

**Enhancement of hybrid dynamic
performance using ANFIS for fast
varying solar radiation and fuzzy logic
controller in high speeds wind**

In this paper, dynamic performance enhancement of grid connected hybrid system consists of wind turbine using PMSG and photovoltaic systems are investigated under different circumstances. In order to maximize the output of solar arrays, maximum power point tracking (MPPT) technique is used by an adaptive neuro-fuzzy inference system (ANFIS) and also control of turbine output power in high speeds wind using pitch angle control technic by fuzzy logic are proposed. For tracking the maximum point, the proposed ANFIS is trained by optimum values. The simulation results show that the ANFIS controller of grid-connected mode can easily meet the load demand and have less fluctuation around the maximum power point (MPP), also it can increase convergence speed to achieve MPP. Also pitch angle controller based on fuzzy logic with inputs such as wind speed and active power can have faster responses which lead us to have flatter power curves, enhance the dynamic performance of wind turbine and prevent the both frazzle and mechanical damages to PMSG. The thorough wind power generation system, PV system and power electronic converter interface by using Matlab/Simulink are proposed.

Keywords: Photovoltaic; PMSG; fuzzy logic; ANFIS; p/q control

Article history: Received 27 January 2014, Received in revised form 23 September 2014, Accepted 2 December 2014

1. Introduction

In recent years, the world is looking for energy alternative sources as the energy demand continues to grow. DGs play a great role in energy conservation, environmental protection, investment, power safety and so on. Wind and solar power generations are two of the most promising renewable power generation technologies due to their advantages that provide. However, each of the aforementioned technologies has its own drawbacks. Nevertheless, hybrid energy systems are used for overcoming intermittency, uncertainty and low availability of each renewable energy source which makes the system more reliable [1]. Hence, there has been different works [2, 3] focusing on PV-Wind hybrid system. There are several ways to integrate different alternative energy sources to form a hybrid system. The methods can be generally classified into two categories: DC coupling and AC coupling. The AC couple has been used in this article. The AC hybrid system characteristics are consisting of: 1- High reliability, if one of the energy sources is out of service, it can be isolated from the system easily, 2- Ready for grid connection, 3- Standardizing interfacing and modular structures, 4- Easy multi-voltage and multi-terminal matching, 5- Well established scale economy.

Developing photovoltaic energy sources can reduce fossil fuel dependency. PV panels are low-energy conversion efficient due to control maximum output power. Therefore, using the MPPT system is highly has been recommended. In the other word, the output

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power of a PV module varies as a function of the voltage and also the MPP point is change by variation of temperature and sun irradiance [4].

Currently, many different technics are applied in order to reach maximum power. The most prevalent technics are perturbation and observation algorithm [5, 6] Incremental conductance [7, 8] fuzzy logic [9, 10] and artificial networks (ANN) [11, 12]. According to above mentioned research, the benefits of perturbation and observation algorithm and incremental conductance are: 1- Low cost implementation, 2- Simple algorithm. And the depletion of these methods is vast fluctuation of output power around the maximum power point even under steady state which results in the loss of available energy [13].

Using fuzzy logic can solve the two mentioned problem dramatically. In fact, with fuzzy logic controller by proper switching will result: reduction in oscillations of output power around the maximum power point and reduction of losses. Furthermore, convergence speed of this way is higher than two mentioned way. One of the depletion of fuzzy logic comparing to neural network is oscillations of output power around the maximum power point [14]. Nowadays, artificial intelligence (AI) techniques have numerous applications in determining the size of PV systems, MPPT control and optimal structure of photovoltaic systems.

Neural network with estimation of the maximum power generated in PV system uses inputs such as environmental parameters, solar irradiance, temperature, wind velocity and time parameter which have been provided in [15].

Neural networks can be integrated with fuzzy logic and with the combination of these two smart tools, a robust AI technique called ANFIS shall be resulted [16-18]. In [19, 20] the structure of ANFIS have been used but one of the major drawbacks in these articles is that they did not connected to the grid in order to the analysis of system performance which it has not been checked.

In terms of wind power generation system (WPGS) is proposed as one of the outstanding renewable energy sources [21]. Amongst the synchronous and asynchronous generators, PMSG is more favorable due to self-excitation, lower weight, smaller size, less maintenance cost and the elimination of gearbox have high efficiency and high power factor comparing to WRSG, SCIG, DFIG and so on.

