MAXIMUM POWER POINT TRACKING TECHNIQUES FOR GRID CONNECTED PHOTOVOLTAIC SYSTEM USING INTELLIGENT CONTROL

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ABSTRACT

This paper aims at studying the different maximum power point tracking techniques used for maximizing the generated power of a grid connected photovoltaic systems. The proposed controllers used in this work are proportional – integral (PI) controller, hybrid PI and fuzzy logic controller (FLC), hybrid PI and Neural Network (NN) controller, hybrid PI and Adaptive Neuro Fuzzy Inference System (ANFIS) controllers. The proposed controllers are used for controlling both DC and AC sides of the dc-dc converter and inverter, respectively. The proposed system and controllers are modeled using MATLAB/Simulink software package. All simulation results are recorded and compared with each other using the conventional and intelligent controllers.

Keywords—Adaptive Neuro Fuzzy Inference System (ANFIS), Maximum Power Point Tracking (MPPT), PV System, Neural Network **(NN)**, PI controller, Fuzzy Logic Control (FLC).

INTRODUCTION

It is recognized that a massive consumption of fossil fuels to achieve the present energy demands has a negative impact on our environment. With the increasing human request for energy, fossil energy reserves are becoming haggard. Renewable energy flows involve natural phenomena such as solar, wind and hydropower. Renewable energy provides more than 21.7% of electricity generation. Several studies assume that more than 45% of the energy in the world will be generated by photovoltaic arrays. As opposed to conventional un-renewable resources such as gasoline, coal, etc..., solar energy is cleaner. Solar Energy are lack of greenhouse gas emission, low maintenance costs, fewer limitations concerning site of installation and without mechanical noise produced from moving parts. PV technology has some disadvantages such as high installation cost, intermittence on the energy production and low efficiency (5-16%).

Maximum output power depends on the radiation intensity, ambient temperature and load impedance. The MPPT is responsible for extracting the maximum possible power from the PV arrays and feed it to the load via the boost converter which steps up the voltage to the required magnitude. This converter tracks MPP of PV module by many methods for tracking. Those methods are tested in steady state performance and the tracking time using MATLAB/Simulink.

When the PV system is connected to the grid, it can transfer the rest energy to the grid after fulfilling the local demand. But when the system generates less than that demand, extra energy is extracted from the grid. A solar cell basically is a p-n semiconductor junction. When exposed to light, a dc current is generated. PV cells can be modeled as a current source in parallel with a diode. When there is no light present to generate any current, the PV cell behaves like a diode. A current source type PV model equivalent circuit is shown in Fig.1

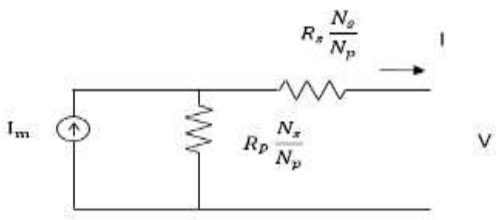

Fig.1. PV module equivalent circuit model.

Where Rs is the array series resistance, Rp is the array parallel resistance, Ns and Np are the number of series and parallel modules respectively, I and V are the output current and voltage of the array and Im is the module current and can be obtained from the following equation [1]

$$I_m = I_{pvN_p} - I_{0N_p}\left[\exp\left[\frac{v + R_s\left[\frac{N_s}{N_p}\right]I}{v_t a N_s}\right] - 1\right] \qquad (1)$$

Where, a is the diode ideality constant, Vt is the thermal voltage of the array and can be obtained from the equation:

$$V_t = \frac{N_{cs}kT}{q} \qquad (2)$$

Ncs is the number of cells connected in series, q is the electron charge, k is Boltzmann's constant and T is the temperature of the P-N junction in Kelvin's. Ipv is the photovoltaic current and can be expressed by:

$$I_{pv} = (I_{pvn} + k_i\Delta T)\frac{G}{G_n} \qquad (3$$

(3)

And I_0 is the reverse leakage current of the diode and can be calculated from

$$I_0 = \frac{I_{scn} + K_i\Delta T}{\exp\left[\frac{V_{ocn+K_{v\Delta T}}}{aV_t}\right] - 1} \qquad (4)$$

Where: I_{pvn} is the generated current at 25°C and 1000W/m2 (nominal conditions), Ki, Kv the current and voltage temperature confidents respectively, G is the irradiance and Gn is the irradiance at nominal conditions, Iscn, Vocn are the short circuit current and open circuit voltage respectively at nominal conditions and ΔT is the difference between the actual and the nominal temperatures in Kelvin's.

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An individual PV cell is usually small, it can produce only 1 or 2 watts of power. To boost the output power of PV cells, we connect them together to form larger units called modules. Modules are then arranged in series-parallel structure to form an array and to achieve the required output power.

The MPPT is responsible for extracting the maximum possible power from the photovoltaic and transfer it to the load after maximizing it by boost converter. To automatically find the voltage or current at which a PV array should operate to obtain the maximum output power (PMPP) under a given temperature and irradiance. Due to the non-linear characteristics of the PV array, it is required (MPPT) methods. The MPPT minimize the overall system cost and maximize the array efficiency.

I (at V equals 0) equals I_{sc} Short Circuit Current (I_{sc}), V (at I equals 0) equals V_{oc} Open Circuit Voltage (V_{oc}). Maximum Power (P_{max}), Current at P_{max} (I_{mpp}), Voltage at P_{max} (V_{mpp}), P_{max} equals $I_{mpp}V_{mpp}$. At the I_{sc} and V_{oc} points, the power will be zero and the maximum value for power will occur between the two.

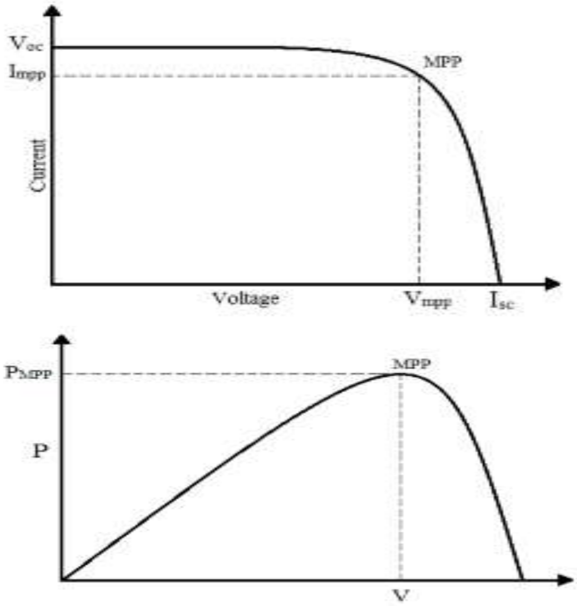

Fig.2. I-V characteristics and P-V characteristics of PV cell curve showing Maximum Power Point

MPPT methods can be differentiated based on various features including the types of sensors, speed, cost, range of effectiveness, hardware requirements, popularity, response time, accuracy and application. These methods can be classified as

(i) Methods based on load line adjustment of (I− V) curve

(ii) Methods based on artificial intelligence (FL) or (NN) MPPT methods.

