An ANFIS Based MPPT Method Combining Fractional Order Controller for Photovoltaic Array 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. AnANFIS 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 increasingenergy demand and concerns over climate changemotivate power generation from renewable energy sources.Solar photovoltaic (PV) and wind have emerged as popularenergy 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 efficientlyintegrating 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 arethe perturb and observe (P&O), and the incremental conductance (InCond). The first method is popular due to its hardwaresimplicity. 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, whichwastes energy while it cannot distinguish between the radiationvariation and the tracker's perturbation. Many solutions are presentedbased on an adaptive step size or optimization functions[3]–[5], [9], [21], [26]. The second InCond method has a greataccuracy with good flexibility to rapidly varying climatic conditions[24]. Therefore, it is possible to recognize when the MPPis 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 andmodified step size algorithms [8], [22]–[24]. A sliding modecontrol has been used to improve tracking accuracy [11] andInCond 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 totheir human-like capability and ability to adapt and improvetheir performance [14], [19], [26], [27]. Many neural networks (NN)-and fuzzy logic (FL)-based techniques are proposed. Anartificial NN algorithm is developed with climatic conditions asinputs and applied to a boost tracker [28]. Using FL theory, afeed-forwardMPPT scheme, a fuzzy controller, and an adaptiveP&O-FL control method are proposed [9], [15], [16], [30].

This paper provides an efficient Grid connected PV MPPT method with reducedcomponents. It computes the instantaneous and junction array conductances.The first one is done using the array current andvoltage, whereas the second one uses the array junction current,which is estimated using ANFIS cell model presented ina recent paper of the authors [17]. Still, it requires informationon the climatic parameters. Hence, it is proposed ANFIS control as ananalytical model with a denoising based wavelet algorithm toestimate them, which helps reducing the hardware using onlyone voltage sensor. The simulation results areprovided 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 proposedthree phase PV system is developed and explained in Section III.Section IV shows in detail the estimation of environmentalparameters. The simulation results based on MATLAB arepresented 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

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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 IL, a parallel diode, shunt resistance Rsh and series resistance Rs. In Fig. 2, ION is the diode current which can be written as:

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

where $\alpha = \frac{q}{AkT_C}$, $k = 1.3807 \times 10^{-23}\ JK^{-1}$ is the Boltzmann's constant, q = 1.6022 × 10−19 C is the charge of electron, TC is the cell's absolute working temperature in Kelvin, A is the p-n junction ideality factor whose value is between 1 and 5, Is is the saturation current, and vpv 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 (ipv) generated by PV cell can be written as,

$$i_{pv} = I_L - I_s I_s\left[exp\left[\alpha\left(V_{pv} + R_s i_{pv}\right)\right] - 1\right] - \frac{v_{pv} + R_s i_{pv}}{R_{sh}} \quad (2)$$

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

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

Where, Isc is the short circuit current, s is the solar irradiation, ki is the cell's short circuit current coefficient and Tref is the reference temperature of the cell. The cell's saturation current Is varies with the temperature according to the following equation [19]:

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

Where, Eg is the band-gap energy of the semiconductor used in the cell and IRS 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

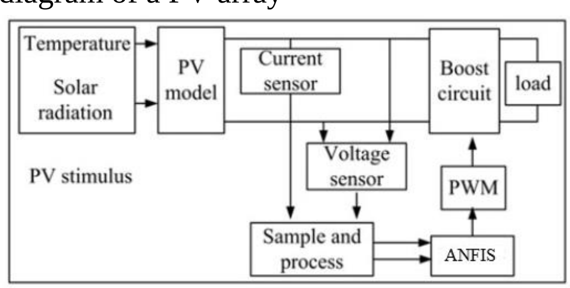

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Figure 1: Block diagram of the PV system.

