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Performance Comparison of PID and Fuzzy Controllers in Distributed MPPT

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ABSTRACT

With an increase of Green Technology applications, Photovoltaic have emerged as the most appropriate solution for electricity generation purposes. However, due to variable temperature and irradiance, under the partial or shaded conditions Maximum Power Point Tracking is needed to determine highest efficiency of the system. The paper describes dynamic modeling and control of variable temperature and irradiance on solar panel in SIMULINK-MATLAB environment. The implementation of Buck Converter is used for power switching and impedance matching on connecting the panel to the load. The effectiveness of the model, with enhanced efficiency through voltage stabilization, is performed using Proportional-Integral-Derivative and Fuzzy-Logic-Controllers. A comparative study is made for PID and FLC on the basis of outputs to deal with online set point variations. FLC gives closer results to Standard Test Conditions when compared with PID. The Fuzzy system developed, using tested membership functions serve as a platform for sustainable standalone and grid-based applications using distributed MPPT.

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1. INTRODUCTION

Solar is a vast, multidisciplinary technology that has expanded tremendously in recent years. The International Energy Agency estimates exponential growth of PV in electricity generation. The roadmap towards increasing PV share in global electricity generation targets 16% growth by 2050 over 11% in 2010. To achieve this vision, the total PV capacity installed needs to rise rapidly, from 36 GW in 2013 to 124 GW per year on average, with a peak of 200 GW per year between 2025 and 2040 [1]. This installation would contribute significant rise of 17% to clean electricity and 20% of all renewable electricity generated through PV (photovoltaic). Solar Renewable Energy Technology (SRET) has brought ample opportunities in Utility-scale and rooftop systems projecting electric power generation from 60GW in 2014 to 250GW by 2020 throughout world. Solar India is marked by Jawaharlal Nehru National Solar Mission that integrates to add 20,000 MW of capacity in electricity generation by 2022. The clean energy security together with reduced carbon emissions have raised per unit of its GDP by 20-25% percent in 2015 over 2005 levels [2]. There are various snapshots for PV efficiency including utilization in infrastructure buildings, commercial banks, solar cities development, solar parks, domestic and e-sustainability, with a vast research potential for big projects in electricity generation and distribution.

Due to the growing demand on electricity, the limited stock and rising prices of conventional sources (such as coal and petroleum, etc.), PV energy becomes a promising alternative being omnipresent, freely available, environment friendly, and has less operational and maintenance costs. With availability of 3000 sunshine hours daily for 300 days in a year, efficient SRET appliances can be developed and installed.

The main requirement for solar design, process and control is that they must be more productive, adaptive to variations in environmental conditions producing high efficiency as per customers and market requirements in the world market's conditions. Therefore, every stage in optimization for production systems can be used for continuous improvement. For this purpose, many tools, techniques, subsystems, and systems can be used. DMPPT (Distributed Maximum Power Point Tracking) technique locates MPP, a unique operating point to deliver highest efficiency even for variable temperature and irradiance [3].

The continuous stride towards achieving the sufficiency in power shortage for economic growth needs to remove barriers of non-regulation of power. Since, the output voltage from the solar panel is applied across a load; fluctuations in temperature and irradiance effect output power. This impedance mismatch is stabilized using Converters acting as an interface between panel and load monitored by Set Point Controllers for real time applications to overcome power fluctuation. Several MPPT techniques are reported in the literature. Offline or Indirect techniques like Curve fitting [4], Fractional Short Circuit Current, Fractional Open Circuit Voltage [5]-[6] and Look Up Table [7] operate upon pre experimented datasets and approximations. Sampling techniques like Perturb and Observe [8], Centered Differentiation [9], Incremental Conductance [10] and Feedback techniques were based on direct samples used earlier until 2007. But many new MPPT Intelligent techniques such as Fuzzy logic[11]-[16], Artificial Neural Network [17], Estimated perturb and perturb [18], Genetic Algorithm [19], Adaptive Neuro-Fuzzy [20] and particle swarm optimization [21]-[22] based MPPT, etc., have been reported since then based on advanced knowledge of the PV panel characteristics. It is justified that the Fuzzy logic system based Intelligent techniques in PV give Good performances, Fast responses, No overshoot and less Fluctuations for rapid temperature and irradiance variations. For analyzing Fuzzy Logic Controller, there is no requirement of exact PV model and hence it can be easily implemented [23]-[29].