The MPPT methods such as Perturb and Observation (P&O), Incremental conductance (INC) are based on load line adjustment of the (I – V) curve. These methods have been found to be less suitable under varying atmospheric and load conditions.

In last few years' artificial intelligence becomes more popular to track MPP such as (Fuzzy Logic Control, Artificial Neural Network and Adaptive Neural Fuzzy Inference System). The main advantage with these algorithms is that it doesn't need the complex mathematical relation solving between power output, solar irradiance, solar temperature and total resistance. Also, the outputs are obtained in a very less time with no oscillations. MPPT to operate the solar panel so that it can provide constant output voltage across the load by using boost converter.

CHARACTERISTICS OF A PHOTOVOLTAIC ARRAY

The electrical characteristics of a PV array are summarized in the relationship between the output current and voltage as the following Fig.4 and Fig.6 The intensity of solar irradiance controls the amount of output current (I), and the operating temperature of the solar cells affects the output voltage (V) of the PV array. Solar cell (I-V) characteristic curves that summaries the relationship between the current and voltage are generally provided by the panel's manufacturer.

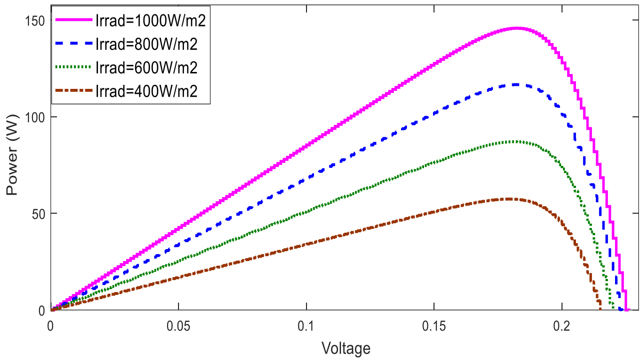

Fig.3. (P-V) characteristic of a solar array for a fixed temperature= 25C, varying irradiance

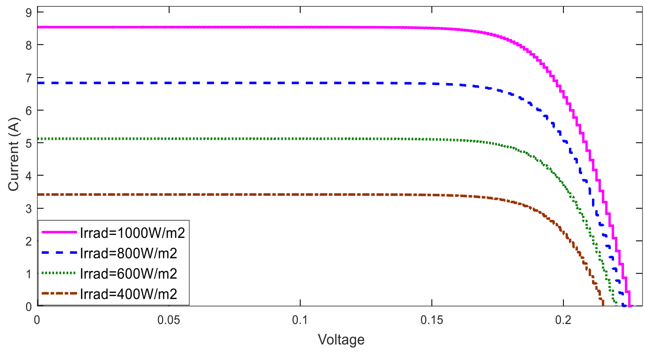

Fig.4. (I-V) Characteristic of a solar array for a fixed temperature=25C, varying irradiance

Fig.3 and Fig.4 display the effect of irradiation on PV current and power. As the irradiation increases the cell voltage, current and power are increase also but there is a maximum point in each case.

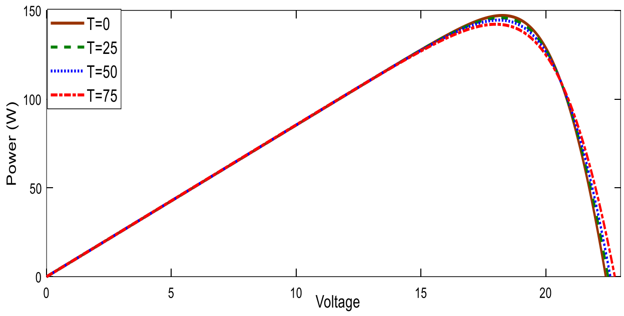

Fig.5. (P-V) Characteristic of a PV array under a fixed irradiance of 1000W/m2, varying temperatures.

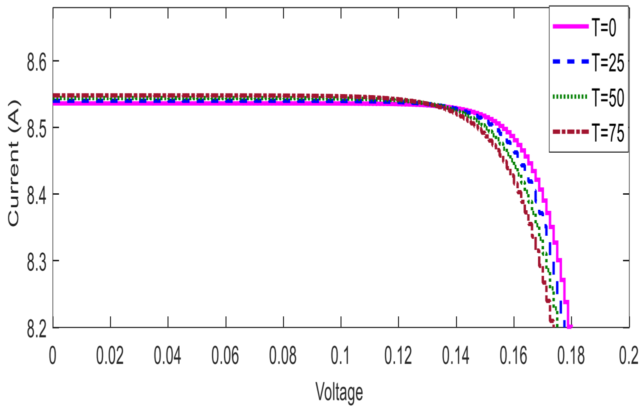

Fig.6. (I-V) Characteristic of a PV array under a fixed irradiance of 1000 W/m2 but varying temperatures.

Fig.5 and Fig.6 display the effect of Temperature on PV current and power. As the temperature increases the cell voltage current and power are decrease also but there is a maximum point in each case. If temperature increases the voltage decreases and a little current increase also, if temperature decreases the voltage increases and a little current decrease. If irradiance increases the current increases and a little voltage increases, if irradiance decreases the current decreases and a little voltage decrease.

Connection of Pv syestem with dc load

Reference to the maximum power transferring theory, an electrical circuit transfers maximum power to the load when source impedance matches the load impedance. That means adaptation. That is provided by the duty cycle (D) ensuring the maximum performance point coincides with the operating point. The DC-DC boost converters are used to convert the uncontrolled DC input voltage, supplied by PV arrays to a controlled DC output at a higher voltage level required by the loads and to reduce the cost.