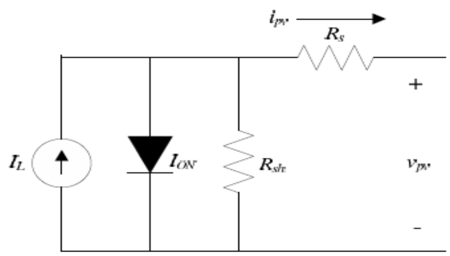

Fig. 2. Equivalent circuit diagram of PV cell

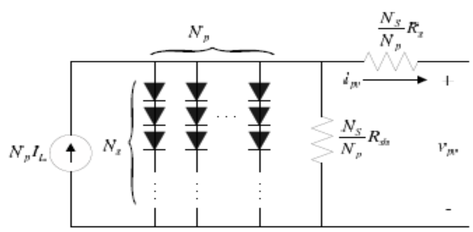

Fig. 3. Equivalent circuit diagram of PV array

Where Ns are the number of cells in series and Np is the number of modules in parallel. In this case, the the array ipv 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 powersare compared and the error is given to a proportional integral (PI) controller, to generate control signals.

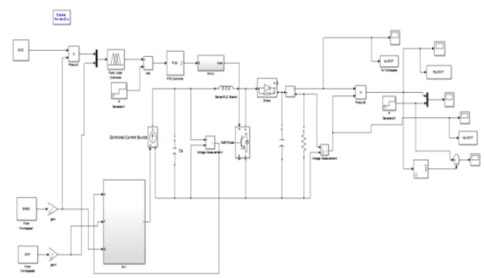

Fig. 4. Matlab/Simulink model of ANFIS based MPPT controller.

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, inordertoadjust the operatingpointofthePVmodule.

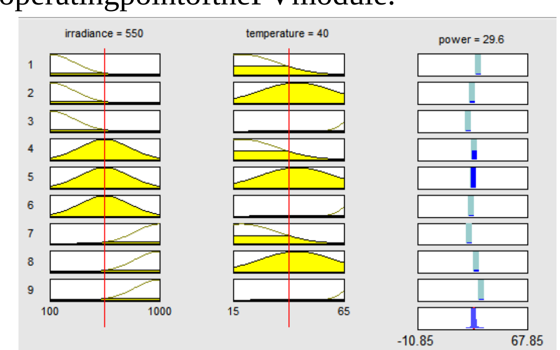

Fig. 5.Output fromfuzzyrulesforspecific valueoftemperatureandirradiance.

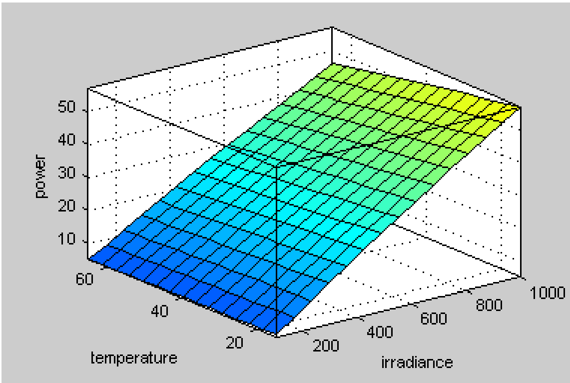

Fig. 6. Surface betweentwoinputs(temperatureandirradiance)andoneoutput (maximum power).

TuningofANFIS Using theMatlab/SimulinkmodelofPV module, the operating temperatureisvariedfrom15 1C to65 1C inastepof5 1C andthe solar irradiancelevelisvariedfrom100W/m2 to 1000W/m2 in a step of50W/m2, togetthetrainingdatasetsforANFIS.Maximum availablepowerforeachpairoftrainingdataisrecorded.Intotal 209 trainingdatasetsand2000epochsareusedtotraintheANFIS. By usinggiveninput/outputdataset,theANFISconstructsafuzzy inference system (FIS)who membershipfunctionparameters aretunedusingthehybridoptimizationmethodoftrainingtheFIS. Thehybridoptimization method is a combination of the least squarestypeofmethodandthebackpropagation algorithm.Itdepictsthat the ANFISoutputcloselymatchestotheactualoutputofmodule even at6%oftrainingerror. Ithastwoinputs(irradiance levelandoperatingtemperature), one outputandthree membership functionsforeachinput. Ninefuzzyrulesare derivedfromsixinputmembershipfunctions.Theserulesare derivedaccordingtotheinputandoutputmapping,soasto producemaximumoutputpowerforeachvalueofinput temperature andirradiance level. The ANFISgeneratedsurfaceisshownin Fig. 6. Itis 3dimensional plotbetween temperatures,irradianceand 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/m2) with a constant cell temperature Tc= 25◦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 $P1$ at Vpv= $Vm1$. Then, $Vm1$ is

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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 *Vm*2, *Vm*3, and *Vm*4, 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 *Yd*(*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) − *Yd*(*V*pv)]MPPT = 0 as predicted in expression (17).

