared at the same irradiance conditions, see fig. 6 model block diagram of the SPV system with different MPPT techniques. The system was simulated under two tests conditions (STC &DTC) and compare the performance of all MPPT controllers

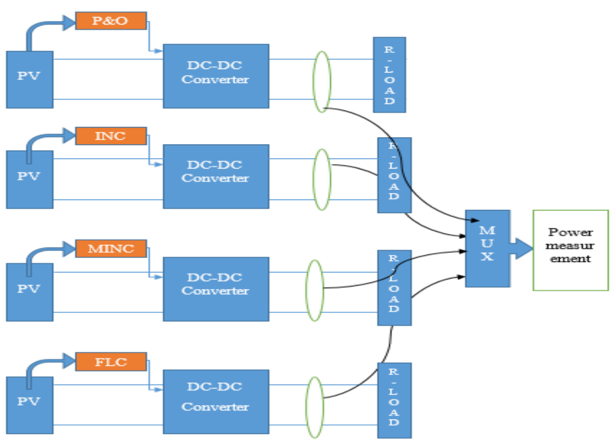


Fig. 6 SPV standalone mode with P&O, INC, MINC, and FLC MPPT controller block diagram

a) Fuzzy Logic Control Method

FLC have more advantages, gives greater robustness, faster response time, high controlling capability of a non-linear system and better accuracy. Very less usage of skilled persons to implement, capability to change the behaviour of process in the required region. The main benefit of FLC is, it can able to cope up with inaccurate sensing mechanism, ability to control roughly designed model not need exact mathematical model. It can easily handle nonlinearity unlike PI controllers. In case of MPPT design model with Fuzzy a variable step size is considered, which depending on the designed control rules. The obtained test results of a PVG with FLC are demonstrated in the Figures 9-11. Equations in a table -II presents the basic design equations of a both inputs and outputs of a fuzzy controller, from that first equation we can find the error value E (k) or operating point location on the P-V curve and from the second equation, we can calculate the change in duty ratio D (k). The calculated inputs are then converted into the linguistic variables, their universe of discourse is divided into three fuzzy subsets denoted as low (L), medium (M) and high (H). Large changes of duty ratio are applied when the error value is far away from the MPP on the left or right side of the P-I curve. A small change of duty ratio is needed when the operating point approaches the MPP. Zero change in duty ratio is required only when the error is zero, which indicates that the system is working on the MPP. For example, If E (k) is actually LI as well as Δ D (k) is actually LV, at that point D (k) is actually HD. This guideline signifies that if the operating aspect lies much coming from the MPP left side of the P-V curve and also the previous adjustment of D is actually zero, the new D is actually HD to track the MPP much faster The set of rules represents the set of linguistic variables in any input MF, for that the proposed FLC has 9 rules as find in Table III.

Table-III: Fuzzy Rules

E(k) / ΔD(k)	LI	MI	HI
LV	HD	MD	MD
MV	HD	MD	MD
HV	MD	LD	LD

Fuzzification process includes computation of inputs and conversion in to a linguistic variable, which is done with the trapezoidal MF in the designed controller. The inputs are connected with fuzzy inference system (FIS), which is developed by the Mamdani method accompanying with max-min operations. The last one in this controller design is defuzzification, which is a crisp output implemented with center of gravity method. The designed controller inputs limits are voltage limits as 0 to 90, current limits as 0 to 5.5 and duty cycle limit 0.4 to 1. The FLC block diagram is showed in fig.7.

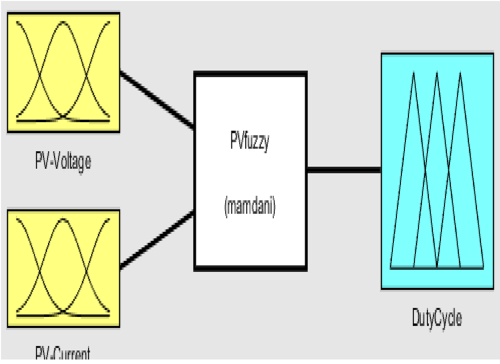


Fig. 7 fuzzy logic designer block diagram

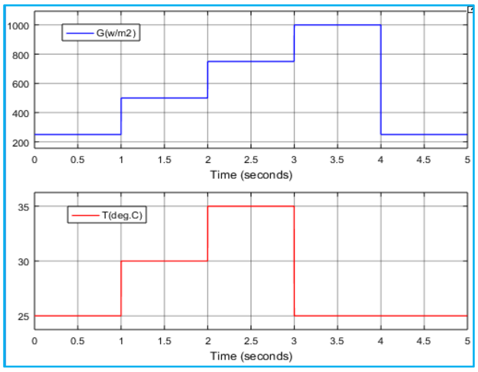


Fig. 8 Variation of G and T in a dynamic condition

See flow chart of FLC in figure 4, the output of FLC is a change in the duty cycle of the DC-DC converter. Which is generated by a defuzzification block in FLC, it converts the linguistic value of output into a crisp output value. Defuzzification input is always a single number, which is an accumulated output of a fuzzy set i.e. it calculated the centroid of all sets and convert into single centroid, this value as an FLC output. Many defuzzification strategies have been proposed in the literature works. One of the most typically used approaches is the Center of Gravity (COG) or centroid defuzzification method [15]. For a continuous aggregated fuzzy set, the COG by:

$$\Delta D = \sum_{I=1}^{n} W_i \, \Delta d_i \tag{10}$$

Here, ΔD is a crisp value, W_i is the weighting factor and Δd_i is a value corresponding to the membership function of ΔD

