Design of Fuzzy Logic MPPT Controller of a Solar PV System under Weather Changing Conditions

Ravi Kumar M, Rajangam K, C. Kamal Basha, P.Chandra Babu Naidu

***Abstract*— The overall performance of solar cell varies with irradiance and temperature with change in the time of day power received from the sun by the solar panel changes .this both irradiance and temperature affects the solar cell efficiency. This, paper presents Fuzzy Logic conventional Incremental Conductance (IC) for Maximum Power Point Tracking (MPPT). This MPPT method operates best performance beater then the conventional Incremental Conductance MPPT techniques mainly under changing the weather changing conditions. The output results of the simulation fuzzy logic based Incremental conductance MPPT technique controller provides the faster response to the Maximum Power Point and low oscillation to the MPPT compare to Conventional incremental conductance MPPT technique under the changing weather conditions(solar radiation, temperature). Compare to other MPPT techniques Fuzzy Logic based MPPT controller is superior and to get MAXIMUM POWER at lesser time.**

***Index Terms*— Solar Cell, Maximum Power Point Tracking, Fuzzy Controller, Incremental Conductance**

I. INTRODUCTION

To changes of the solar radiations and temperature, the outputs of photovoltaic solar cell also changing. So to get better overall efficiency it is important task to track maximum power point (MPP) in under varying weather changing conditions. The two major drawbacks of Incremental Conductance (IC) method is slow convergence to the optimum operating point and moving away from the maximum optimum point when the irradiance varies quickly. At present, solar cell (PV) generation is expected as an improved status for renewable energy sources application because of typical advantages such as ease of distribution, high reliability, nonappearance of fuel cost, low maintenance[1]. Time off demand and wear for of the absence of moving parts. No pollution is emitted here i.e. 100% environmental friendly. So here we are attempting to show a non-ordinary vitality era framework utilizing PV panel In past years, several techniques have been projected for tracking the maximum power point (MPP). The maximum usually applied hill-climbing MPPT technique is the P&O algorithm[2, 3]. Additional identical standard hill-climbing MPPT algorithm is the incremental conductance (INC) algorithm [3, 4]. At MPP point, the lacking in originality of the power with respect to the voltage will be threatened, this is the main fact of this MPPT algorithm. The sum of the instantaneous and incremental conductance is negative on the right-hand side of the MPP, while the sum is positive on the left-hand side of the MPP. A more understated, up till now possible method for performing the IC. procedure is to the IC technique is to generate an error signal, which is the sum of instantaneous conductance (I/V) and the incremental conductance (dI/dV) as suggested in[6]; we know that *e* goes to zero at the MPP.

In this paper, a new fuzzy logic based incremental conductance technique is proposed, which proposals fast and precise convergence to the maximum power point as related to conventional incremental conductance technique. The fuzzy logic based MPPT controller is designed for grid connected photovoltaic system. The DC link voltage and current injection to the grid is also controlled by using a voltage controller and current controller respectively. PI controller is used to minimize the error between the reference current and grid current. AI search techniques like, Genetic algorithm and Firefly algorithm are used to optimize the PI controller gains.

Simulation model is developed in MATLAB/SIMULINK software and a 100 kilo watt grid connected photovoltaic (PV) system has been built and tested to investigate the dynamic performance of the algorithm. The simulation results show the advantage of the proposed MPPT controller. The overall paper is as follows. Section 1 gives the introduction and literature survey of the work section 2 gives simulation model of PV array, Theoretical aspect of MPPT is presented in section 3. Section 4 gives the proposed method for tracking the maximum power point using fuzzy controller, whereas simulation performance and comparison is defined in section 5. Conclusion is briefly drawn in section 6.

II. SIMULINK MODEL OF THE PV SYSTEM

The corresponding circuit of PV cell shown in Figure:1 and the simple equations from the theory of semiconductors mathematically describe *I-V* characteristic of a solar PV array take out.

$$I_p = I_{pv} - I_r \exp[(qV_i / KTA) - 1] - \frac{V_i}{R_{sh}} \quad (1)$$

Where I_p is the output current of PV array (A), I_{pv} is the current generated by the incident light (it is directly proportional to the sun irradiation) V_i is the output voltage of the PV array (V), q is the charge of an electron, K is the Boltzmann's constant in J/K, A is the P-N junction ideality factor, T is the cell temperature (K), I_r is cell reverse saturation current.