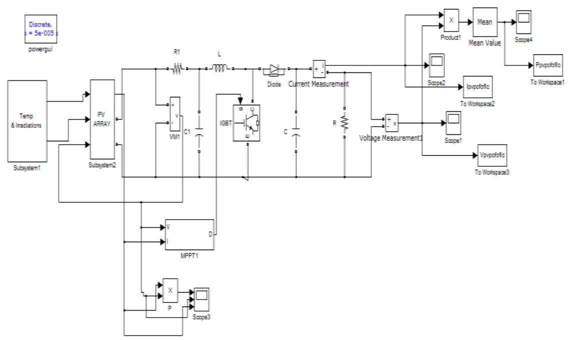
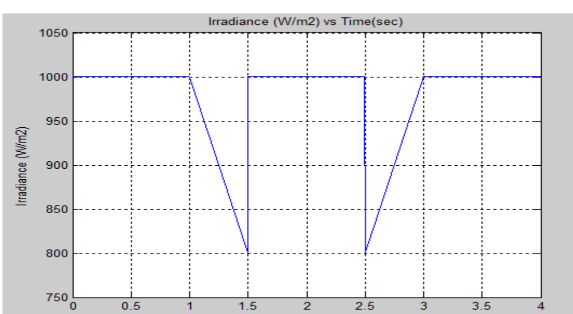
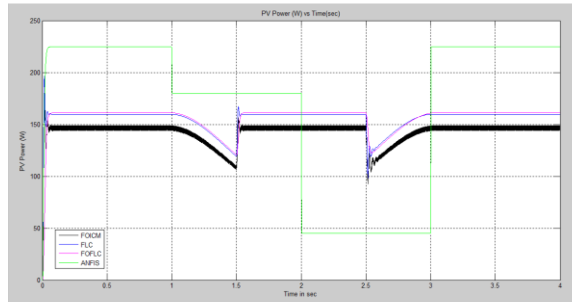


Fig 7 Completed Matlab/Simulink Model of the Proposed ANFIS based PV Systems.



(a)



(b)

Fig 8. (a) Input Step Irradiation (b) Array voltage *V*pv.

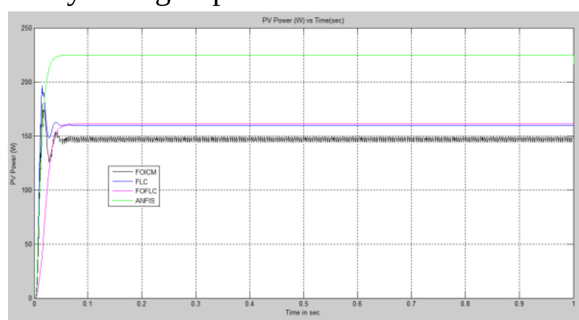


Fig. 9. Array Power*P*pv.

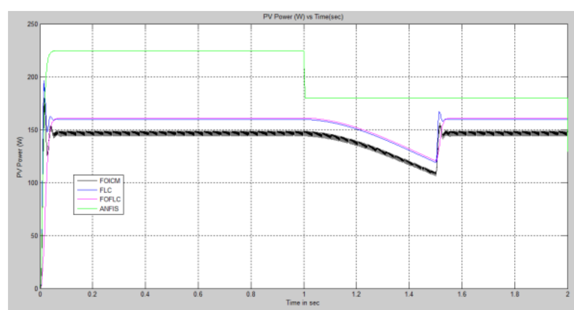


Fig. 10. Array power *P*pv under variation of irradiation

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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