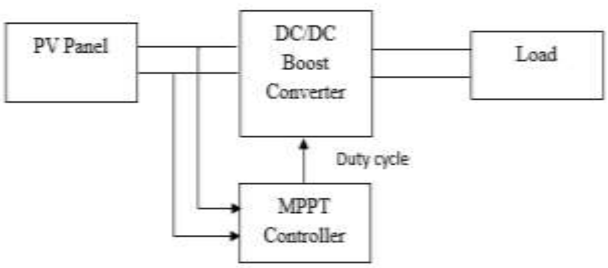

Fig.7 Photovoltaic system

As we can see in Fig. 7, the MPPT system varies the duty-ratio of the semiconductor switch in the dc–dc converter to match source and load impedance and to give maximum power to the load.

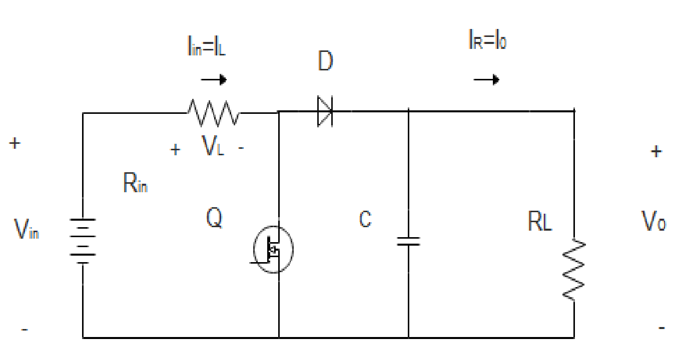

Fig.8. DC-DC boost converter

Fig.8 shows DC-DC step-up converter consists of current smoothing inductor L, voltage filtering capacitor C, diode D, power electronic switch device IGBT and PV array voltage Vin. The boost converter is used to step up the PV array voltage to suitable level for PV application. As the duty cycle increases the inductor current increases and the PV array voltage decreases as the following equations.

$$V_o = \frac{V_{in}}{1-D} \quad (5)$$

From inductor current ripple analysis, change in inductor current,

$$\Delta I_L = (V_{in}D)/(f_s\ L) \quad (6)$$

Grid integrated solar pv system

As PV solar energy acts as an alternative electricity resource. The PV system aims to deliver maximum electric power from PV panels to the grid. First, a dc-dc Converter is used to boost up PV arrays output voltage. The converter also tracks the MPP by many algorithms. In this system we will use PID controller, FLC, NN control and ANFIS control. PV array ‘s voltage and power need to sense for tracking MPP in these methods. Then, a pulse width modulation (PWM) based dc-ac inverter is used for enforcing sinusoidal voltage waveform with matching of phase frequency and voltage with grid. The output voltage wave shape of PWM inverter is square wave. Therefore, we used L filter for conjunction the inverter to the grid. The low pass filter converts PWM square wave to pure sine wave.

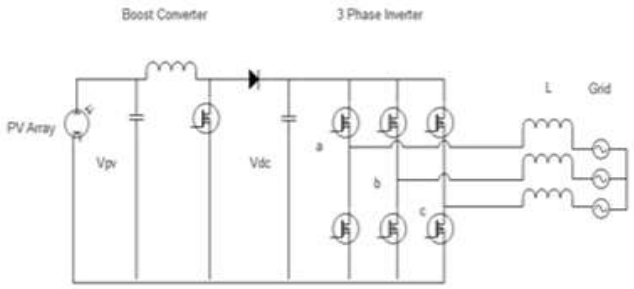

Fig.9 Power Circuit Configuration of Grid Connected PV System

Fig.9 shows the circuit configuration of three phase grid connected PV system. The model of system is consisting of PV array, DC-DC boost converter, DC link, DC-AC inverter and grid. The inverter transfers the active power to the grid that is calculated from the PV array maximum power in order to ensure maximum power transferred to the grid.

MPPT using PI contoller
It is necessary to control active power to achieve the stable grid requirements. Inverter control in the grid connected PV system involves two major tasks. First is to ensure that the PV module is operated at the MPP. Second is to inject sinusoidal current into the grid. PI controller maintains zero output error between actual and set point/desired output. It integrates the error over a period of time until error value reaches zero. According to the control strategy for inverter the dc voltage is set by PI controller that compares actual DC bus voltage and reference generated by MPPT and provides Id (active reference current) enjoined an inverter control in which the PI controller is fed with an instantaneous current error. The integral term in the PI controller improves the tracking by reducing the instantaneous error between the reference and actual current. The resulting error signal forms two reference signals Vref. These reference signals are compared with a triangular carrier signal and intersections are sought to produce PWM signals for the inverter switches. As the inverter is used in a grid-connected PV system, a proportional-integral (PI) current control scheme keeps the output current sinusoidal and to have high performance under rapidly changing conditions and to maintain the power factor at near unity. The controller senses the grid voltage and grid current and give the corresponding grid active and reactive power. Also, the power controller senses the inverter output voltage and current and give the corresponding active, reactive power. Then PI controller get the direct axis reference current (Idref) which is the first input of current controller. By using PI controller, we can get quadrature axis reference current which is the second input of current controller. We also sense the load voltage and load current and determine the load RMS value.

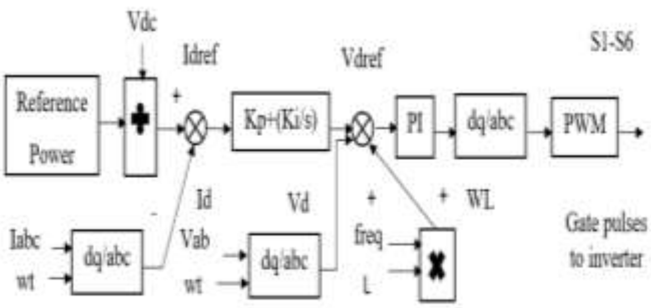

Fig.10 Block Diagram of PI Controller

As we can see in Fig.10 the voltage and current of the inverter are Vabc and Iabc. The dc bus voltage Vdc and Id are the feedback voltage and current, gained by the park transformation which are fed to the PI controller. The controller compares the grid active power with the reference power and the error signal is fed to the power controller which gets the reference current signal in direct and quadrature axes through synchronous reference frame theory. This again converted into three phase component and this reference voltage Vref is compared with the direct axis component of the grid voltage Vabc then error signal is computed and transformed into phased components and the supplied to the PWM generator which will produce the controlled pulses for controlling the inverter switching state.

