

## Fractional order - ANFIS (FO-ANFIS) method for maximum power point tracking (MPPT) in a PV system

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**Abstract:** In this paper, a fractional-order ANFIS (FO-ANFIS) method for maximum power point tracking (MPPT) in a photovoltaic (PV) system is presented. By combining the robustness of ANFIS with the accuracy of fractional order, the proposed method can improve the tracking accuracy in weather variations compared with the conventional fuzzy MPPT. The MPPT technique helps to trim down by means of only one voltage sensor, while increases the array power efficiency and MPPT response time. The simulation results are provided to validate the MPPT algorithm operation as well as the climatic parameters estimation capabilities. An ANFIS based boost DC to DC converter is used to harness power from Solar. The proposed converter architecture has reduced number of power conversion stages with less component count and reduced losses compared with existing PV systems. This improves the efficiency and the reliability of the system. Simulation results obtained using MATLAB/Simulink show the performance of the proposed ANFIS control strategy for power flow management under various modes of operation.

**Key words:** DC to DC Converter, PV system, MPPT, ANFIS.

### I. Introduction

Rapid depletion of fossil fuel reserves, ever increasing energy demand and concerns over climate change motivate power generation from renewable energy sources. Solar photovoltaic (PV) and wind have emerged as popular energy sources due to their ecofriendly nature and cost effectiveness. However, these sources are intermittent in nature. Hence, it is a challenge to supply stable and continuous power using these sources. This can be addressed by efficiently integrating with energy storage elements.

However, they suffer from a relatively low conversion efficiency, which makes their optimization necessary. This is done by extracting their maximum power for fluctuating climatic environments. Well-known "maximum power point tracking (MPPT)" is done through a particular control of a converter. Various techniques have been proposed depending on their complexity, sensors used, convergence, setup, and in further aspects [2]–[8], [22]–[25].

The most common methods are the perturb and observe (P&O), and the incremental conductance (InCond). The first method is popular due to its hardware simplicity. It functions by creating a perturbation in the voltage, which results in variation in the array power [3], [20]. However, the system oscillates around the MP points, which wastes energy while it cannot distinguish between the radiation variation and the tracker's perturbation. Many solutions are presented based on an adaptive step size or optimization functions [3]–[5], [9], [21], [26]. The second InCond method has a great accuracy with good flexibility to rapidly varying climatic conditions [24]. Therefore, it is possible to recognize when the MPP is achieved within a given accuracy [7], [22] by computing the instantaneous and InConds and verifying if they are identical.

However, it involves an increased hardware and software complexity. Many improvements are proposed using variable and modified step size algorithms [8], [22]–[24]. A sliding mode control has been used to improve tracking accuracy [11] and InCond using reference voltage and direct duty ratio perturbation [12]. Finally, a model-based (MB) control is used [13]. Nowadays, intelligent systems are progressively used due to their human-like capability and ability to adapt and improve their performance [14], [19], [26], [27]. Many neural networks (NN)-and fuzzy logic (FL)-based techniques are proposed. An artificial NN algorithm is developed with climatic conditions as inputs and applied to a boost tracker [28]. Using

FL theory, a feedforward MPPT scheme, a fuzzy controller, and an adaptive P&O-FL control method are proposed [9], [15], [16], [30].

This paper provides an efficient Grid connected PV MPPT method with reduced components. It computes the instantaneous and junction array conductances. The first one is done using the array current and voltage, whereas the second one uses the array junction current, which is estimated using ANFIS cell model presented in a recent paper of the authors [17]. Still, it requires information on the climatic parameters. Hence, it is proposed ANFIS control as an analytical model with a denoising based wavelet algorithm to estimate them, which helps reducing the hardware using only one voltage sensor. The simulation results are provided to validate the proposed ANFIS

- PV based MPPT scheme capabilities. This paper is organized as follows: Section II provides an overview of Modeling of PV system. The proposed three phase PV system is developed and explained in Section III. Section IV shows in detail the estimation of environmental parameters. The simulation results based on MATLAB are presented in Section V and Section VII gives a conclusion.

