Maximum Power Point Tracking using Type-I Fuzzy Logic Controller in P-V system

Jeeban Kumar Nayak
Department of Electrical Engineering
National Institute of Technology
Rourkela, India
jeeban1994@gmail.com

Arnab Ghosh, *Senior Member, IEEE*
Department of Electrical Engineering
National Institute of Technology
Rourkela, India
aghosh.ee@gmail.com

Vikash Gurugubelli, *Student Member, IEEE*
Department of Electrical Engineering
National Institute of Technology
Rourkela, India
vikas0225@gmail.com

***Abstract*—When it comes to increasing the effectiveness of photovoltaic systems, maximum power point tracking (MPPT) is of the utmost significance. There are a variety of strategies that have been put forward in order to maximize the amount of electricity that can be generated by photovoltaic modules regardless of the climate. The purpose of this study was to suggest an intelligent technique for monitoring the highest power point using a Type-I Fuzzy Logic Controller (FLC). A photovoltaic solar generator that is connected to a DC-DC Boost converter makes up the entirety of this device. The MATLAB/simulation results show that the proposed maximum power tracker tracked maximum power precisely and effectively in all conditions tried. The proposed method outperforms the conventional methods such as P&O, INC, Voltage reference, Current reference methods etc. in tracking efficacy and reaction time.**

Keywords—Maximum Power Point Tracking, P&O method, DC-DC Boost Converter, Fuzzy Logic Controller.

I. INTRODUCTION

The desire for energy is determined by a number of variables, including changes in lifestyle and consumer behavior, as well as population growth, economic growth, technological advancements, and economic development. For instance, the amount of energy that is required generally rises in tandem with the growth of industries and the size of communities [1-3]. Changes in consumer behaviour, such as an increase in the use of technological gadgets, can similarly drive up the demand for energy. Meeting energy demand can have significant environmental, economic, and social consequences. For example, if energy is produced primarily from fossil fuels, this can lead to increased greenhouse gas emissions and air pollution [4-7]. In addition, if energy supplies are insufficient or unreliable, this can lead to disruptions in economic activity and social unrest. Research actions should be implemented to resolve the demand for energy. These research actions include investing in sustainable energy sources, increasing energy efficiency, encouraging energy conservation, and diversifying energy suppliers. These measures have the potential to help guarantee a more sustainable and dependable energy future while also minimizing the potential negative effects that may be caused by the use of energy [8-12].

Solar energy is an easy way to meet the elevated demand for energy that is currently being seen. Solar energy installation not only lessens reliance on fossil fuels like gasoline and coal but also has the potential to create local employment opportunities. Solar energy has become increasingly popular as a result of its many advantages, including its absence of upfront costs, its positive impact on the natural world, and its reasonable running and upkeep expenses [13-18]. As a result of an increase in demand, solar power production must become more efficient; consequently, it is essential to make the most of the electricity it can produce. However, the widespread adoption of photovoltaic systems is being hampered by two significant reasons. The high expense of implementation and the poor effectiveness of energy production are both of these issues [19-22]. One useful strategy for lowering the cost of photovoltaic power systems and improving the efficiency with which solar energy is used is the maximum power point monitoring system for photovoltaic modules [23-25]. In order to extract the most power possible from a solar module and transfer it to the demand, a method known as maximum power point tracking, or MPPT, is utilised. This increases the system's efficiency.

The contributions of this paper are (a) Modeling and characteristics of the P-V cell. (b) The type-I fuzzy logic rule-based MPPT technique is designed and implemented. (c) The simulation study on the type-I fuzzy logic rule-based MPPT technique is presented.

II. SYSTEM MATHEMATICAL MODELLING

A. Mathematical Modelling of P-V cell

PV cells generate electricity by using the photovoltaic effect, which converts the photon energy present in light into the corresponding form of electron energy. In order to replicate the equivalent circuit of a PV cell, a model consisting of a single diode is used. The one-diode model is simple and it is easy for power electronics professionals to study [2].