Inverter uses a fast-switching control (voltage-oriented control), so it uses the active power feedback from grid to control the active and reactive power flow to maintain the grid current sinusoidal and within specified limits.

Also, in order to fulfill a unity power factor, the q-axis reference is set to zero. The proposed MPPT identifies the correct direction of the MPP by processing the d-axis current reflecting the power grid side and the signal error of the PI designed to represent only the change in power due to the changing of atmospheric conditions.

FUZZY LOGIC FOR TUNING A PID CONTROLLER

Conventional PID controller does not give desirable performance for systems. Hence it is necessary to automatically tune the PID parameters for achieving effective response.

The automatic tuning of PID controller has been done using fuzzy logic. A fuzzy logic system transforms a linguistic control into an automatic control strategy. Fig.11 shows the block diagram of a fuzzy PID controller. The inputs to the fuzzy controller are the error (e) and the rate of change of error (Δe) while the outputs are controller gains *KP*,*Ki* &*Kd.*

$$e(k) = Pref – Pout \quad (7)$$

$$\Delta e(k) = e(k) – e(k-1) \quad (8)$$

The output power of a DC-DC boost-converter is controlled by the fuzzy logic control (FLC) as it uses linguistic variables inputs instead of numerical variables.

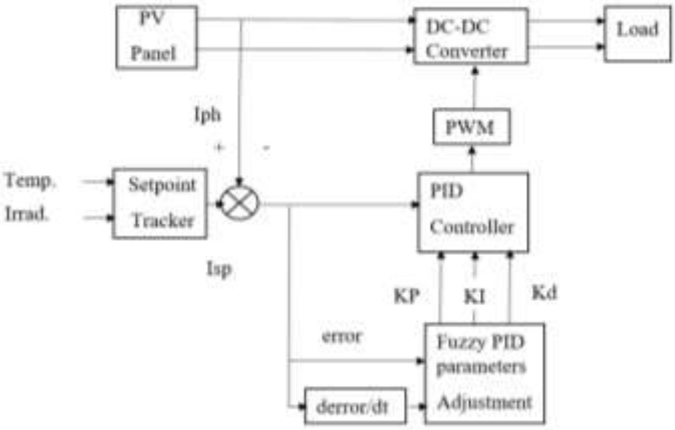

Fig.11 Block diagram of a fuzzy-PID controller

The fuzzifier converts the numerical values of the input into linguistic fuzzy variables. The error (e(k)) and change in error (Δe(k)) are calculated from above equations (7), (8). The error is the difference between the boost output power and reference power, while the change in error is the difference between the present error and pervious error.

The variables and rule base table describe the control algorithm. The rule base depends on the error signal e(k), the change in error signal Δe(k), and switching duty-cycle signal. The rules for inputs and outputs of the fuzzy logic controller are represented in Table1. As the inputs e(k), Δe(k), and duty cycle axes are divided into three regions which are positive, negative, and zero regions. Each region is divided into sub-regions, including Negative Big (NB), Negative Small (NS), Positive Small (PS), and Positive Big (PB). There are 25 rules in total such as in Table1.

Once *e* and Δ*e* are calculated and converted to the linguistic variables, the fuzzy logic controller output, which is a change in duty-cycle Δα of the power converter, can be looked up in a rule base. In the defuzzification stage, the fuzzy logic controller output is converted from a linguistic variable to a numerical variable still using a membership function. This provides an analog signal that will control the power converter to reach MPP under varying atmospheric conditions

E / ΔE	NB	NS	ZE	PS	PB
NB	ZE	ZE	NB	NB	NB
NS	ZE	ZE	NS	NS	NS
ZE	NS	ZE	ZE	ZE	PS
PS	PS	PS	PS	ZE	ZE
PB	PB	PB	PB	ZE	ZE

Table1 Fuzzy linguistic variables

For the MPP fuzzy logic tracking method, the regulator assembly passes through the set of four conventional steps : fuzzification, rule bases, fuzzy inference and defuzzification as follow :

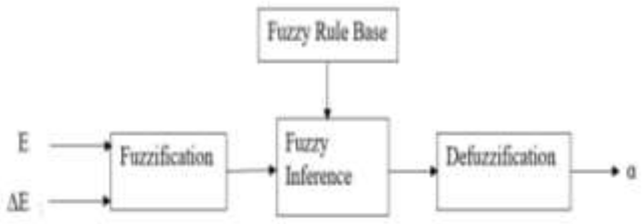

Fig.12 Fuzzy logic MPPT controller

A continuos tracking of the MPP of the PV array, by adjusting of a boost duty cycle, got via the fuzzy logic based MPPT control, according to the variation of the two following inputs e and Δe as Fig.13.

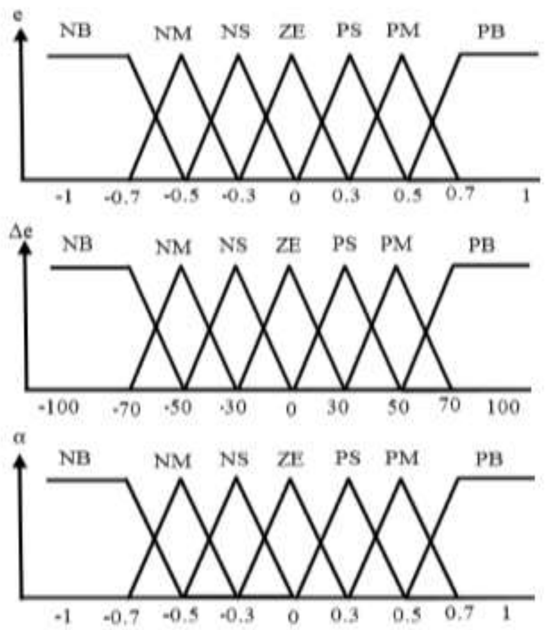

Fig.13 Membership functions of the input and output

The PV power difference (ΔP) will be increased or decreased in the positive or in negative direction with a small or a large value until it approximates the MPP and the error almost equals zero.