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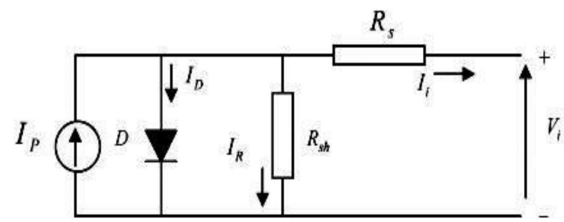

Figure 1: Equivalent circuit of solar cell

The Photo current I_{pv} is depend on the solar radiation and the cell temperature as stared as the

$$I_{pv} = (I_{sc} + K_i(T - T_r))\frac{G}{100} \qquad (2)$$

Where I_{sc} is the PV array short circuit Current at reference temperature and radiation (A), K_i is the short circuit current temperature coefficient (A/K) and G is the solar radiation (W/m^2).

The reverse saturation current I_r varies with temperature according to the following:

$$I_r = Irr(\frac{T}{T_r})^3 \exp[\frac{1.115}{k^1 A}(\frac{1}{T_r} - \frac{1}{T})] \qquad (3)$$

Where T_r is the cell reference temperature, *Irr* is the reverse saturation current at T_r, K^1 is the Boltzmann's constant in eV/K and the energy band gap of the semi -conductor used in the cell is equal to 1.115.

The open circuit Voltage of the PV array

$$V_{oc} = \frac{AkT}{q}\ln(\frac{I_{pv} + I_r}{I_r}) \qquad (4)$$

From (2) to (4), we get

$$Ir = \frac{(I_{sc} + k_i(T - T_r))\frac{G}{100}}{\exp[(V_{oc}q / AKT) - 1]} \times \qquad (5)$$
$$\left((\frac{T_r}{T})^3 \exp[-\frac{1.115}{k^1 A}(\frac{1}{T_r} - \frac{1}{T})] \right)$$

And from (1)

$$R_{sh} = \frac{V_{oc}}{-I_{rs}(\exp[(qV_{oc} / kTA) - 1]} \qquad (6)$$

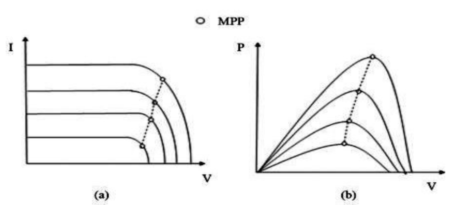

Figure 2: (a) I-V and (b) P-V characteristics of PV panel at different environmental conditions

III. Maximum Power Point Tracking

The main objective is to track and extract Maximum Power from the PV array for a given solar irradiation. The maximum power consistent to the peak operating point is determined for a different solar irradiation level. Customarily a dc-dc converter is utilized between the input source and load for the resolve of MPPT. The characteristics of PV cell shown below Figure 3:

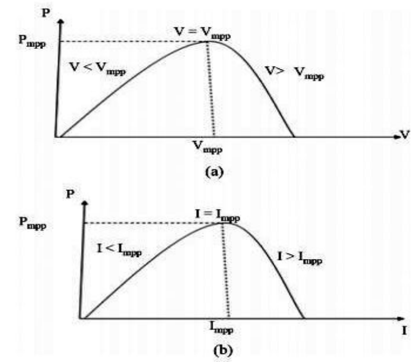

Figure 3: (a) P-V curve variation with voltage (b) P-V curve variation with power with current

The incremental conductance (IC) method is based on the fact that the slope of the PV array power curve is zero at the MPP, positive on the left of the MPP, and negative on the right.

For a PV system, the derivative of panel output power with its voltage is expressed as-

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V\frac{dI}{dV} = I + V\frac{I}{V} \qquad (7)$$

The solution of Eq-(7) is zero at MPP, positive on the left of the MPP and negative on the right of the MPP. So, it can be rewritten as

$$I / V = -I / V, \text{ at MPP}$$
$$I / V > -I / V, \text{ left of MPP}$$
$$I / V < -I / V, \text{ right of MPP} \qquad (8)$$

Thus, MPP can be tracked by associating the sudden conductance (I/V) to the incremental conductance (I/ V). It is the same efficient as P&O, decent yield under quickly changing weather conditions. Here, also the same perturbation size problem as the P&O exists and an attempt has been made to solve by taking variable step size. But, it requires complex and costly control circuits.