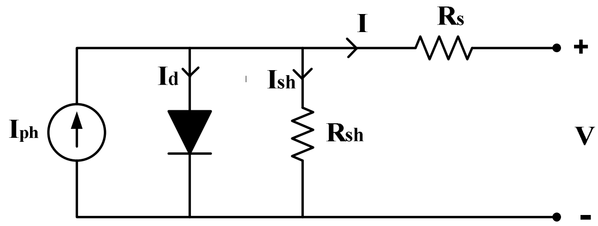

Fig. 1. Equivalent Circuit diagram of a PV-Cell

The mathematical expressions of PV panels at any temperature and irradiation are:

$$I = I_{ph} - I_o(e^{\frac{V+IR_s}{\eta V_T}} - 1) - (\frac{V + IR_s}{R_{sh}}) \quad (1)$$

$$I_{sc} = I_{scref}[1 + \alpha(T - T_{ref})]\frac{G}{G_{ref}} \quad (2)$$

$$V_{oc} = V_{oc-ref}[1 + \eta \times \ln(\frac{G}{G_{ref}}) + \beta(T - T_{ref})] \quad (3)$$

where, V_{oc} denotes the open circuit(OC) voltage, V_{oc-ref} is OC voltage at STC, I_{sc} denotes short circuit (SC) current, T is PV module temperature ($^{\circ}C$), I_{scref} is SC current at STC,

979-8-3503-1997-2/23/$31.00 ©2023 IEEE

I_{ph} denotes the photo-current generated from solar cell, V is load voltage, I is load current, I_0 is reverse saturation current of diode, G denotes the solar irradition (W/m²), T_{ref} is PV array temperature at STC (˚C). G_{ref} represents the reference irradiance under STC (1kW/m²), α denotes the temperature coefficient of short circuit current (/˚C), k is Boltzmann constant, R_{sh} is parallel resistance, and R_s is series resistance.

In Eq. (1), R_{sh} is usually very big, so the part containing it will be omitted. Solar cells create temperature-dependent energy. I_{ph}, a photo-current related to solar energy, forms electron-hole pairs. PV cell standard test conditions (STC) are 1000 W/m^2 solar irradiation, 25°C temperature. The PV Panels are affected by weather and irradiance as shown in Eqs. (2) and (3).

B. Characteristics of PV panel:

The property of the PV panel is highly nonlinear in nature [4] which can be observed from figures 2 and 3. For the simulation purpose, Kyocera solar KC200GT solar panel model is used. The parameter of this panel model is given in Table I.

Table I The value of the parameters of PV panel at an irradiance of 1000 W/m^2

Parameters	Value
P_m	200.15 (W)
V_m	26.3 (V)
I_m	7.62 (A)
V_{oc}	33 (V)
I_{sc}	8.21(A)

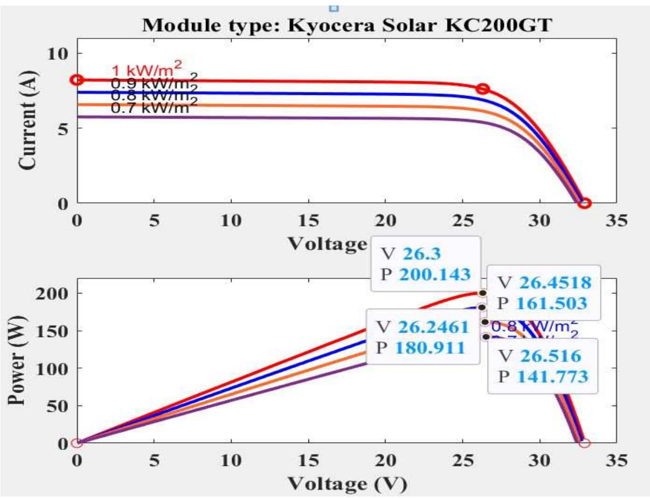

Fig. 2. *P-V* and *I-V* properties of a PV panel at variable irradiance and fixed temperature (25^{0}C)

Fig. 2 shows how the PV current and power is varying at different irradiation levels at fixed temperature (25^{0}C). The PV voltage is decreasing with the decrease in irradiance. The following Table II shows the values of P_m at their respective irradiance levels.