The fuzzy inference step where as the defuzzification computes the incremental change duty cycle Δα :

$$\Delta \alpha = \frac{\sum_{i=1}^{n} (d\alpha_i + u_i)}{\sum_{i=1}^{n} u_i} \qquad (9)$$

ARTIFICIAL NEURAL NETWORKS METHOD (ANN)

An ANN is a collection of electrical neurons connected based on various topologies according to applications. Neural networks have three layers: input, hidden, and output layers as shown in Fig.14. The input variables can be PV array parameters such as V_{oc} and I_{sc}, atmospheric data like irradiance and temperature, or any combination of them.

The output is usually a reference signal like a duty cycle signal or reference power used to drive the power converter to operate at the MPP.MPP depends on the algorithms used by the hidden layer and how well the neural network training. The links between the nodes are all weighted. The link between nodes i and j is labeled as having a weight of wij to accurately identify the MPP, the wij's have been determined through a training process, whereby the PV array is tested. And the patterns between the inputs and output of the neural network are recorded.

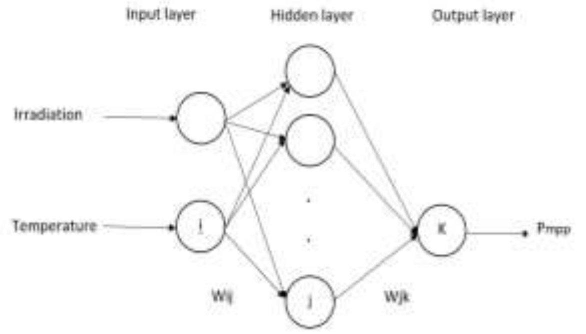

Fig.14 Neural network structure for MPPT

The characteristics of a PV array also change with time, so the neural network has to be periodically trained to give accurate MPPT. If we use irradiance and temperature as the inputs to the ANNs. The output of the ANNs is a reference signal which can be compared with the instantaneous power to generate the control signal needed to drive the solar panel to MPP through a PI controller.

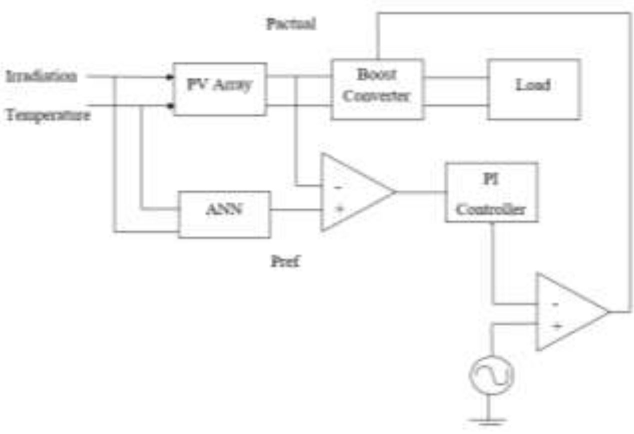

Fig.15 PV array ANN-PI structure

ADAPTIVE NEURO FUZZY INFERENCE SYSTEM(ANFIS)

Artificial intelligence systems are those systems which can make decisions like humans by adapting themselves to the situations and taking correct decisions automatically for future similar situations. Fuzzy systems are easy to explain knowledge in the rule base. And Neural networks get creativity from biological neuron systems and mathematical theories. Adaptive neuro-fuzzy inference system ANFIS constructs an input output mapping based on both human knowledge (fuzzy if then rules) and on generated input output data pairs by using a hybrid algorithm.

Each layer of the ANN uses a FL function. The second layer uses the Membership function, the third one uses the rules, the fourth one is the sum of the third layer nodes, the first and the fifth ones are the input and the output layers. ANFIS is the benefits of both types of machine learning algorithms (Fuzzy Logic and Neural Network) into single technique methods.

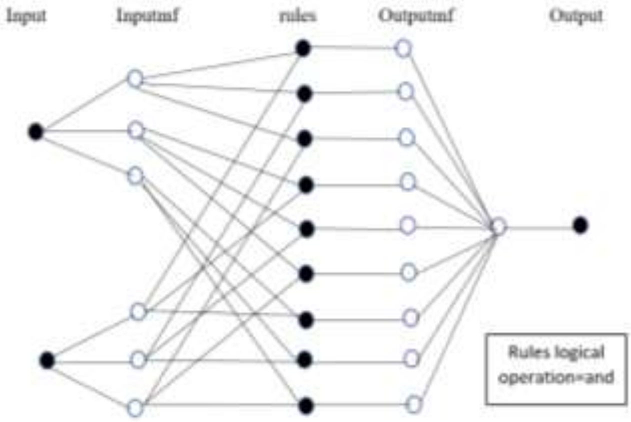

Fig.16 Five layers Anfis model

As we can see in Fig.16, ANFIS contains five layers, and each layer's nodes depend on the number of inputs, membership function and rules and mostly on a single output. The MATLAB program includes an ANFIS tool used to build the FL controller, this system utilizes of training the ANFIS depend on the training data. This data contains vectors of the two inputs are the ambient temperature and the solar irradiation, and as output, the reference power to run the system at MPP.

The block diagram of ANFIS based MPPT is shown in Fig.17. It is consisted of solar PV module, DC-DC boost converter, proportional integral (PI) controller, PWM signal generator and ANFIS reference model.

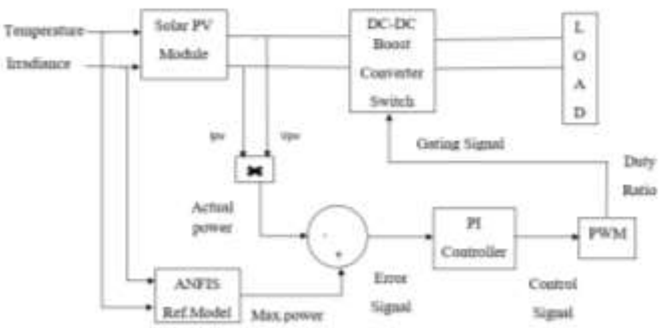

Fig.17 ANFIS based MPPT controller structure

In above Figure irradiance value and operating temperature are taken as the inputs for the ANFIS model that gives out the fresh value of maximum available power from the PV module at a certain temperature and irradiance level. The actual output power from the PV module, at same temperature and irradiance level, is calculated by using multiplication algorithm on sensed operating voltage and currents. Two powers are compared and the error is given to a proportional integral (PI) controller, to generate control signal. That signal is given to the PWM generator and control the duty cycle of DC-DC boost converter to adjust the operating point of the PV module.

DC-DC boost converter is designed to be placed between solar PV module and load to transfer maximum power to load by changing duty cycle.