Various Converters are available that aim increase, decrease or maintaining same output power/voltage across load. These are classified into Buck Converter (Step Down), Boost Converter (Step Up), Buck-Boost Converter (Both Step Up and Step Down), Cuk Converter (Both Step Up and Step Down reversing polarity of voltage), and SEPIC **(**Single-ended primary-inductor converter) allowing voltage at its output to be higher than, less than, or equal to that at its input without inversion. The degree of output voltage at Converter varies sharply when used to locate DMPP. Controller monitors the desired set point from Converter continuously in process applications. The Controller establishes set of control functions required to make appropriate adjustments in the desired voltage output of panel using Converter [30], [31]. Simple circuitry with direct feed and short circuit protection for inrush current makes Buck converter most acceptable converter for temperature and irradiance variation [32]-[33].

2. RESEARCH METHOD

In this study, firstly a systematic analysis of solar panel module based on mathematical modeling in Simulink-MATLAB is performed for the panel operated by 36 cells generating 60W. Thereafter, to understand the operation of variable temperature and irradiance investigation is experimented on model. MPP is obtained at STC (Standard Test Conditions) maintaining temperature of 25°C (298.15K) and irradiance of 1000 W/m^2. Any deviation in STC distorts MPP and results in power discrepancy, hence MPPT is employed. The MPPT system is supported by implementing DC/DC Buck Converter followed by PID and FLC to monitor output of Converter. An estimation of different temperature and irradiance conditions is carried out with the comparison of voltage conversion ratio and duty cycle for the converter. The Converter is tracked to desired STC set point by using control functions for Conventional PID and Fuzzy Controllers adaptive to changes in temperature and irradiance. A comparison is formulated for estimating performance of PID and FLC.

PV panel uses an array of solar cells that convert light into electric energy using photo-electric effect. Solar cell equations are used to model the dc equivalent circuit of solar cell [34]. The model is tested for different range of temperature from 5°C to 45°C and irradiance including constant, step and trapezoidal functions [35].

The DC equivalent of solar cell is represented by a current source in parallel with shunt and series resistance described in Figure 1.

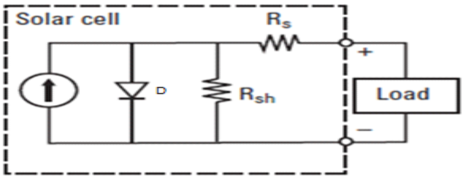

Figure 1. Solar Cell DC equivalent model

The complete subsystem of panel is displayed in Figure 2, followed by I-V (Current Voltage) and P-V (Power Voltage) Characteristic curves obtained after simulation plotted in Figure 3. The values for MPP delivered at load for panel is P_{MAX} =59.39W with V_{OC}=21.07Vand I_{SC}=3.7981A.

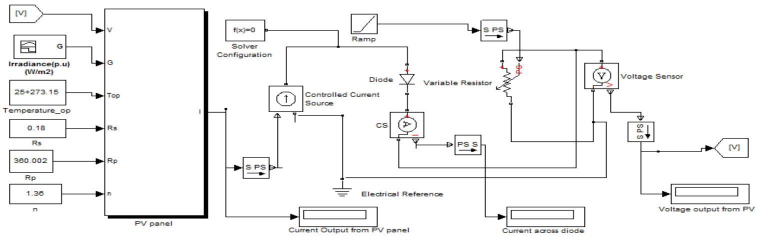

Figure 2. Solar Panel Subsystem

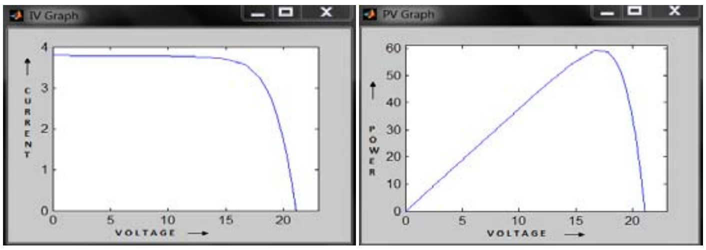

Figure 3. I-V and P-V Characteristics of solar panel

The graphs of Figure 3 predict that solar panel behaves neither as a current source nor as a voltage source. For variations in temperature and irradiance, panel output varies severely across the resistive load. The intersection of source and load characteristics can fix MPP. Figure 4 shows more closely MPP variation with load. R2 is desired operating load line for MPP. R1 is voltage source region and R3 is current source characterized region. Thus, optimizing R1 and R3 closer to R2 in all possible conditions will give MPP even on variation in load.