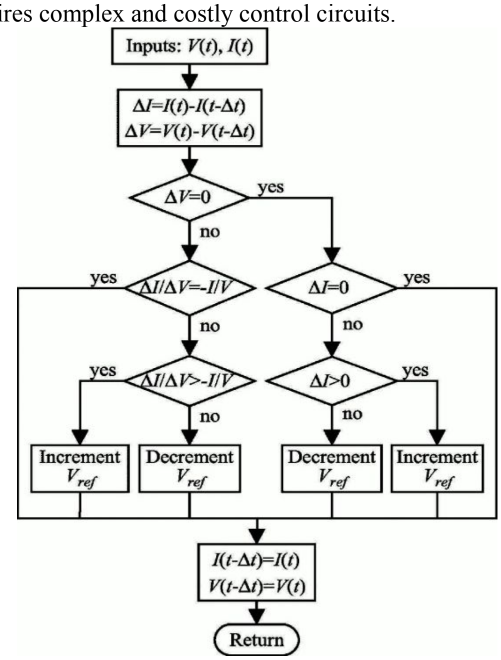

Figure-4: Flow chart of IC algorithm

B. Modelling Of Grid Connected Photovoltaic System

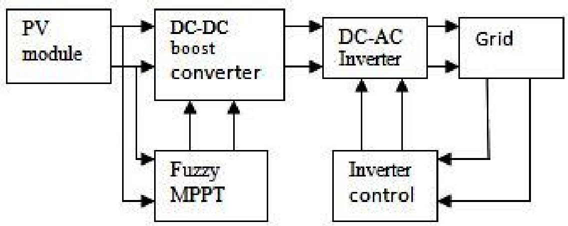

Figure-5: Block Diagram Model of Grid Connected Photovoltaic System

IV. PROPOSED FUZZY LOGIC MPPT CONTROLLER

Fuzzy logic controllers have the advantages of working with indefinite inputs, not needing an precise mathematical model, and behaviour nonlinearity. The proposed controller is designed to eliminate all the mentioned drawbacks. The control objective of this fuzzy controller is to track the maximum power point as fast as possible under varying weather condition. Fuzzy logic control generally consists of three stages: *A)* Fuzzification *B)* Fuzzy rule matrix & inference engine and *C)* Defuzzification

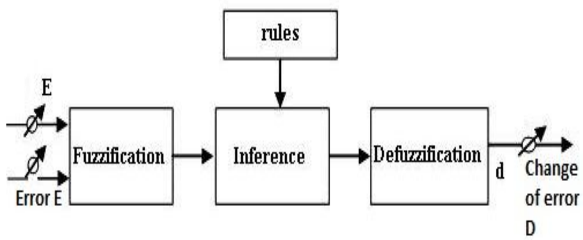

Figure-6: configuration of fuzzy controller for MPPT

A. Fuzzification

The Fuzzification includes the development of changing crisp values into grades of membership for linguistic terms of fuzzy sets. The membership function is used to associate a grade to each linguistic term. In this thesis FLC MPPT method has two input variables, error ER and change in error and an output variable. The two input variables are described by:

$$ER(\mathrm{k}) = \frac{\mathrm{P}_{pv}(\mathrm{k}) - \mathrm{P}_{Pv}(k-1)}{I_{pv}(\mathrm{k}) - I_{Pv}(k-1)} \quad (9)$$

And

$$\mathrm{ER(k)} = E(\mathrm{k}) - \mathrm{E(k-1)} \quad (10)$$

Where, P_{pv} *(k)* and I_{pv} are the power and current of the array, respectively. At MPP *ER (K)* is zero at the maximum power point of PV array. Those input variables are expressed in terms of seven linguistic variables or labels, such as "Negative Large *(NL)"*, "Negative Medium (NM)", "Negative Small *(NS)"*, "Zero *(ZE)"*, "Positive Small *(PS)"*, "and Positive Medium (PM)", "Positive Large *(PL)"*. For fast convergence and more accuracy output variable which is nothing but the duty ratio (*D*) of the power converter has nine linguistic variables such as "Negative Ultimate *(NU)"*, "Negative Large *(NL)"*, "Negative Medium *(NM)"*, "Negative Small *(NS*)"," Zero *(ZE)"*, "Positive Small *(PS")*, "Positive Medium *(PM)"*, "Positive Large *(PL)"*, "Positive Ultimate *(PU)"*.The input and output membership functions are shown in Fig-7 and Fig-8 respectively.