The PV cell temperature varies from 10° C to 70 °C and the solar irradiance varies from 50 to 1200W/m2. By varying these two inputs data will be simulated.

The data set for temperature and irradiation is continuously varying. So, data is trained using ANFIS technique and the optimal power supplied by PV is recorded as shown in Fig.18.

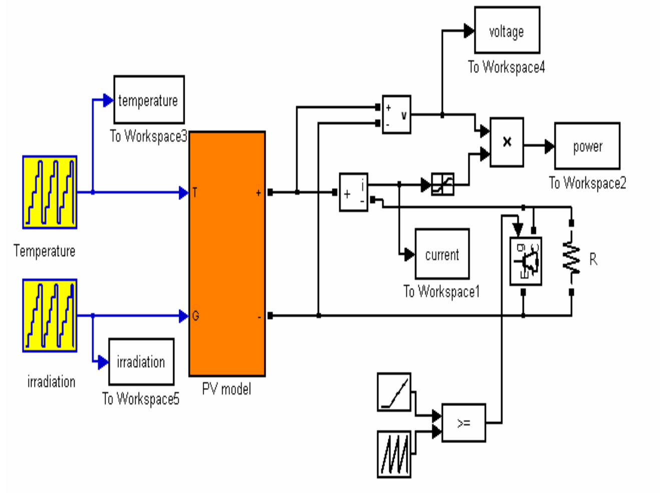

Fig.18 Training of ANFIS using MATLAB Simulink

Simulation results

The proposed PID controller, FLC, ANN and ANFIS controller are tested under SIMULINK (MATLAB) to a100-KW Grid-Connected PV Array, shown in Fig. 20. In this case, changes in solar radiation are applied to check the robustness and stability of the proposed controllers. Irradiation pattern is shown in Fig. 19. It changes 1000- 500-1000 W/m2 for one second each irradiation level.

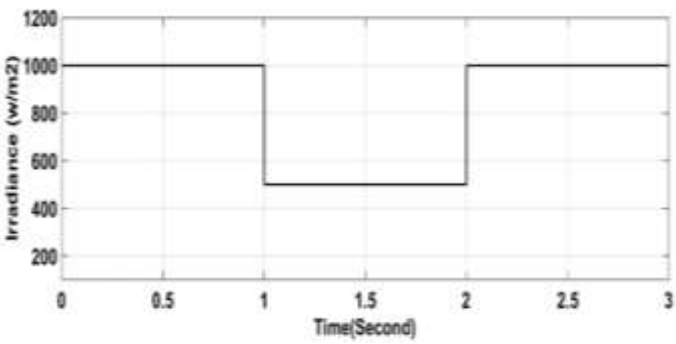

Fig.19 Irradiance pattern

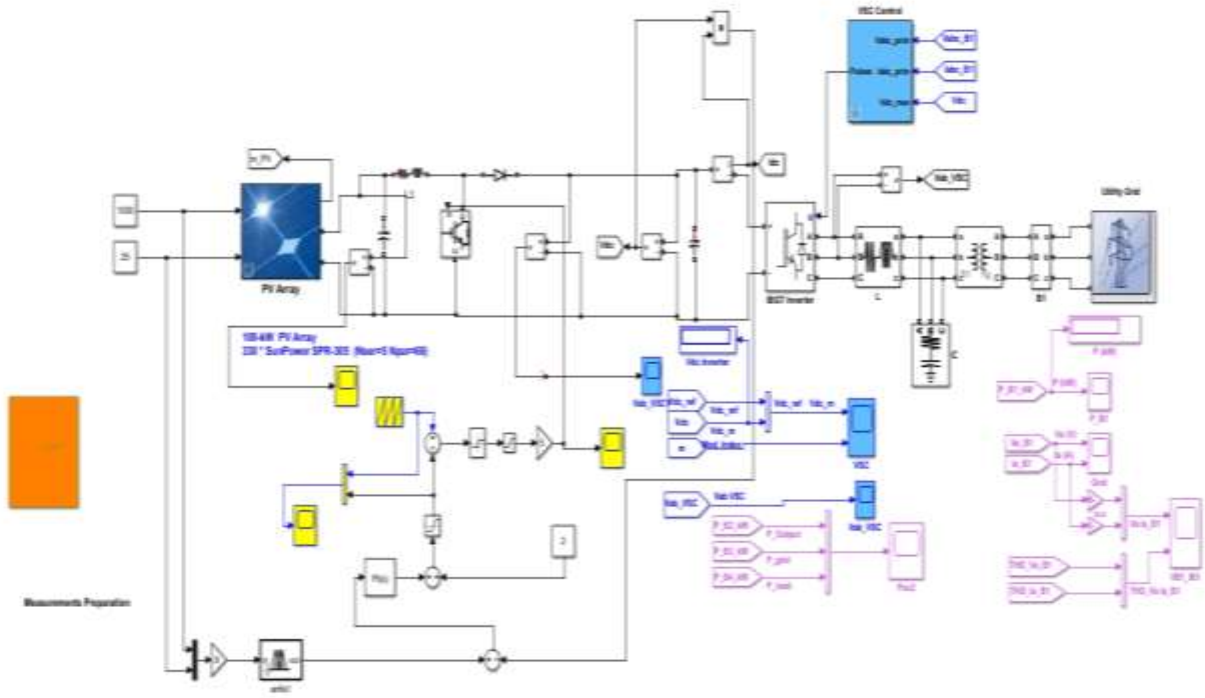

Fig.20 100-kW Grid-connected PV Array Anfis model

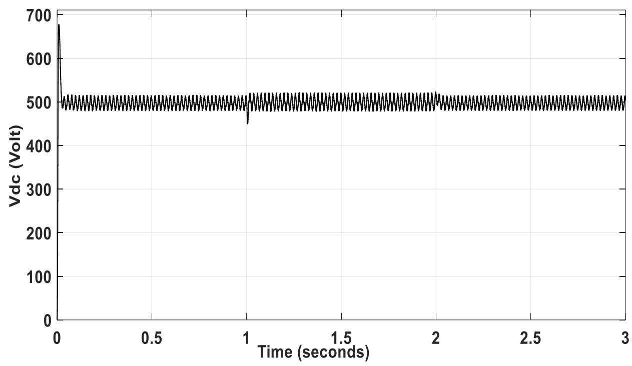

Fig.21 Vdc of PID Controller

The dc link voltage has a slight overshot about 150 V in the transient state and fast steady state reaching time. The estimated voltage causing the DC converter duty cycle to move the operating voltage to a new value reference at 500Volt by using PI,FL,NN and ANFIS controllers with different irradiatin levels as illustrated in Figures (21,22,23,24) respectivly .