## II. Proposed PV Array Model

The schematic diagram of a three-phase grid-connected PV system which is main focus of this paper is shown in Fig. 1. The considered PV system consists of a PV array, a DC link capacitor  $C$ , a three-phase inverter, a filter inductor  $L$  and connected to

the grid with voltage ea, eb, ec. In this paper, the main target is to control the voltage vdc across the capacitor C and to make the input current in phase with grid voltage for unity power factor by means of appropriate control signals through the switches of the inverter. The mathematical model of the system is presented in the next subsections. A. PV Cell and Array Modeling PV cell is a simple p-n junction diode which converts the irradiation into electricity. Fig. 2 shows an equivalent circuit diagram of a PV cell which consists of a light generated current source  $I_L$ , a parallel diode, shunt resistance  $R_{sh}$  and series resistance  $R_s$ . In Fig. 2,  $I_{ON}$  is the diode current which can be written as:

$$I_{ON} = I_s \left[ \exp\left[\alpha(V_{pv} + R_s i_{pv})\right] - 1 \right] \tag{1}$$

where  $\alpha = \frac{q}{AKT_C}$ ,  $k = 1.3807 \times 10^{-23} \text{ JK}^{-1}$  is the Boltzmann's constant,  $q = 1.6022 \times 10^{-19} \text{ C}$  is the charge of electron,  $T_C$  is the cell's absolute working temperature in Kelvin,  $A$  is the p-n junction ideality factor whose value is between 1 and 5,  $I_s$  is the saturation current, and  $v_{pv}$  is the output voltage of PV array which in this case is the voltage across C, i.e., vdc. Now, by applying Kirchhoff's Current Law (KCL) in Fig. 1, the output current ( $i_{pv}$ ) generated by PV cell can be written as,

$$i_{pv} = I_L - I_s \left[ \exp\left[\alpha(V_{pv} + R_s i_{pv})\right] - 1 \right] - \frac{v_{pv} + I R_s}{R_{sh}}$$

The light generated current  $I_L$  depends on the solar irradiation which can be related by the following equation:

$$I_L = \left[ I_{sc} + K_i(T_c - T_{ref}) \right] \frac{s}{1000} \tag{3}$$

Where,  $I_{sc}$  is the short circuit current,  $s$  is the solar irradiation,  $k_i$  is the cell's short circuit current coefficient and  $T_{ref}$  is the reference temperature of the cell. The cell's saturation current  $I_s$  varies with the temperature according to the following equation [19]:

$$I_s = I_{RS} \left[ \frac{T_C}{T_{ref}} \right]^3 \exp \left[ \frac{qE_g}{Ak} \left( \frac{1}{T_{ref}} - \frac{1}{T_C} \right) \right] \tag{4}$$

Where,  $E_g$  is the band-gap energy of the semiconductor used in the cell and  $I_{RS}$  is the reverse saturation current of the cell at reference temperature and solar irradiation. Since the output voltage of PV cell is very low, a number of PV cells are connected together in series in order to obtain higher voltages. A number of PV cells are put together and encapsulated with glass, plastic, and other transparent materials to protect from harsh environment, to form a PV module. To obtain the required voltage and power, a number of modules are connected in parallel to form a PV array. Fig. 3 shows an electrical equivalent circuit diagram of a PV array

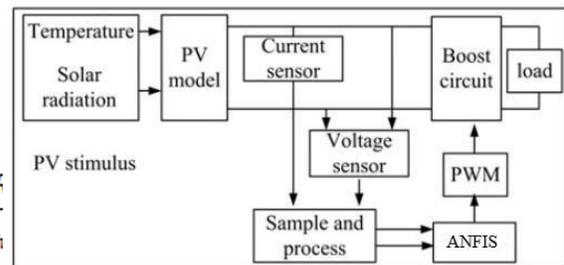


Figure 1: Block diagram of the PV system.