B. Fuzzy Rule Algorithm

In this paper 49 fuzzy control rules are used as shown in Table I .Fuzzy rules are designed based on the zero error condition at the steady state of the MPP. The main aim of the rule is to track maximum optimum point by increasing or decreasing the duty ratio of the power converter. As an example control rule in Table-I:

IF *ER* is NL AND *ER* is *ZE* THEN *D* is *NL* This implies that if the operating point is distant from MPP towards right hand side and the change of slope in P-I curve is about zero; decrease duty ratio largely (NL). In the same way duty ratio is increases largely (PL) if ER is PL and is ZE.

In this fuzzy inference method, Mamdani's method is used Max-Min operation fuzzy combination law.

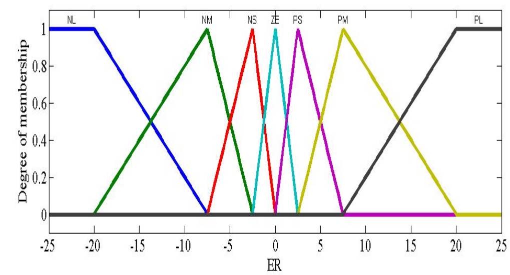

Figure-7: Input membership function (error ER and change error ER) of fuzzy logic controller

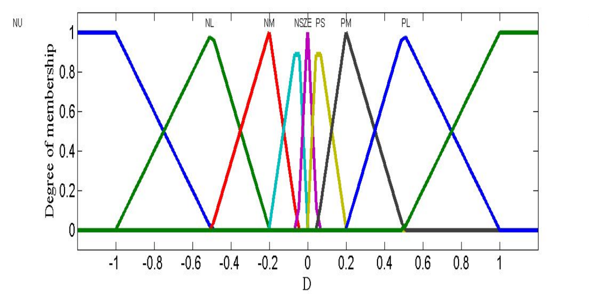

Figure-8: Output membership function (Δd) of fuzzy logic controller

ER / ΔER	NL	NM	NS	ZE	PS	PM	PL
NL	NU	NU	NL	NM	NS	ZE	ZE
NM	NU	NL	NL	NM	NS	ZE	ZE
NS	NL	NL	NM	NS	ZE	PS	PM
ZE	NL	NM	NS	ZE	PS	PM	PL
PS	NM	NS	ZE	PS	PM	PL	PL
PM	ZE	ZE	PS	PM	PL	PU	PU
PL	ZE	ZE	PS	PM	PL	PU	PU

Table-I: Fuzzy Rule Base Table

C. Defuzzification

This is the third stage of the fuzzy controller, where the fuzzy control subset must be converted to the crisp value. As mentioned earlier the output of the fuzzy controller is the duty ratio of the dc/dc converter, which is a crisp value. So the centre of area algorithm (COA) is used to convert the fuzzy subset to duty ratio and the output D can be calculated by:

$$\Delta D = \frac{\sum_{k=1}^{n} \mu(\Delta D_k).\Delta D_k}{\sum_{k=1}^{n} \mu(\Delta D_k)} \qquad (11)$$

Where, D is the fuzzy controller output and D_k is the center of max–min composition at the output membership function. Fig-4 shows the configuration of fuzzy controller, which consist Input-output variables, Fuzzification, fuzzy inference rule and defuzzification.

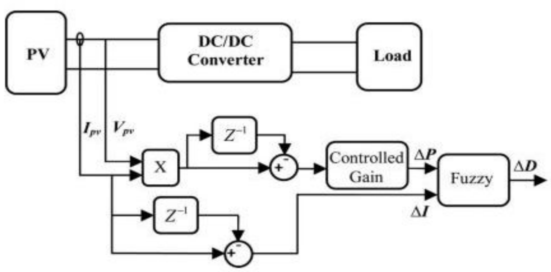

Figure-9: Block diagram of the PV array system along with the proposed MPPT controller.