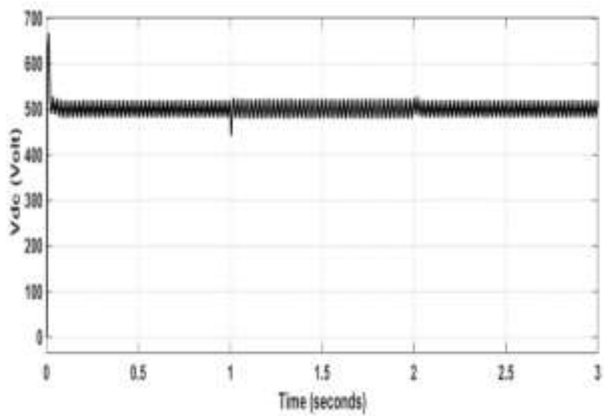

Fig.22 Vdc of Hybrid Fuzzy PID Controller

The MPPT using PID Controller method is a bit difficult to execute as it needs to get the PI controller gains offline and requires accurate model .

The MPPT output PV power using hybrid fuzzy logic controller and PI controller, hybrid neural network controller and PI controller, methods are easier, faster and have good transient performance. Such as in Figures (30,31) .

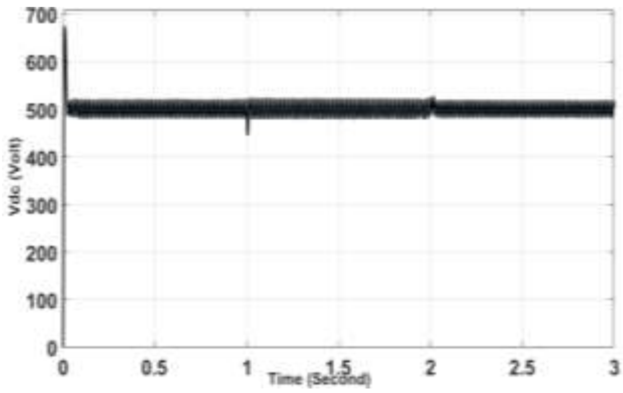

Fig.23 Vdc of Hybrid Neural Network PID Controller

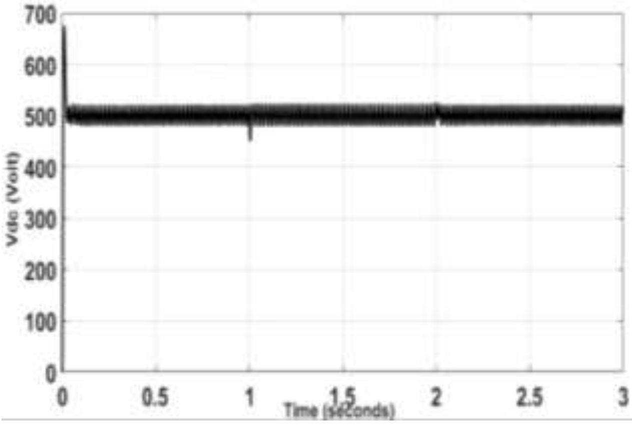

Fig.24 Vdc of ANFIS controller

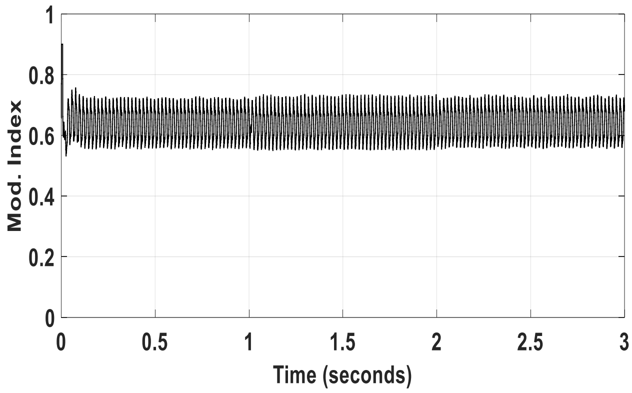

Fig.25 Modulation Index of PID controller

As we can see in Figures (25,26,27,28). When irradiation change the modulation index appears constant around 0.65 with all different methods.