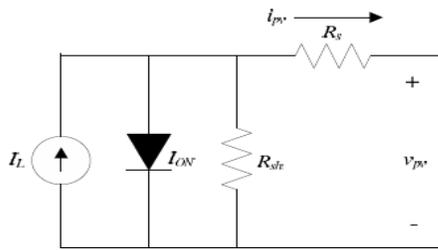


Fig. 2. Equivalent circuit diagram of PV cell

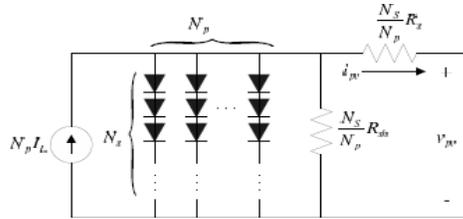


Fig. 3. Equivalent circuit diagram of PV array

Where  $N_s$  are the number of cells in series and  $N_p$  is the number of modules in parallel. In this case, the the array  $i_{pv}$  can be written as

$$i_{pv} = N_p I_L - N_p I_s \left[ \exp \left[ \alpha \left( \frac{v_{pv}}{N_s} - \frac{R_s i_{pv}}{N_p} \right) \right] - 1 \right] - \frac{N_p}{R_{sh}} \left( \frac{v_{pv}}{N_s} - \frac{R_s i_{pv}}{N_p} \right) \quad (5)$$

### III Proposed MPPT using ANFIS

The proposed Matlab/Simulink model of ANFIS based maximum power point tracking controller is depicted in Fig. 4. Irradiance level and operating temperature of PV module are taken as the input training data set for the ANFIS. The ANFIS reference model gives out the crisp value of maximum available power from the PV module at a specific temperature and irradiance level. At the same temperature and irradiance level, the actual output power from the PV module, is calculated using the multiplication growth of sensed operating voltage and current. Two powers are compared and the error is given to a proportional integral (PI) controller, to generate control signals.

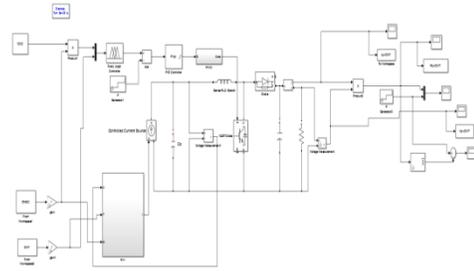


Fig. 4. Matlab/Simulink model of ANFIS based MPPT controller.

The control signal generated by the PI controller is given to the PWM generator. The PWM signal is generated using high frequency of carrier signal as compared to the control or modulating signal. The frequency of carrier signal used is 50kHz. The generated PWM signals control the duty cycle of DC-DC converter, in order to adjust the operating point of the PV module.

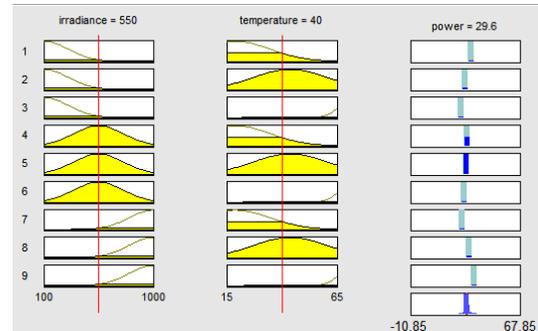


Fig. 5. Output from fuzzy rules for specific value of temperature and irradiance.

Fig. 6. Surface between two inputs (temperature and irradiance) and one output (maximum power).