The output of FLC is the change in duty cycle (ΔD) and is expressed as

$$D(k)=d(k-1)+ S_f.\Delta d \tag{11}$$

Where S_f is the output scaling factor of fuzzy MPPT controller.

b) Simulation Results of FLCMPPT-PVG system under DTC

Figure 9(a)&(b) shows the designed FLC inference system rule execution viewer and surface viewer respectively, figure 10 shows the variation of load current, voltage under DTC conditions, from this we can understand how current and voltage varies w.r.t dynamic change in SPV input G &T, even though load constant. The dc-dc converter boosts the voltage from 73V to 120V at time 3 seconds due to T & G are reaches 25°C and 1kw/m^2. Fig.11 shows the load side power variation from 50W to nearly 300W due to change in PV input climatic conditions, from the figure we can find at 3.5 seconds the FLCMPPT-PVG output power reaches study MPP.

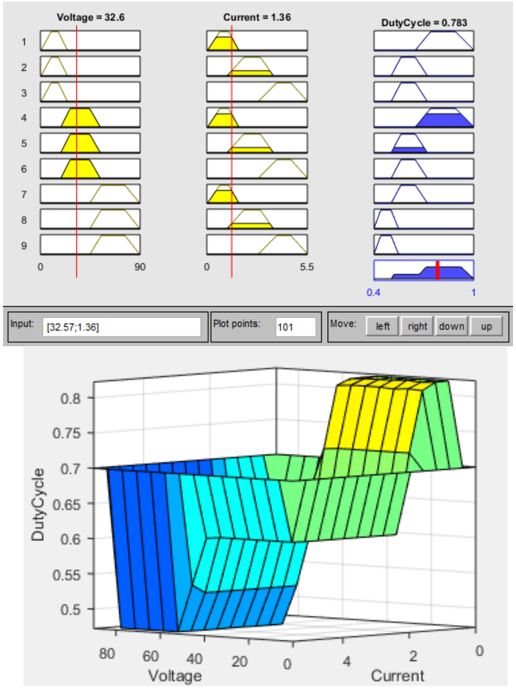


Fig. 9 Designed Fuzzy inference system (a) FIS rule viewer (b) Surface view of FIS with 101 plot points.

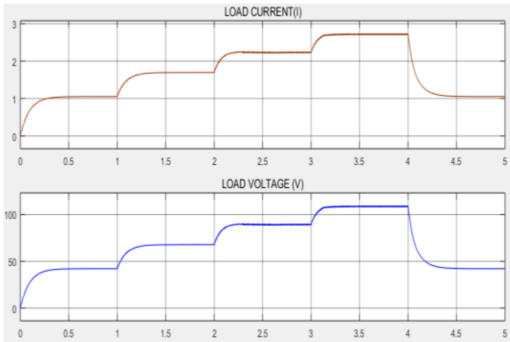


Fig. 10 SPV output current, voltage

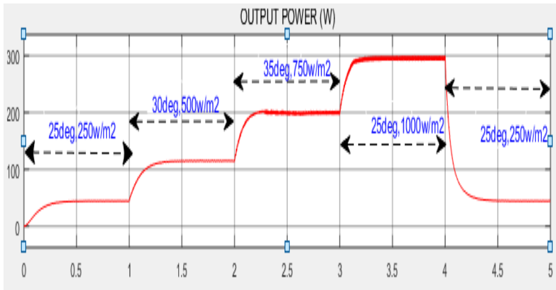


Fig. 11 SPV output power with FLC controller under DTC

c) Case-I: Simulation Comparison Results of four MPPT-PVG systems under STC.

Initially, both (conventional and intelligent) controllers tested at an STC condition (25°C and 1kw/m^2), later tested at DTC conditions see figure 8. Figure 10-11 illustrate the simulation results of the FLC-PVG, figure 12 illustrates the change in PV generation of four MPPT controllers operated individually, from the comparison we can easily recognize the power extraction is much more in FLC-MPPT based PVG standalone system. The rise time of FLC is extremely reduced 152.953ms and power amplitude is 299.6 W, in case of P&O it is 226.204ms & 288W, in INC technique it is 214.501ms & 286.5w and the last case IINC rise time is 219.651ms, power of 294.6W extracted. The maximum Solar PVG power (Pmax) is 305.9W. Accuracy and efficiency of any kind of MPPT strategy are necessary, it can be evaluated by just how close it takes the system to true MPP. Greater the precision better is the efficiency of the MPPT method. MPPT efficiency formula shown in Eq. 12. Tracking rate is also a key factor in some cases like battery charging in electric drives and systems, so it needs to be work effectively under continuously and fast-changing atmosphere problems [10].

$$\text{Efficiency} = \frac{\text{Tracking Power}}{\text{PV maximum power}} \qquad (12)$$

d) Case-II: Simulation Comparison Results of four MPPT-PVG systems under DTC.