Table II Maximum PV power at different Irradiance level

Irradiance (W/m^2)	1000	900	800	700
P_m(W)	200.14	181	161.5	142

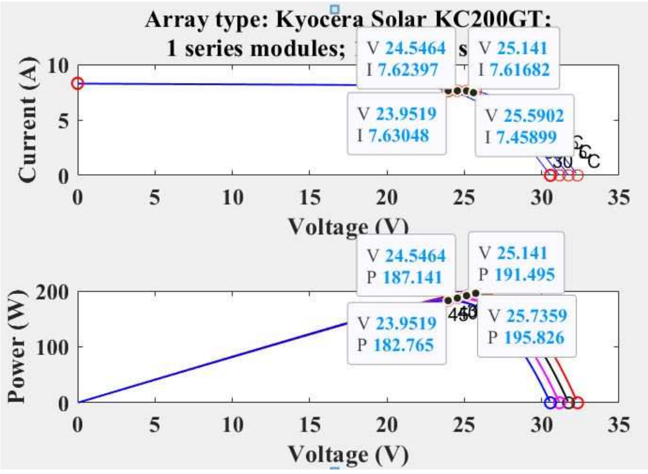

Fig.3 *P-V*and *I-V* properties of PV panel at variable temperatures and fixed irradiance (1 kW/m^2)

Figure 3 shows the I-V and P-V properties of PV panels at variable temperatures and fixed irradiance (1kW/m^2). At 25^{0}C the Pmp is 200W. The maximum PV power(P_m) and V_m decrease with an increase in temperature. Table III shows the values of P_m and V_m at different temperatures.

Table III. Maximum PV power at different temperatures

Temperature (^{0}C)	30	35	40	45
Power (W)	195.826	191.5	187.14	182.76
Voltage (V)	25.73	25.14	24.54	23.95

C. DC-DC Boost Converter:

To achieve or extract maximum power, a DC-DC power converter is required to connect between the solar panel and the load. This interfacing power converter (DC-DC) may be Buck, Boost, Buck-Boost, SEPIC or CUK converter. In this proposed work, the Boost converter is considered as shown in figure 3. The mathematical equations used for the Boost converter are given below.

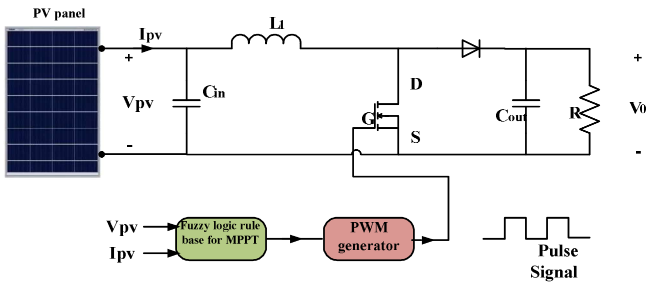

Fig. 3. MPPT control PV Panel with Boost converter

The equation for the system's efficiency may be expressed by equation (6), and it is based on the PV voltage and the output voltage of the Boost converter, which are indicated in equation (4).

$$V_0 = \frac{V_{pv}}{(1-D)} \tag{4}$$

$$I_o = I_{pv}(1-D) \tag{5}$$

$$\eta = \frac{V_0 I_0}{V_{pv} I_{pv}} = \frac{1}{(1-D)^2} \frac{R}{R_{eq}} \tag{6}$$

From Eq (4) and (5), the input impedance is given in Eq. (7). Where D is duty cycle.

$$R_{in} = R(1-D)^2 \quad (7)$$

The PV module's working point is determined by the load's impedance. Boost converter duty cycle regulation matches impedance. PV Panel directly connected to load cannot ensure optimum power point. When the PV Panel's comparable impedance equals the load's, maximum power moves from source to load [6,11]. The DC-DC converter works at MPP by regulating its duty cycle to match the load and equivalent impedance for all irradiations and temperatures. The Boost converter interfaces with modelling and practical PV Panel operation at MPP. Fig. 3 shows a PV panel with an MPPT-integrated boost converter.

III. TYPE-I FUZZY LOGIC RULE BASED MPPT TECHNIQUE

In PV systems, the type-I fuzzy logic strategy is used frequently because it can adapt rapidly to shifting conditions [7] than either the perturb and observe or the incremental conductance algorithm. Both of these approaches are commonly used. Because of this, the use of the fuzzy logic technique has become increasingly ubiquitous. The flow chart for the curved MPPT technique is shown in figure 4, which is an illustration of the flow chart. It is possible to use FLC as a controller to acquire the maximum amount of power that the PV modules are capable of generating, FLC can be utilised as a controller to monitor and adjust the system. Fuzzification, rule assessment, and defuzzification are the three distinct phases which can be distinguished within the FLC procedure. Figure 4 illustrates these aspects of a Type-I Fuzzy Logic System (FLS) along with the overall layout of the system.