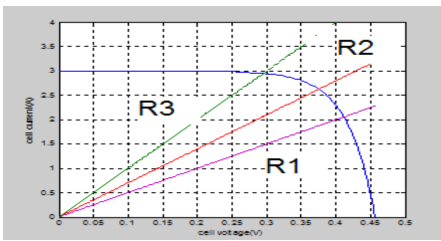

Figure 4. MPP with variations in load

Simulation results show that, increasing temperature increases current source (high internal impedance) region to shift towards R3 i.e. left of load line and vice versa. An expression is determined, considering the power output obtained from a PV system for variable temperature incremented by incremental change in power, voltage and current given by equation (1) and (2).

$$P+\Delta P = (I+\Delta I).(V+\Delta V) \qquad (1)$$

After ignoring small terms simplifies to:

$$\Delta P = \Delta V.I + \Delta I.V \qquad (2)$$

ΔP must be zero at peak point. Therefore, at peak point the above expression in the limit gives equation (3) representing Dynamic impedance of the source,

$$\frac{dV}{dI} = -\frac{V}{I} \qquad (3)$$

Where,
- P : PV power output
- ΔP : Incremental Power output from PV
- I : PV current output
- ΔI : Incremental current output from PV
- V : PV voltage output
- ΔV : Incremental voltage output from PV
- dV/dI : Dynamic impedance of source

In accordance with Maximum Power Transfer Theorem, Maximum Power is delivered to load when source internal impedance matches load impedance. Hence, MPP needs to be tracked by adjusting these variations using MPPT as shown in Figure 5. The preferable results for MPP relative to changing temperature and irradiance can be obtained using Converter and Controller.

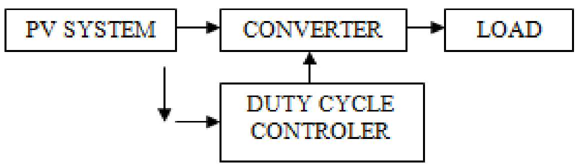

Figure 5 Block diagram for MPP Tracker

The mismatch in output power characteristics is compensated by using Buck Converter. It is used to "buck up" or reduce output voltage with passive semiconductor devices to obtain voltage stabilization. Four main components are used in designing buck converters. These include switching power MOSFET, diode, and inductor followed by filter capacitor and load at output. The output of PV panel is used to feed Drain input of MOSFET. The drain current is then adjusted by set of pulses received at Gate from Controller designed. A control circuit is used to monitor the output voltage from the converter and maintain it at the desired level. Figure 6 shows modeling of Buck converter with control pulse generator applied at Gate terminal of MOSFET.

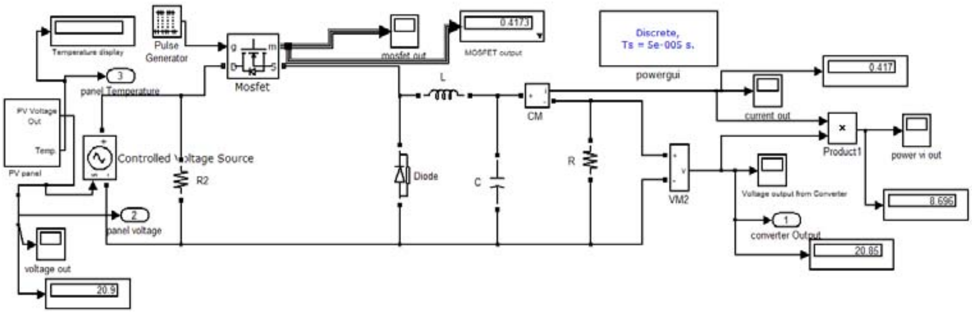

Figure 6. Buck Converter using controlled Pulse Generator at gate

MOSFET acts as a switch. It is ON or OFF depending on pulses that determine converter operating frequency. A variation in converter duty cycle is provided based on the proportion of each switching period through which MOSFET is turned ON and OFF. Two different models were studied based on state space model equations and use of direct components available in MATLAB-SIMULINK. Instead of using ON and OFF variables, direct component model gave better response. The Gate of MOSFET when triggered by train of pulses from the controller causes current flow through inductor, building up oscillations in inductor. When MOSFET is turned ON, voltage is reduced by magnetic field developed across inductor. When MOSFET is turned OFF, EMF is suddenly reversed in the inductor that opposes further drop in current. Thus, pulses applied from controller helps in maintaining constant voltage output for ON and OFF phase. The appropriate adjustments in voltage output of panel are obtained by connecting Controller in Converter system. The basic block diagram using Controller, PV and Converter subsystem is shown in Figure 7.