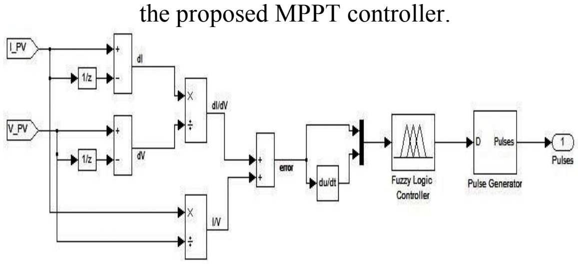

Figure-10: Simulation model of proposed fuzzy logic MPPT controller

D. Inverter Control Scheme

In inverter control scheme, a cascaded control structure with an outside dc link voltage control loop and an internal current control loop is used. The voltage source inverter (VSI) connected to the grid through an L filter. In this section, a dynamic analytical model of the VSI is developed in its unique three-phase *abc* frame. Then, this model is transformed into a synchronous reference frame.

The dynamic model in the *dq* frame is represented as

$$\begin{bmatrix} \frac{di_d}{dt} \\ \frac{di_q}{dt} \\ \frac{dv_{dc}}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & w & \frac{d_d}{L} \\ -w & -\frac{R}{L} & \frac{d_q}{L} \\ -\frac{d_d}{C} & -\frac{d_q}{C} & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_d \\ V_{dc} \end{bmatrix} + \begin{bmatrix} -\frac{1}{L} & 0 & 0 \\ 0 & -\frac{1}{L} & 0 \\ 0 & 0 & -\frac{1}{L} \end{bmatrix} \begin{bmatrix} V_d \\ V_q \\ I_{pv} \end{bmatrix} \qquad (12)$$

Where,

I_d, i_q is the d- and q-axis grid currents, respectively;

V_d,v_q is d- and q-axis grid voltages, respectively;

d_d, d_q is the d- and q-axis duty ratios.

E. Voltage Control

In the case of a unity power factor ($i_q = 0$), the third equation in the model (14) is repeated as

$$C\frac{dV_{dc}}{dt} = I_{pv} - d_d i_d \qquad (13)$$

At the beginning of a sequence, the weather conditions are considered constant; hence, an equivalent input is defined as

$$F_{dc} = I_{pv} - d_d i_d \qquad (14)$$

In order to adjust the dc voltage at a fixed value, the error $\in = V_{dc}^{*} - V_{dc}$ is passed through a PI-type compensator, as shown in Figure.5. The closed-loop transfer function of dc voltage regulation has the following form as-

$$\frac{V_{dc}(s)}{V_{dc}^{*}(s)} = \frac{K_{up}}{C} \frac{\frac{K_{ui}}{K_{up}} + s}{s^2 + \frac{K_{up}}{C}s + \frac{K_{ui}}{C}} \qquad (15)$$

Where, K_{up} and K_{ui} are the proportional and integral parameters, these parameters are improved by using heuristic algorithm for well performance. In the diagram, the voltage loop is an outer loop, while the current loop is an inner loop. The internal loop has been designed to achieve short resolving times in order to accomplish a fast improvement of the error. The outer loop can be designed to be slower. Thus, the inner and outer loops can be considered Decoupled, and they can be linearized.

F. Current Control

It can be understood as of Eq-(12) that there is cross-coupling between the *d* and *q* mechanisms. However, cross-coupling can move the active performance of the supervisor. Consequently, it is very significant to decouple the two axes for improved performance. This effect can be skilled with the feed forward decoupling control method. Assuming that.

$$\begin{aligned} V_{rd} &= -V_d + d_d V_{dc} + wLi_q \\ V_{rq} &= -V_q + d_d V_{dc} - wLi_d \end{aligned} \qquad (16)$$

Where. ω is the angular frequency of the utility.

Then, the system model is transformed to

$$\begin{aligned} \frac{di_d}{dt} &= -\frac{R}{L}i_d + \frac{1}{L}V_{rd} \\ \frac{di_q}{dt} &= -\frac{R}{L}i_d + \frac{1}{L}V_{rq} \\ \frac{dV_{dc}}{dt} &= -\frac{I_{pv}}{C} - \frac{V_d + V_{rd}}{CV_{dc}}i_d - \frac{V_q + V_{rq}}{CV_{dc}}i_q \end{aligned} \qquad (17)$$

The cross coupling variables are removed in the above-mentioned model. Hence, the currents id and iq can be controlled individually by acting upon inputs Vd and Vq, respectively. Furthermore, by using PI-type regulators, a fast dynamic response and zero steady state error can be attained. The diagram of the current controller is shown in Fig-11. Since the switching frequency is much higher than the line frequency, the sampling and hold delay is neglected. The diagram is suitable for both id and iq loops. The closed-loop transfer function of the d,q current loops is as-

$$\frac{i_d(s)}{i_d^*(s)} = \frac{i_d(s)}{i_d^*(s)} = \frac{K_{ip}}{L}\frac{s+\frac{Kii}{Kip}}{S^2+\frac{(K_{ip}+R)}{L}s+\frac{Kii}{L}} \quad (18)$$

In the diagram K_{ip} and k_{ij} are the proportional and integral parameters, respectively; i^* is the reference current signal, and I is the feedback current.