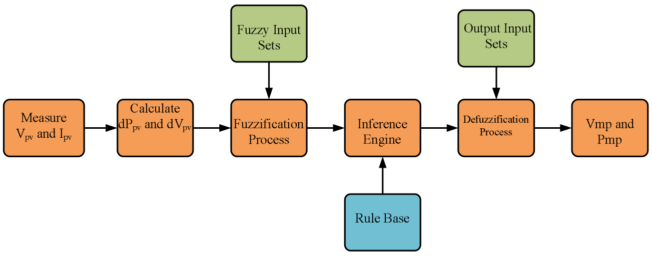

Fig. 4. The flow chart of Fuzzy logic MPPT method

To make fuzzy inputs, the fuzzification method combines a precise input with a recorded membership function, such as the change in voltage measurement[8]. This is done in order to produce fuzzy inputs. It is necessary to begin by assigning a membership function to each individual input before attempting to convert the crisp inputs into fuzzyfied inputs. Following are the assignment of the membership functions, the fuzzification process involves taking real-time inputs and comparing them with the information that has been recorded pertaining to the membership functions in order to generate ambiguous input values.

The rule assessment is the second phase in the processing of fuzzy logic. In this step, the fuzzy processor consults linguistic rules to ascertain the appropriate course of control action that should be taken in reaction to a specific collection of input values. A fuzzy outcome is produced for each possible form of subsequent action as the end product of rule assessment. The last step of fuzzy logic processing, when a sharp value is selected from the domain of possible output fuzzy sets to represent the expected value of the output variable.

During this procedure, each of the fuzzy output values modifies the corresponding output membership function (MF) they are responsible for. In this study, the triangular membership function is used for fuzzification and defuzzification due to its simplicity, intuitive interpretation, flexibility, smoothness, robustness, and computational efficiency. The centroid method is one of the defuzzification strategies that is utilised the most frequently[8].

For the purpose of monitoring the highest power of PV systems, a type-I Mamdani fuzzy logic controller has been used because it offers a number of benefits, including the fact that it is reliable, that it is reasonably easy to create, and that it does not require the understanding of a precise model. Compared to the traditional P&O technique, the fluctuation around MPP is significantly reduced, and the reaction time is significantly sped up. The E(error) and CE (Change in error) are going to be fed into the FLC according to the plan. [9]. The output that is suggested to come from the FLC is denoted by the notation dV*. This representation is accurate for the modulation signal that is transmitted to the PWM generator to generate switching pulses. The definitions of the incoming variables can be found in (8) and (9). The process of "fuzzification" entails linguistic variables based on membership functions being created from the numerical input variables. This conversion takes place during fuzzification. The membership of E, CE, and dV* are depicted correspondingly in figures 6, 7, and 8. All of the inputs and outputs are represented by five-level fuzzy system: NL (Negative Large), NS (Negative Small), ZE (Zero), PS (Positive Small), and PL. (Positive Large).

$$E = \frac{dP_{pv}}{dV_{pv}} = \frac{P(t)-P(t-1)}{V(t)-V(t-1)} \quad (8)$$

$$CE = E(t) - E(t-1) \quad (9)$$

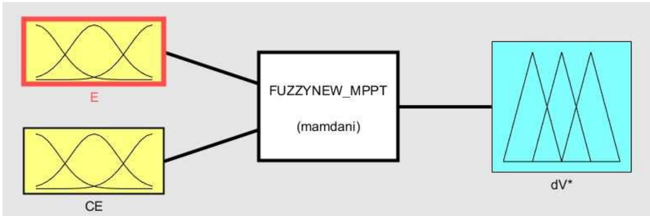

Fig. 5. Fuzzy logic designer function

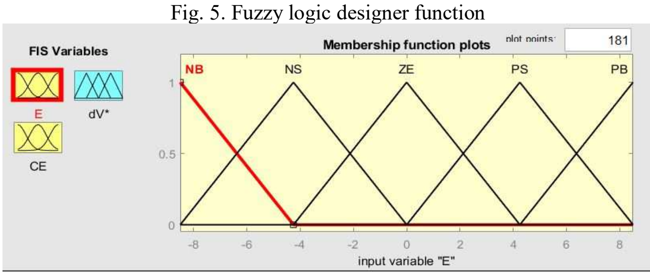

Fig. 6. The MFs of the input variable (E)