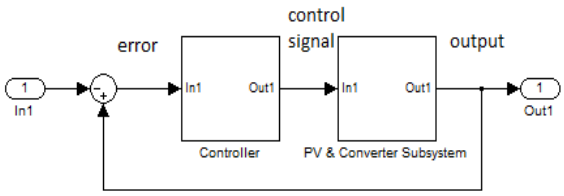

Figure 7. Block diagram of Controller with PV and converter subsystem

The Controller used in Figure 7 can be constructed using Conventional PID or an Intelligent FLC Controllers.

2.1 PID CONTROLLER

PID (Proportional-Integral-Derivative) controller is one of the earliest conventional industrial controllers. It has many advantages like economic, simple and easy to tune. The Simulink model for the nonlinear system using a conventional PID controller is developed. The mathematical expression for the same is given in equation expressed by equation (4).

$$U(t) = K_{P.}\, e(t) + K_I \int e(t)\, dt + K_D \quad (4)$$

Where, U (t) : Control Signal
e (t) : Tracking Error, the difference between the desired and the actual output.
K_P : Proportional Gain (Tuning Parameter)
K_I : Integral Gain (Tuning Parameter)
K_D : Derivative Gain (Tuning Parameter)

The model in Figure 8 shows Buck Converter with PID Controller. The simulation is performed for different values of tuning parameters K_P, K_I and K_D to get desired Set Point.

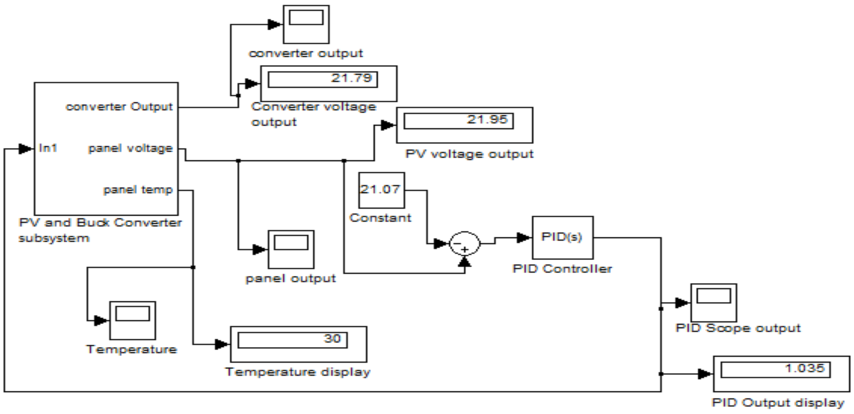

Figure 8. Buck converter with PID Controller

Table 1 shows the results of different values of variable tuning parameters and controller output.

Table 1. Converter Outputs using PID

K_P	K_I	K_D	Converter output	PID Controller output
0	0	0	0.01097	0
0	0	0.5	0.01097	0.07892
0	0	0.8	0.01097	0.1263
0	0	1	0.01097	0.1578
0	0	1.2	0.01097	0.1894
0	0	1.5	0.01097	0.2368
0.5	0	0	0.01097	0.4385
0.8	0	0	0.01097	0.7016
1	0	0	0.01097	0.877
1.2	0	0	21.89	1.052
1.5	0	0	21.91	1.315
0	0.5	0	0.01097	0.373
0	1	0	0.01097	0.746
0	1.2	0	0.01097	0.8952
0	1.5	0	21.89	1.119
0	1	1	0.01097	0.9038
1	1	0	21.79	1.035
1	0	1	21.79	1.035
1	1	1	21.79	1.035

It can be seen from the Table 1, that selecting value of any of the tuning parameters less than unity, MOSFET remains in OFF state. However, on increasing any one of the parameters greater than or equal to unity, MOSFET is turned ON and both Converter and Controller output is obtained.

Out of the above tested values, the value of $K_P = 1$, $K_I = 1$ and $K_D = 1$ is selected and simulation results are obtained as shown in Figure 9.