Tuning of ANFIS Using the Matlab/Simulink model of PV module, the operating temperature is varied from 15 1C to 65 1C in a step of 5 1C and the solar irradiance level is varied from 100W/m<sup>2</sup> to 1000W/m<sup>2</sup> in a step of 50W/m<sup>2</sup>, to get the training data sets for ANFIS. Maximum available power for each pair of training data is recorded. In total 209 training data sets and 2000 epochs are used to train the ANFIS. By using given input/output dataset, the ANFIS constructs a fuzzy inference system (FIS) who membership function

parameters are tuned using the hybrid optimization method of training the FIS. The hybrid optimization method is a combination of the least squares type of method and the back propagation algorithm. It depicts that the ANFIS output closely matches to the actual output of module even at 6% of training error. It has two inputs (irradiance level and operating temperature), one output and three membership functions for each input. Nine fuzzy rules are derived from six input membership functions. These rules are derived according to the input and output mapping, so as to produce maximum output power for each value of input temperature and irradiance level. The ANFIS generated surface is shown in Fig. 6. It is 3dimensional plot between temperatures, irradiance and maximum power.

## V. Mat lab Simulation Results

Simulations were done using a PV array built of two mono crystalline 80-W modules (Figs. 1 and 2). To examine the performance of the proposed MPPT algorithm by means of MATLAB/Simulink, we simulated, in a short time period of 0.4 s, three step variations in solar radiation (250, 500, 750, and 1000W/m<sup>2</sup>) with a constant cell temperature  $T_c = 25^\circ\text{C}$ . The resulting array operating voltage and current are shown in Figs. 8 and 9.

We can notice that the array voltage and current track significantly their corresponding references, which means that the array is operating at its maximum power. This can be confirmed by observing its power, which is following precisely the corresponding MPP (Fig. 8). The tracking capability of the algorithm under varying solar radiation is shown in Fig. 9. It is shown in Fig. 11 that, due to the first

radiation value, the voltage varies through a certain range before it converges to its first MP point  $P_1$  at  $V_{pv} = V_{m1}$ . Then,  $V_{m1}$  is used as the initial value for the next iteration. This procedure is continued to reach  $P_2$ ,  $P_3$ , and  $P_4$  when  $V_{pv}$  equals to

Tuning of ANFIS Using the Matlab/Simulink model of PV module, the operating temperature is varied from 15 1C to 65 1C in a step of 5 1C and the solar irradiance level is varied from 100W/m<sup>2</sup> to 1000W/m<sup>2</sup> in a step of 50W/m<sup>2</sup>, to get the training data sets for ANFIS. Maximum available power for each pair of training data is recorded. In total 209 training data sets and 2000 epochs are used to train the ANFIS. By using given input/output dataset, the ANFIS constructs a fuzzy inference system (FIS) who membership function parameters are tuned using the hybrid optimization method of training the FIS. The hybrid optimization method is a combination of the least squares type of method and the back propagation algorithm. It depicts that the ANFIS output closely matches to the actual output of module even at 6% of training error. It has two inputs (irradiance level and operating temperature), one output and three membership functions for each input. Nine fuzzy rules are derived from six input membership functions. These rules are derived according to the input and output mapping, so as to produce maximum output power for each value of input temperature and irradiance level.

$V_{m2}$ ,  $V_{m3}$ , and  $V_{m4}$ , respectively. Then, the instantaneous and junction conductances are tested if they satisfy the condition in expression (17). It is seen clearly that the curves of  $Y_{pv}(V_{pv})$  and  $Y_d(V_{pv})$  intersect exactly when the MPP is achieved, which confirms the validity of the proposed scheme. Moreover, this condition can also be verified by confirming that the difference between the two conductances at the MPP condition is equal to zero, i.e.,  $[Y_{pv}(V_{pv}) - Y_d(V_{pv})]_{MPPT} = 0$  as predicted in expression (17).