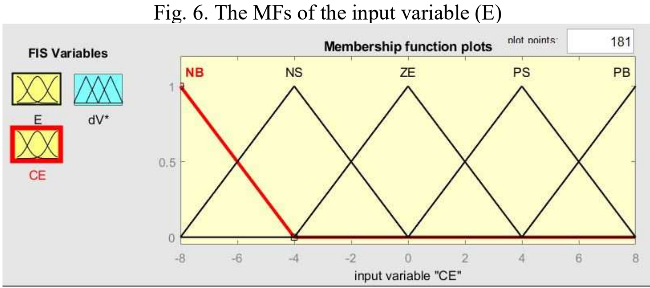

Fig. 7. The MFs of the input variable (CE)

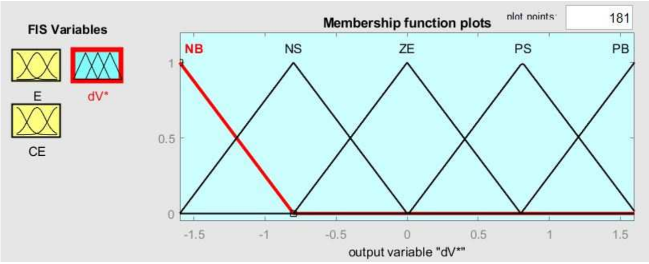

Fig. 8 The MFs of the output variable (dV*)

Table IV contains an outline of the suggested regulations. The flexible guidelines are intended to keep track of the highest power source of the photovoltaic system even when the weather circumstances are variable. When developing these guidelines, rapid shifts in solar radiation were considered, which shows the three-dimension (3D) surface representation of the MFs for the proposed FLC MPPT method in figure 9.

Table IV. Rule base used in the FLC

CE \ E	NL	NS	ZE	PS	PL
NL	PL	PS	NL	NS	NS
NS	PS	PS	NL	NS	NS
ZE	NS	NS	NS	PL	PL
PS	NS	PL	PS	NL	PL
PL	NL	NL	PL	PS	PL

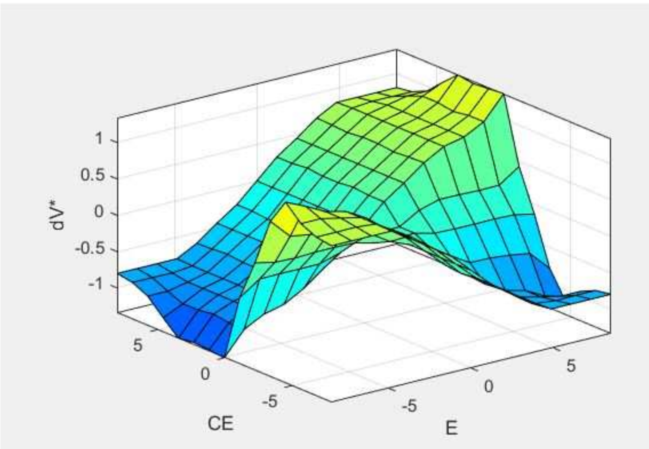

Fig.9 Three-dimensional (3D) surface function for the proposed FLC MPPT method

IV. SIMULATION RESULTS AND DISCUSSIONS

The suggested MPPT technique is demonstrated to effectively and precisely monitor the maximum power under various environmental circumstances, serving as a verification of the MPP tracker for the solar modelling system. To simulate the system, MA TLAB/SIMULINK is used. The computer model is depicted in figure 10. The MATLAB simulation is carried out for 1sec throughout the simulation work. The MOSFET is gated by a signal produced by the MPPT control block.

The boost converter is built to operate within the parameters of a maximum power of 200 watts, a maximum power point voltage of 26.3 V, and an output voltage that may be adjusted to be anywhere between 24 and 38 V. The load is set to be 3.5 Ω for maximum power. The values of the parameters of the solar panel used for simulation are shown in Table I.