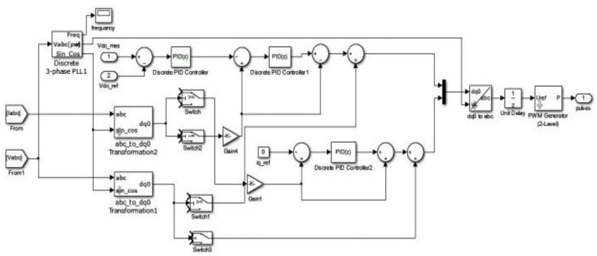

Figure-11: Inverter control of grid connected PV system

G. simulation model of grid connected PV system

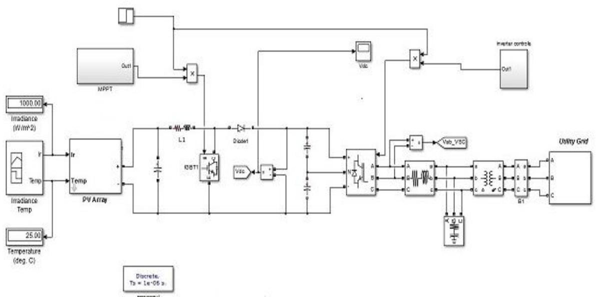

Figure-12: Simulation model of grid connected PV system

V. Results and Discussion

A. the proposed fuzzy logic MPPT controller has simulated and modelled by using MATLAB / Simulink and shown the I-V and P-V characteristics of PV arrays. The modelled PV array consists of 66 parallel strings and 5 series- connected modules. The specification of one PV module is shown in table-II.

Parameter	Symbol	Value
Maximum output Power	P_{mpp}	305.2 w
Maximum Voltage	V_{mpp}	54.7V
Maximum current	I_{mpp}	5.58A
Open-circuit Voltage	V_{oc}	64.2V
Short-circuit current	I_{sc}	5.96A
Series Resistance	Rs	0.038Ω
Shunt resistance	R_{sh}	993.5Ω
Number of series-connected cells	N_s	96

Table II: Manufacture Characteristics of one PV module

In Solar PV array system the weather changing conditions (irradiation and temperature) show the most major role to draw the maximum power. Fig-14 shows the I-V and P-V Characteristics of PV array at different weather changing conditions. Fig-13 shows the Module I-V and P-V characteristics of PV module at different weather changing conditions.