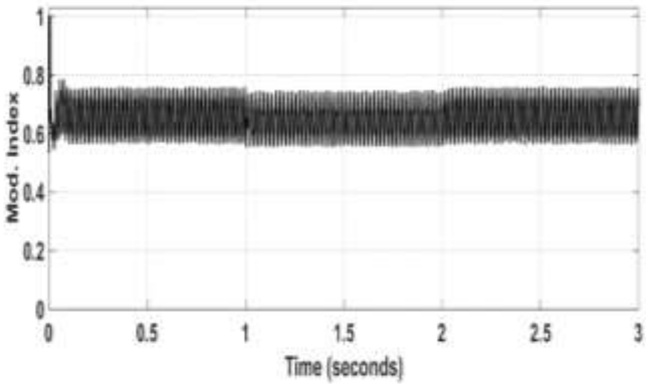

Fig.26 Modulation Index of Hybrid Fuzzy PID Controller

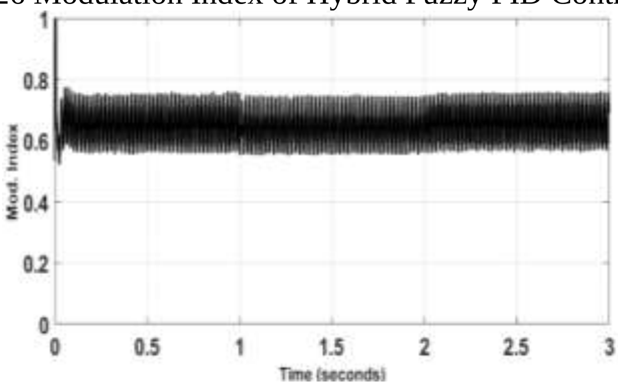

Fig.27 Modulation Index of Hybrid NN PID Controller

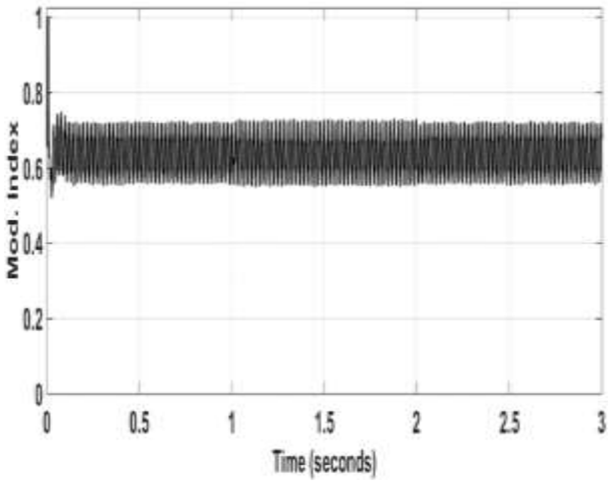

Fig.:28 Modulation Index of Hybrid ANFIS PID Controller

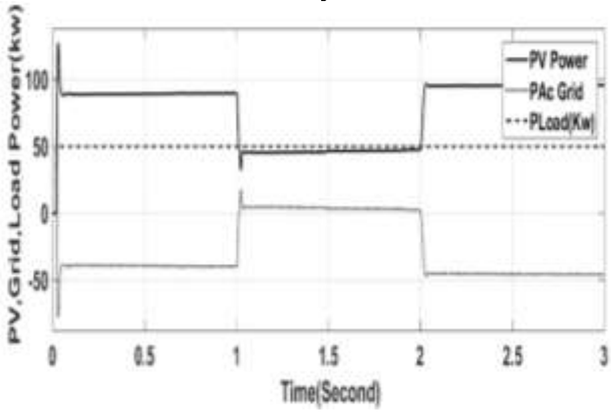

Fig.29 PV power, Grid power, Load power of PID controller

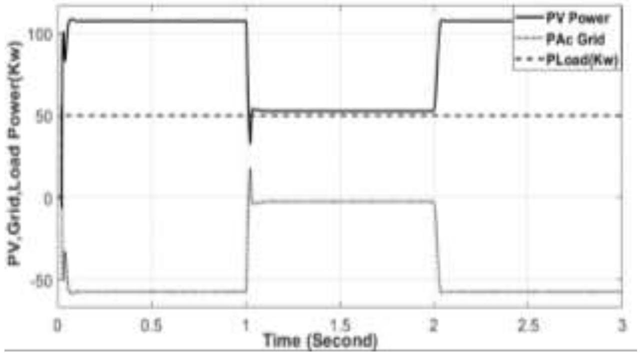

Fig.30 PV power, Grid power, Load power of Hybrid Fuzzy PID Controller

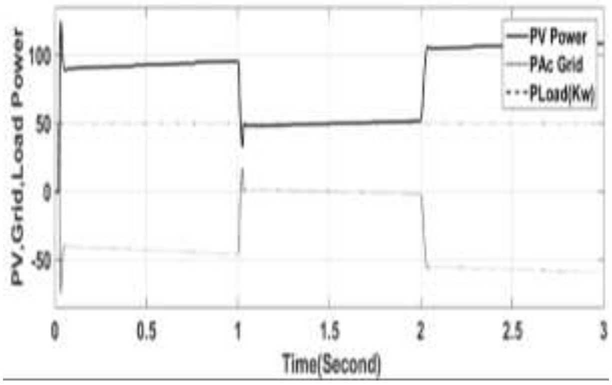

Fig.31 PV power, Grid power, Load power of Hybrid Neural Network PID Controller

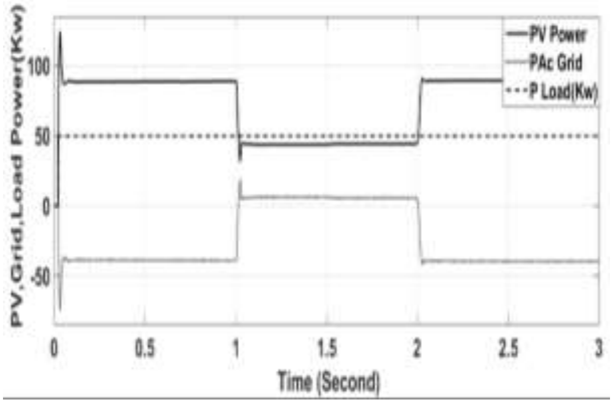

Fig.32 PV power, Grid power, Load power of Hybrid ANFIS PID Controller

By adjusting the operating voltage to a new value reference at 500Volt, this setting a new reference current for the inverter to match the output power to a new control set point MPP of 100 KWatt as in Figures (29,30,31,32).

Comparative study of PV output power figures for MPPT control

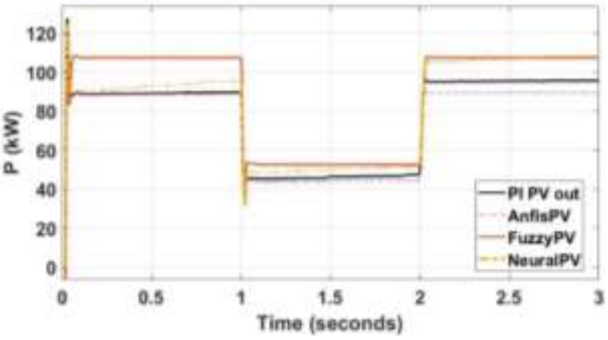

Fig 33 Comparison of proposed MPPT methods with variable irradiance

The optimum power of the PV system is the output of the FLC as we can see in Fig.33 comparing with the other controllers PI, NN and ANFIS.

CONCLUSION

PI controller, FLC, ANN and ANFIS based MPPT are designed and tested in MATLAB/Simulink environment, based on the simulation it can be concluded that with all the controllers the PV panel can deliver the maximum power efficiently with the variation of solar irradiation.

The MPPT using fuzzy logic controller method is easy and get fast and more accurate response, good transient performance. However, the performance of hybrid fuzzy PID MPPT is better than ANFIS based MPPT in terms of tracking speed and static error. The fuzzy logic-based MPPT technique resulted in high efficiency with lower steady-state error as compared to the PI technique. Other artificial intelligence techniques offered higher efficiency. Oscillatory response has been observed during steady-state MPPT in cases of NN and ANFIS techniques.

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