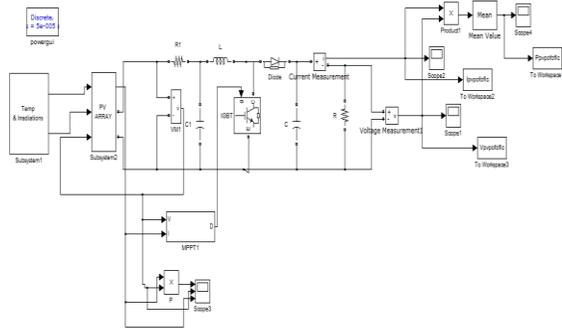
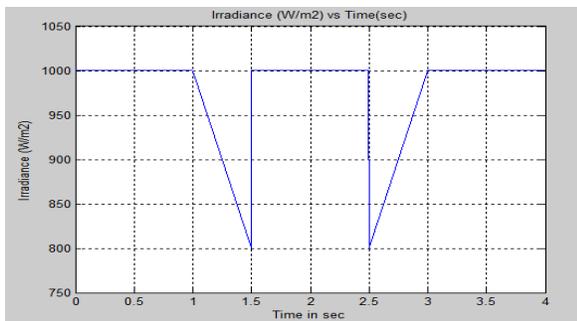
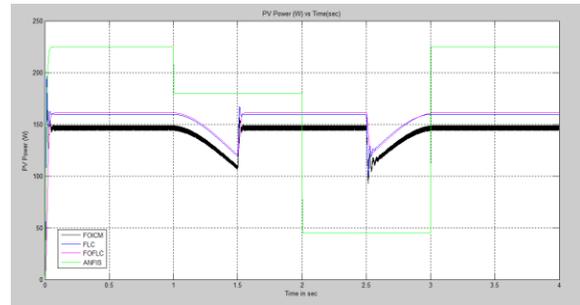


Fig 7 Completed Matlab/Simulink Model of the Proposed ANFIS based PV Systems.



(a)



(b)

Fig 8. (a) Input Step Irradiation (b) Array voltage  $V_{pv}$ .

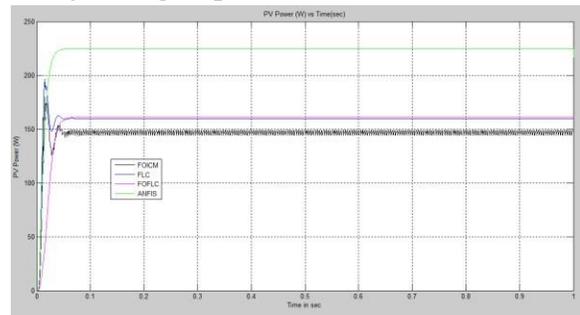


Fig. 9. Array Power  $P_{pv}$ .

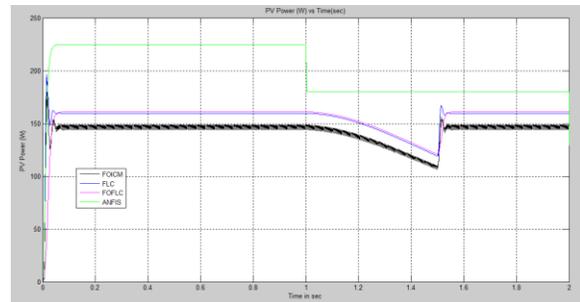


Fig. 10. Array power  $P_{pv}$  under variation of irradiation

The simulation results presented in Figs. 8–13 show obviously that the developed algorithm ensures the maximum power operation of the PV array. Its estimated power follows the maximum power under very fast varying solar radiation with a very good precision.

The mean MPPT error through the entire solar radiation range is found to be around 1.75%, which is very reasonable. Moreover, the radiation variations are done through a very short period of time ( $t = 0.4$  s). Therefore, it can be said that the algorithm reacts adequately to fast fluctuations in climatic conditions and operates using only one voltage sensor, which results in a reduced hardware implementation.

### V. CONCLUSION

This paper develops an optimal MPPT method that has been tested under varying climatic conditions. It has been shown that it can be implemented with reduced hardware setup since only one voltage sensor has been used. The array current, solar radiation and cell temperature are estimated using an ANFIS model and a climatic parameters estimator. The simulation results supported by experimental verification confirm the effectiveness of the presented method under varying solar radiation. The Simulation results exhibit a mean MPPT efficiency error of 2% with a response time of 1.7 ms, which ensures that the developed technique can extract accurately the maximum power from a PV array with a very low response time, which makes its operation optimal with reduced hardware.

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