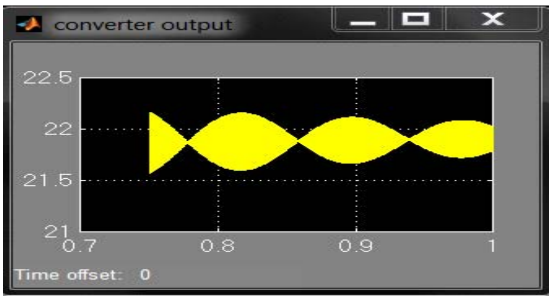

Figure 9. Converter output using PID Controller

The Block diagram of Controller with PV and Converter subsystem is now implemented using FLC.

2.2 FUZZY LOGIC CONTROLLER

Fuzzy logic (FL) has been available as a control methodology for over four decades in various applications to engineering control systems. Theory of fuzzy sets was introduced by Lotfi A. Zadeh, Professor for computer science at the University of California in Berkeley in 1965 [36] and the industrial application of the first fuzzy controller was initiated by E. H. Mamdani in 1974 [37]. Fuzzy systems have obtained a major role in engineering systems and consumer products since then. Fuzzy Logic is a multi-valued logic that allows intermediate values to be defined between conventional evaluations like true/false, yes/no, high/low, etc. Fuzzy logic is a powerful problem solving methodology that provides remarkable simple way to draw definite conclusions from vague, ambiguous or imprecise information [38]. The fuzzy system is a knowledge-based system which utilizes fuzzy if-then rules and fuzzy logic in order to obtain the output of the system.

There are many advantages of using Fuzzy controllers. Firstly, a Fuzzy Logic Controller gives much better output in comparison to the conventional PID controller. The response of FLC system is stable and can be easily varied according to the changing demand for the input. Secondly, the effects of the tuning parameters are jointly analyzed and easy to monitor for varying outputs of PV with changing temperature and irradiance. Thirdly, FLC can be easily tuned according to the desired output by changing the design parameters of membership functions responsible for system performance**.**

FLC implementation in the present work is used to adjust the converter duty cycle by varying the gate voltage according to the changing values of the panel voltage and set point. Practically, panel sensors are incorporated at the end of PV subsystem to measure the online variations in temperature and irradiance. Simulink model designed using FLC is given in Figure 10.

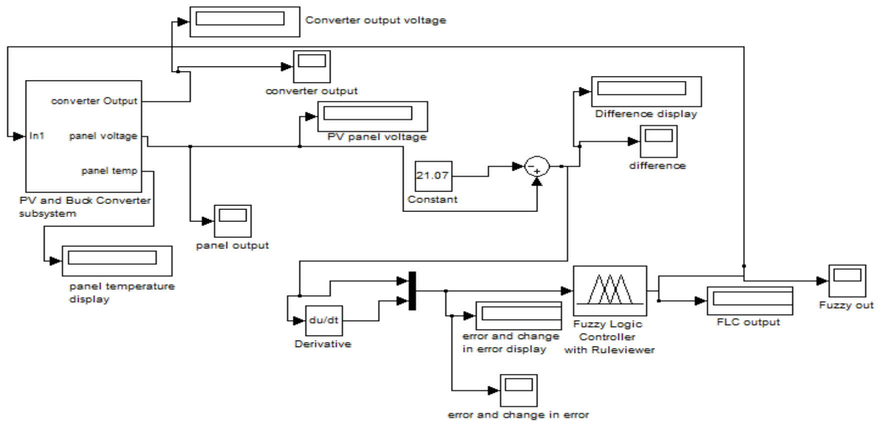

Figure 10. Fuzzy Logic Controller correcting Converter output

Presently, a two-input single-output fuzzy logic controller is designed at a sampling instant n. The input variables error E (n) and change in error ΔE (n) are expressed in equations (5) and (6).

$$E(n) = \frac{P(n)-P(n-1)}{I(n)-I(n-1)} \quad (5)$$

$$\Delta E(n) = E(n) - E(n-1) \quad (6)$$

The output variable is Duty cycle (DC) of the converter given by expression in equation (7).

$$DC = \frac{Vout}{Vin} \quad (7)$$

Where,

E (n)	:	Error Input
ΔE (n)	:	Change in Error Input
P (n)	:	PV power computed at an instant n
P (n-1)	:	PV power computed at an instant n-1

I (n)	:	PV current computed at an instant n
I (n)	:	PV current computed at an instant n-1
DC	:	Duty Cycle
V_{OUT}	:	Output Voltage of Converter
V_{IN}	:	Input Voltage of Converter

The input variables in a fuzzy control system are mapped into sets of membership functions termed "fuzzy sets". The process, of converting a crisp input value to a fuzzy value, is called "fuzzification". The "mappings" of input variables into membership functions and truth values help the controller to make decisions for what action is to be taken based on a set of "rules".