The superior performance is obtained by implementing the FLC as compared to traditional controller for different irradiance levels of DTC, which is demonstrated by the simulation results. The variation of irradiance is at different levels from 200 to 1,000 W/m^2 as shown in Figure 8.

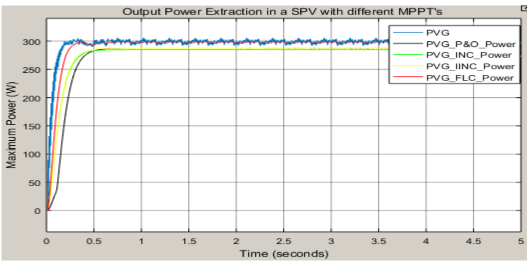


Fig. 12 Output power generation comparison under STC condition

Figure 13 shows the output power variation of PV system with controllers, here the FLC-MPPT-PVG performed faster response time toward the MPP than conventional at all insolation levels, particularly at the temperature and irradiance level of 35°C and 750W/m^2 fuzzy controller responded quickly to reach the MPP. Table III below summarizes the response time and Power generation of the all algorithm.

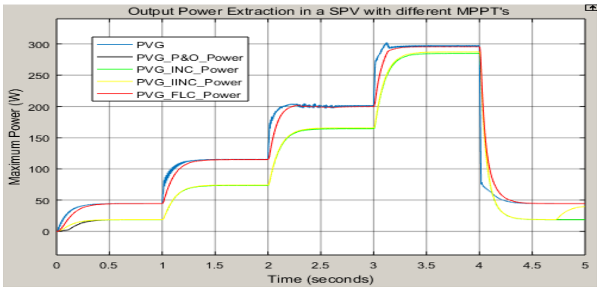


Fig.13 Output power generation comparison under DTC condition

Table –III: Response time of different MPPT controllers under DTC

G & T	25°C & 250 W/m^2		30°C & 500 W/m^2		35°C & 750 W/m^2		25°C & 1000 W/m^2	
Response time & Power extraction to reach MPP	Time (Seconds)	Power (Watts)	Time (Seconds)	Power (Watts)	Time (Seconds)	Power (Watts)	Time (Seconds)	Power (Watts)
FLC	0.640	44.3	1.498	115.1	2.278	204.5	3.49	299.6
P&O	0.641	18.67	1.494	74.16	2.5	166.2	3.5	288
INC	0.640	18.54	1.5	73.56	2.5	164.9	3.5	286.5
IINC	0.64	18.69	1.494	74.18	2.5	166.2	3.5	294.6

From the above table and figure 13 we can understand that the performance of FLC is more, and in some cases, the obtained response time is same for all three P&O, INC and IINC MPPT's but power extraction is some have more. If you observe the P&O and IINC MPPT' response time and power may be the same but ripple content in power was different.

Table-IV: Performance Comparison

MPPT methods	Complexity	Digital or Analog	Rise time	Sensed parameters	Prior training	Efficiency	Control strategy	Accuracy
P&O	Low	Both	High	V&I	No	Medium	Sampling	Medium
Inc Cond	Medium	Digital	Medium	V&I	No	Medium	Sampling	Medium

MInc Cond	Medium	Digital	Less	V&I	No	High	Sampling	High
FLC	High	Digital	Very Less	V&I	Yes	Very high	Probabilistic	Very high

V. CONCLUSION & FUTURE SCOPE

A. Conclusion:

The PV system nonlinear qualities are primarily differed by the variation in irradiance and temperature levels, which leads to power losses and reduce efficiency. Creating of a fuzzy logic based MPPT with standalone PV system can act effectively under STC and DTC conditions have actually been talked about in this article, along with this performance comparison also clearly analyzed with three popular conventional techniques (P&O, INC, and IINC).

We can understood from test results as the traditional algorithms took more rising time and low efficiency, which are 94.15%, 93.67% and 96.3% of P&O, INC, IINC respectively at STC condition, however the recommended FLMPPT acquired 97.94% with response time 0.779 seconds at STC, from this results we can conclude that the FLC-MPPT-PVG system was more faster tracking and utilizing efficiency was improved due to variable step size of iteration, which is varied according to fuzzy rules. From Table –III, we can additionally observe that the differences between the four MPPT strategies are really very slight, so the selection of MPPT may get confused, in my view it can be chosen based on our system demand i.e response time, efficiency, cost, application. This writeup will certainly be a good reference for the researchers, students who work in MPPT.

B. Future Scope:

The oscillations in FLMPPT output power can improve by other adaptive control methods with less response time and the simulation conducted in standalone mode only, it can also extend with grid-connected mode.

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