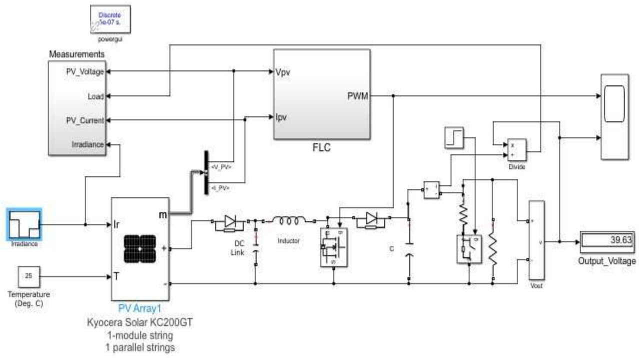

Fig. 10. Simulink model of MPPT using Fuzzy Logic Controller

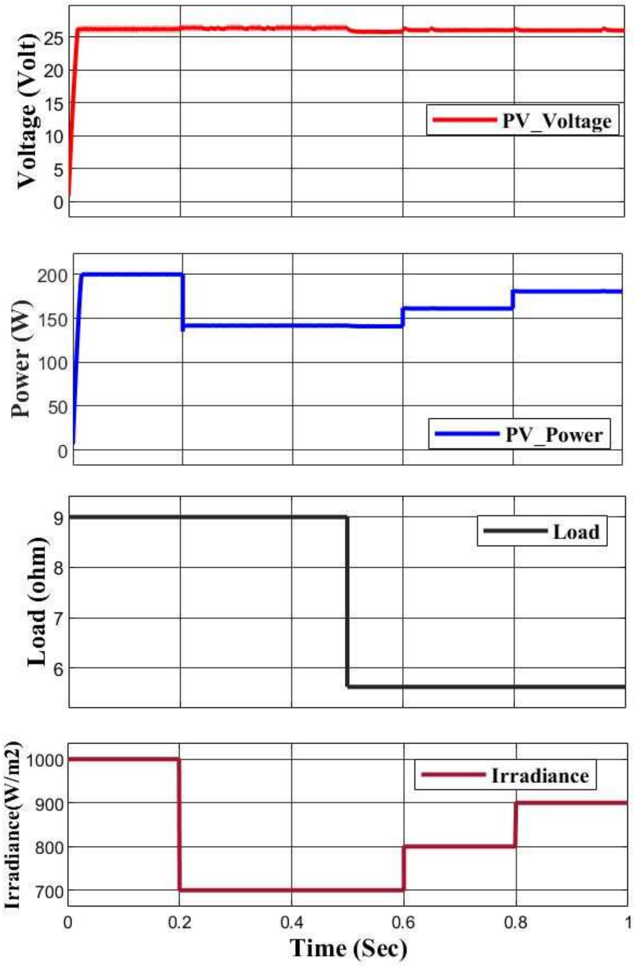

Fig. 11 Simulation results of MPPT using Fuzzy Logic Controller with variable irradiance and load at constant temperature

A. *Case-I (Both load and irradiance are changing at constant temperature)*

From the figure 11, it is clearly observed that the load is changing from 9 Ω to 5.5 Ω at 0.5 s, that time irradiance level is 700 W/m^2 and the PV power is remained constant i.e., 142 W and PV voltage is also constant i.e., 26 V. The irradiance is also changing from 1000 W/m^2 to 700 W/m^2, 800 W/m^2 and 900 W/m^2 at 0.2 s, 0.6 s, and 0.8 s, respectively. At the time of Irradiance changing, the power extracted from the PV panel is maximum power w.r.t. their P_{mp}. The maximum power at different irradiation level is shown in figure 2 and Table II.

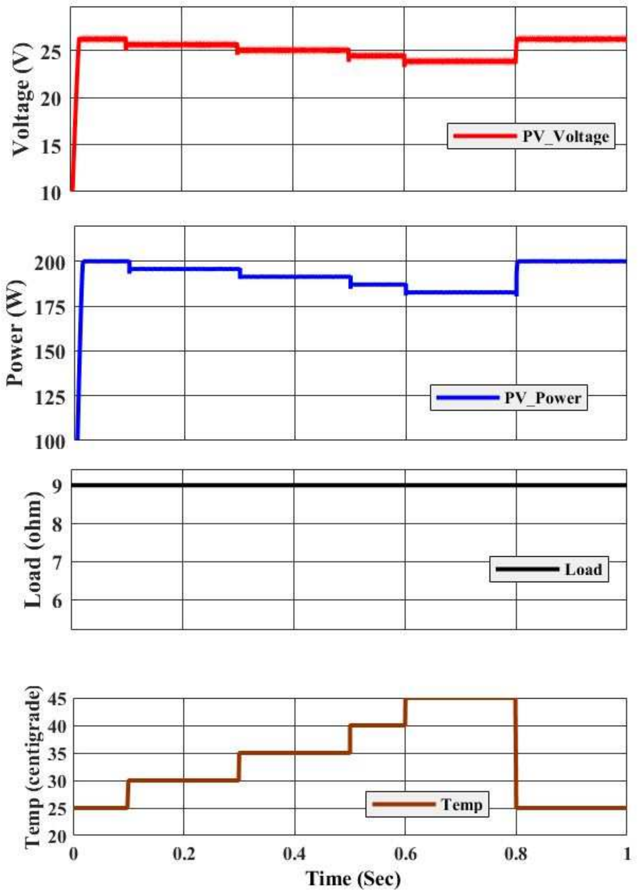

Fig.12 Simulation results of MPPT using Fuzzy Logic Controller with variable temperature at constant irradiance and load