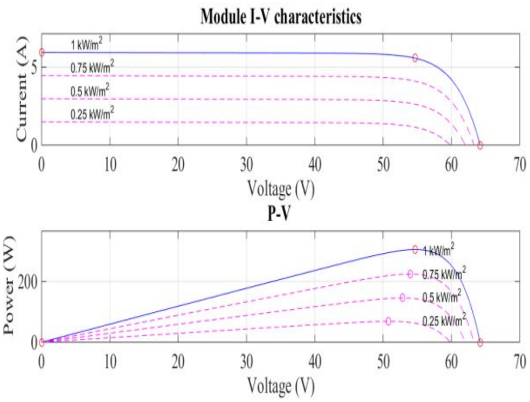

Figure-13: module I-V and P-V characteristics of PV module

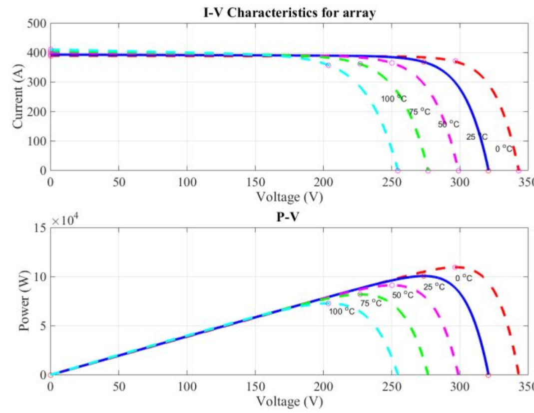

Figure-14: I-V and P-V characteristics of Solar PV array

Comparison Between proposed MPPT controller and conventional MPPT controller

The simulation results executed to show the better results of fuzzy logic controller as compared to conventional Incremental Conductance MPPT controller. So in this simulation, the solar radiation changes its value as follows: 1000W/m^2 from the time t = 0s to 0.6 s, 500 W/m^2 from the time t = 0.6 s to 1.4 s , and again 1000 W/m^2 from the time t = 1.4 s to 2 s, in the meantime the temperature is kept constant at 25^0 C. the PV array output power is 100.7 KW at 1000 W/m^2 , and 47.8 KW at 500W/m^2 as shown in Figure-15. it is shown The fuzzy logic controller track the maximum operating point very fast under varying weather condition as compared to conventional IC MPPT controller. The major drawback of slow convergence to the maximum power point is inherently eliminated by using the fuzzy logic controller.

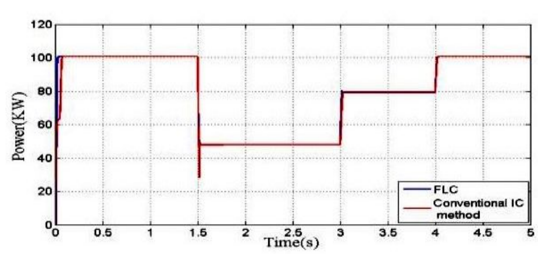

Figure-15: Fuzzy logic controller based track the MPP

Proposed MPPT Controller under Constant Irradiation

In Fig -15 it is shown that the proposed MPPT controller track the maximum operating point very fast where conventional controller is converge slowly. The convergence to the maximum power point by fuzzy logic controller is shown by a dash line at point A and the dot line at point B represents convergence of conventional IC controller.

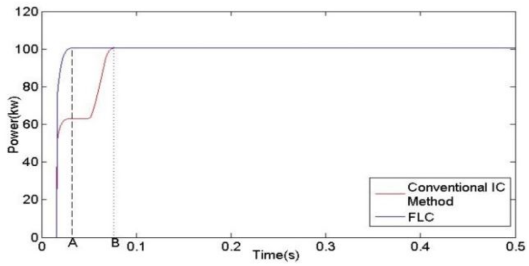

Figure -16: output power of the PV arrays for a constant irradiance

Proposed MPPT Controller in Rapidly Changing Conditions

The second drawback of moving away from the maximum optimum point with fast deviation of irradiance are also removed by retaining fuzzy logic control MPPT scheme as shown in above Fig-15 and Fig-16. At t= 0.6 s, the irradiance varies quickly from 1000 W/m^2 to 500 W/m^2 and the fuzzy controller offers a better result compared to IC controller as illustrated by fig.16. In the same way at t=1.4 s, the irradiance varies from 500 W/m^2 to 1000 W/m^2 and the better MPP tracking by fuzzy controller are shown by Fig-17.

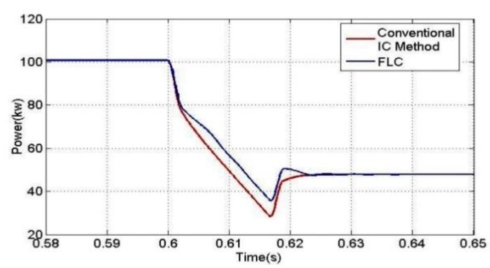

Figure-17: Output power of PV arrays for rapid irradiation change high to low

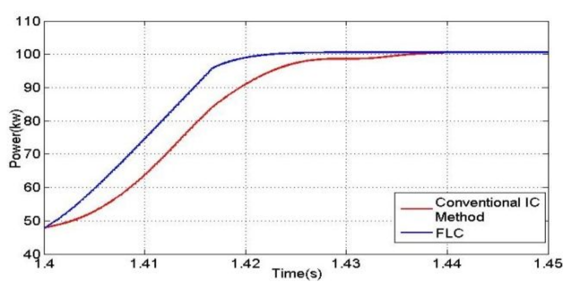

Figure-18: Output power of PV arrays for rapid irradiation change low to high

The strength of fuzzy rules to increase or decrease the duty ratio of the converter the operating point is distant from MPP and present results. So the general requirements are simplicity, good tracking speed, small oscillation, good accuracy are achieved by the proposed controller compared to conventional IC controller as shown in by Figure-14. The proposed fuzzy logic MPPT controller can extract energy more than the conventional controller. It is shown that the overall efficiency will also increase as the total output power is increased and the total cost will be less.