The developed FLC uses two inputs with universe of discourse for error input taken [-8, +8] and change in error chosen to be [-10, +10] for the panel voltage. The range of the input variables can be changed according to the changing demand for the varying input. The universe of discourse for the output duty cycle of converter is chosen to be as [-8, 8]. The controller designed is described by two inputs assigned with five membership functions namely, NB negative big, NS negative small, Z zero, PS positive small and PB positive big.

The controller makes decisions for what action is to be taken based on a set of "rules" implementing the expert knowledge in a form of IF-THEN rule structure. The system was tested for various subsets of error and change in error with changing crossover points. However, Gaussian membership functions proved smooth and non-zero at all points with 0.5 crossovers providing less over/under shoot with faster Rise time.

The fuzzy logic developed model can be derived from a 55-rule matrix that consists of 25 rules given in Table 2.

Table 2. Fuzzy membership Functions

E (n) \ ΔE(n)	NB	NS	Z	PS	PB
NB	Z	Z	NB	NB	NB
NS	Z	Z	NS	NS	NS
Z	NS	Z	Z	Z	PS
PS	PS	PS	PS	Z	Z
PB	PB	PB	PB	Z	Z

On the basis of these rules, the system works, and the implication method is applied. After the implication method, the output for each rule is aggregated and the defuzzification is done to find the crisp output. The output of the converter using Fuzzy Logic Control system is shown in Figure 11.

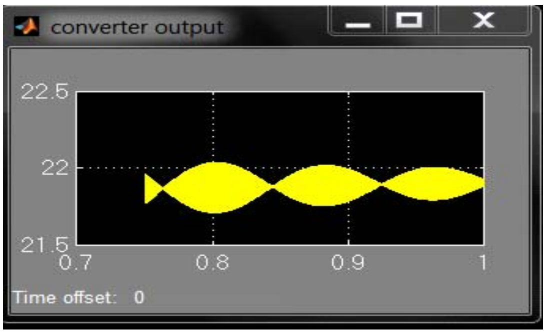

Figure 11. Converter output using FLC

3. COMPARISON OF PID AND FLC

A Comparative study of Converter output using PID and FLC is done on the basis of the reading of Converter output and the Duty cycle. This can be seen from Table 3.

Table 3. Comparison of converter Outputs using PID and FLC

Parameter	Set point Fixed STC= 21.07 V Panel output for variable T and G= 21.86 V PID Controller	 FLC Controller
Converter Output	21.82 V	21.40 V
Duty Cycle	0.998	0.978

The set point obtained at output of Converter using FLC is closer to desired set point in comparison to the PID. Also, The Duty cycle in case of FLC is less compared to PID. Duty cycle describes the proportion of time for which circuit is operated. The higher the duty cycle, higher the consumption of components and lesser the span for which it can be operated. The step down Buck Converter gives less duty cycle in FLC when compared with PID. Thus, the output of model using FLC is under control and closer to set point even when the disturbance is added to the system with less duty cycle. The model developed can be easily implemented in the industry.

4. RESULTS AND ANLYSIS

The modeling performance of solar panel operated on Buck Converter interface is studied using PID and FLC Controller. A comparison of results as in Table 3 describes FLC results closer to Standard Test Conditions (STC) when compared to conventional PID.

The panel characteristics implemented for Fuzzy and PID controllers show that duty cycle is less than unity in both cases. However, STC results MPP closer in FLC as compared to PID. Thus, Buck converters can monitor MPP more closely to STC by selected membership functions and parameter modeling of FLC. Moreover, less cost for computing and faster response are advantages of FLC over traditional controllers. More satisfactory results for FLC are observed for fixed and varying input in both the cases i.e. temperature and irradiance.

5. CONCLUSIONS

When analyzing solar PV applications, distributed MPPT needs to be tracked. This paper explores MPPT method for online variations using Buck Converter through PID and FLC when operated in real time applications. The work encourages continuing on-going research to improve current assessment using future tools like Hybrid FLC.

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