B. Case-II (Temperature is varying but load and irradiance is constant)

The terminal voltage of PV panel (V_{pv}) is negative temperature coefficient. So the V_{pv} decreases with increase in temperature and P_{pv} is also decreases with increase in temperature as shown is Table III which is validated through MATLAB simulation and shown in figure 12. From this figure, it is clearly observed that when temperature is changing from 25^0C to 30^0C at 0.1 sec, the PV voltage and power drops to 25.7V and195.8W. When temperature is rising from 30^0C to 35^0C at time 0.3 sec, the PV voltage and power again drops to 25V and 191W. At time 0.6 sec, the temperature increases fro 40^0C to 45^0C, the voltage and power again decreases to 24V and 182W. When the temperature is changing from 45^0C to 25^0C at time 0.8 sec, the PV volatage and power increases to 26V and 200W.

V. CONCLUSION

In this article, we present a MATLAB/SIMULINK based model of a photovoltaic system and the architecture of a Boost converter equipped to monitor the maximum power point. The simulations are evaluated in the presence of perturbations to solar irradiance level and Different magnitudes of load. The suggested technique successfully follows the optimum power point in simulations with varying environmental circumstances. Compared to more traditional approaches, the reaction time is reduced, and the frequency of fluctuation around MPP is reduced as it is a variable step method.

REFERENCES

[1] H. Abouadane, A. Fakkar, D. Sera, A. Lashab, S. Spataru, and T. Kerekes, "Multiple-power-sample based P&O MPPT for fast-changing irradiance conditions for a simple implementation," *IEEE Journal of Photovoltaics* , vol.10, no. 5, pp.1481-1488, July 2020.

[2] M. L. Azad, P.K. Sadhu, and S. Das, "Comparative Study Between P&O and Incremental Conduction MPPT Techniques-A Review," *International Conference on Intelligent Engineering and Management (ICIEM)*, pp. 217-222, 2020

[3] V. Kumar, and M. Singh, "Derated mode of power generation in PV system using modified perturb and observe MPPT algorithm," *Journal of Modern Power Systems and Clean Energy*, vol.9, no. 5 ,pp. 1183-1192, Sept 2020.

[4] V. Gurugubelli, A. Ghosh, and A. K. Panda, "Comparison of Deadzone and Vanderpol Oscillator Controlled Voltage Source Inverters in Islanded Microgrid," In *2021 IEEE 2nd International Conference on Smart Technologies for Power, Energy and Control (STPEC)*, pp. 1-6, Dec. 2021.

[5] S. Patel, A. Ghosh, and P. K. Ray, "Design of Fractional Order Controller Integrated with Renewable Resource in Multi Area Islanded Microgrid," In *2020 IEEE International Conference on Power Electronics, Smart Grid and Renewable Energy* pp. 1-6, 2020.

[6] H. Tiwari, and A. Ghosh, "Power flow control in solar PV fed DC Microgrid with storage," In *2020 IEEE 9th Power India International Conference (PIICON)*, pp. 1-6, 2020.

[7] J. K. Nayak, G. Vikash, and A. Ghosh, "Design and Control of Bidirectional SEPIC/Zeta Converter," *Advanced Power Electronics Converters for Future Renewable Energy Systems*, CRC Press, Taylor & Francis Group, Feb. 2023.

[8] C. R. Ananthraj, G. Vikash, and A. Ghosh, "Modelling a Battery and SOC Calculation Using Coulomb Counting Technique and Simulation of Equalising Techniques Used in Battery Management Systems," *Advanced Power Electronics Converters for Future Renewable Energy Systems*, CRC Press, Taylor & Francis Group, Feb. 2023.

[9] G. Vikash, D. Funde, and A. Ghosh, "Implementation of the Virtual Synchronous Machine in Grid-Connected and Stand-alone Mode," *DC—DC Converters for Future Renewable Energy Systems*, Springer, Singapore, pp. 335-353, Jan. 2022.