Proposed Controller

The results of proposed fuzzy logic controller is better than existing MPPT controller which shows the fast convergence to the Maximum power point compare to other controller.

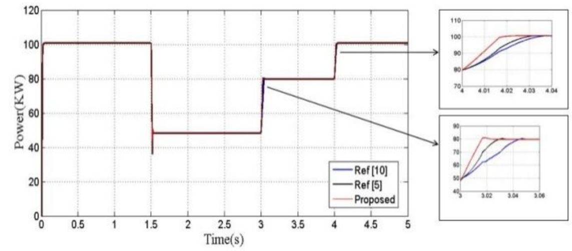

Figure-18: Output power PV system using proposed controller

At t=3s the irradiance is changed from 500 W/m^2 to 800 W/m^2 and the fast convergence shown in Fig-14. Again at t=4s the irradiance is changed from 800 W/m^2 to 100 W/m^2 and the best performance are shown in Fig-14.

DC-Link Voltage

In this paper, dc-link voltage is controlled by using PI controller and the controller gains are optimized by using Genetic algorithm and firefly algorithm. In Figure-19 it is shown that for varying irradiance firefly algorithm gives better performance.

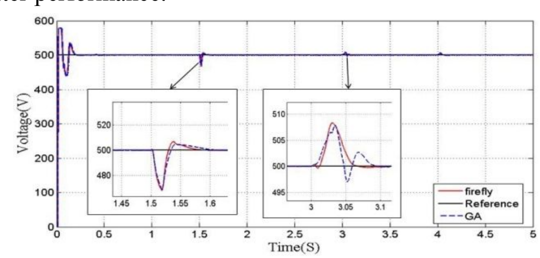

Figure-19: DC-link Voltage of the PV system

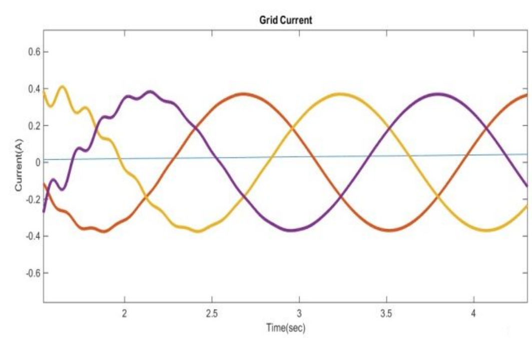

Figure-20: Currents injected to the grid

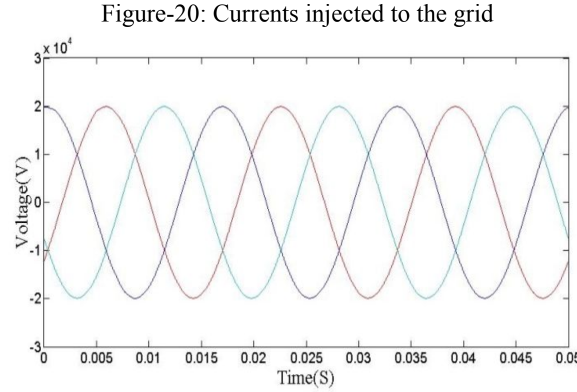

Figure-21: Grid voltage of the PV system

Algorithm	Voltage controller gain		Current controller gain			
	Kp	Ki	Kp1	Ki1	Kp2	Ki2
GA	5.9859	787.5783	0.3955	24.1470	57.0962	1455.7
FA	7.0253	794.4408	0.3481	23.1115	55.8387	1494.9

Table-III Voltage and Current Controller Gains

CONCLUSION

In this paper, a fuzzy logic controller for maximum power point tracking is proposed. The proposed method successfully adjusts the Incremental conductance for MPPT method under quickly changing weather conditions. Due to the straightforwardness in control algorithm, it is easier and simple to implement, modify and tune the control rules of fuzzy controller. The suggested MPPT method reduces the drawbacks of conventional Incremental Conductance based MPPT method. The simulation results in MATLAB for the fuzzy controller validate faster response to the maximum power point and also have lesser oscillations around the MPP under rapid/quick variation of solar radiation.

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