[10] S. Patel, A. Ghosh, P.K. Ray, "Adaptive power management in PV/Battery integrated hybrid microgrid system," In *2022 IEEE International Conference on Power Electronics, Smart Grid, and Renewable Energy (PESGRE),* pp. 1-6, January, 2022.

[11] V. Gurugubelli, A. Ghosh, and A. K. Panda, "Different Oscillator Controlled Parallel Three-Phase Inverters in Standalone Microgrid," In *Sustainable Energy and Technological Advancements: Proceedings of ISSETA 2021*, Springer Singapore, pp. 67-79, Mar. 2022.

[12] B.Sujith, A.Ghosh, and V. Gurugubelli, "Design of PFC boost converter with stand-alone inverter for microgrid applications," In *IEEE Delhi Section Conference (DELCON)*, pp. 1-5, Feb. 2022.

[13] J. Kumar Nayak, H. Thalla, and A. Ghosh, "Efficient Maximum Power Point Tracking Algorithms for Photovoltaic Systems with Reduced Number of Sensors," *Process Integration and Optimization for Sustainability*, vol.7, no. 1-2, pp 191-213, Mar. 2023.

[14] V. Gurugubelli, A. Ghosh, and A. K. Panda, "A New Virtual Oscillator Control for Synchronization of Single-Phase Parallel Inverters in Islanded Microgrid," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 44, no. 4, pp. 8842-8859, Dec. 2022.

[15] S. K. Panda and A. Ghosh, "A Computational Analysis of Interfacing Converters with Advanced Control Methodologies for Microgrid Application," *Technology and Economics of Smart Grids and Sustainable Energy*, vol.5, no.1, pp.1-18, Springer 2020.

[16] P. K. Mahapatra, S. K. Gudla, V. Gurugubelli, A. Ghosh, and A. K. Panda, "Fuzzy Adaptive Droop Controlled Parallel Inverters for Microgrid Applications," In *2022 IEEE 10th Power India International Conference (PIICON)*, pp. 1-6, Nov. 2022.

[17] G. Vikash, A. Ghosh, and A. Panda, "Design and Implementation of Optimized Virtual Oscillatory Controllers for Grid-Forming Inverters" *ISA Transactions*, 2023.

[18] A. Singh and A. Ghosh, "Comparison of Quantitative Feedback Theory Dependent Controller with Conventional PID and Sliding Mode Controllers on DC-DC Boost Converter for Microgrid Applications," *Technology and Economics of Smart Grids and Sustainable Energy*, Springer Nature Singapore, vol.7, no.11, pp.1-12, 2022.

[19] G. Vikash, A. Anand, and A. Ghosh, "A New Hybrid Islanding Detection Technique for Microgrid Using Virtual Synchronous Machine," *Advanced Power Electronics Converters for Future Renewable Energy Systems*, CRC Press, Taylor & Francis Group, Feb. 2023.

[20] A. Roy and A. Ghosh, "Current Controlled Grid-Interfaced Photovoltaic Boost Inverter with Particle Swarm Optimisation based MPPT Algorithm," in *2021 IEEE International Conference on Sustainable Energy and Future Electric Transportation (SEFET-2021)*, Jan. 2021.

[21] S. Sinha and B. Prabodh, "Power management of hybrid energy storage system in a standalone DC microgrid," *Journal of Energy Storage,* no. 30, pp. 101523, 2020.

[22] A. Singh and A. Ghosh, "Design and Analysis of PID, Type II and Type III controllers for Fourth Order Boost Converter," in *IEEE 7th International Conference on Electrical Energy Systems (ICEES-2021)*, pp.323-328, Mar. 2021.

[23] S. Dora, V. Gurugubelli, A. Ghosh, and A. K. Panda, "Parallel operation of inverters by using Model Predictive Control in Islanded Microgrid," In *2022 IEEE 10th Power India International Conference (PIICON)*, pp. 1-6, Nov. 2022.

[24] H. Tiwari, and A. Ghosh, "Power flow control in solar PV fed DC Microgrid with storage." In *2020 IEEE 9th Power India International Conference (PIICON)*, pp. 1-6, 2020.

[25] S. Patel, A. Ghosh, P.K. Ray, "Improved power flow management with proposed fuzzy integrated hybrid optimized fractional order cascaded proportional derivative filter (1+ proportional integral) controller in hybrid microgrid systems," *ISA Transactions*, 136, pp. 742-754, May 2022.