MPPT controller somehow changes the rotor speed according to variation of wind speed that the tip speed ratio (TSR) is maintained in optimum value. One of the approaches to reach the maximum power point is pitch angle control (B) which in small turbines with low power delivery is not possible due to mechanical difficulties in production [22, 23]. In high speeds wind the extra production of active power via wind turbine leads to increases consuming of reactive power in generator and in which case, we should utilize the reactive power compensator for injecting reactive power that has extra cost too. Moreover, in above rated wind speed operation, mechanical erosion and damages will make us to have more maintenance cost and this lead us to use controller with fast and suitable response.

In the past, PIDs were used mostly in controllers design but by introduction of fuzzy logic instead of PID, created a better performance and best preventative way to eliminate the profound mathematical understanding of system. In comparing PIDs and fuzzy logic systems, fuzzy logic has more stability, faster and smoother response, smaller overshoot and does not need a fast processor; also it's more powerful than other non-linear controllers [24]. In [25-27] pitch angle controller based on fuzzy logic is presented. In [27] active

power and in [25, 26] both reactive power and rotational rotor speed are used as input signals and because in mentioned items wind speed's been ignored, the controller has not fast and smoother response and may cause mechanical damages to synchronous generator. Also, another problem in these articles is that they are not practically connected to grid in the simulation [26-28].

In this paper, a hybrid wind and PV system connected to main grid has been proposed as case study. Temperature and irradiance as inputs data are given to the designed model and the output will be optimal voltage (V_{mpp}) corresponding to the MPP delivery from the PV system, then the optimum values will be utilized for training the ANFIS. Also, fuzzy logic controller has been used to control the speed of the wind turbine when it is connected to main grid. As a result, by using these methods the dynamic performance of hybrid PV-Wind system has been improved.

The paper is organized as follows: In part 2 structures of photovoltaic module, MPPT and ANFIS technic have been described. In part 3 PMSG generator and pitch angle controller based on fuzzy logic are discussed. In part 4 p-q controller is described. In part 5 the simulation results are presented based on case studies. Finally, the conclusion is presented in part 6.

2. Photovoltaic cell model

Fig.1 shows equivalent circuit of one photovoltaic cell [5, 6]. Characteristic of one solar array is explained in equation (1):

$$I = I_{pv} - I_0 \left[\exp \left(\frac{V + R_s I}{V_t n} \right) - 1 \right] - \frac{V + R_s I}{R_p} \quad (1)$$

Where, I is the output current, V is the output voltage I_{pv} is the generated current under a given insolation, I_0 is the diode reverse saturation current, n is the ideality factor for a p-n junction, R_s is the series loss resistance, and R_{sh} is the shunt loss resistance. V_{th} is known as the thermal voltage. Red sun 90W is taken as the reference module for simulation and the name-plate details are given in Table 1. The array is the combination of 4 cells in series and 3 cells in parallel of the 90W module; hence an array generates 1080W.

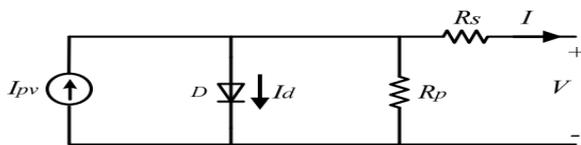


Fig. 1. Equivalent circuit of one PV cell

Table 1: Red sun 90w module

I_{MP} (Current at maximum power)	4.94 A
V_{MP} (Voltage at maximum power)	18.65V
P_{MAX} (Maximum power)	90W
V_{OC} (Open circuit voltage)	22.32
I_{SC} (Short circuit current)	5.24
N_P (Total number of parallel cells)	1
N_S (Total number of series cells)	36

2.1. Adaptive neuro-fuzzy inference systems

ANFIS refers to adaptive neuro-fuzzy inference system. An adaptive neural network has the advantages of learning ability, optimization and balancing. However a fuzzy logic is method based on rules that these rules are constructed by the knowledge of experts. ANFIS combines the advantages of using adaptive neural network and fuzzy logic. ANFIS makes use of Sugeno type. Consider a simple equation Sugeno fuzzy model with two inputs of x

and y and one output of z . The fuzzy rules can typically be as follows:

Rule 1: If x is A_1 and y is B_1 ; then

$$f_1 = p_1x + q_1y + r_1 \quad (2)$$

Rule 2: If x is A_2 and y is B_2 ; then

$$f_2 = p_2x + q_2y + r_2 \quad (3)$$

The ANFIS structure of the above statements is shown in the following Fig.2:

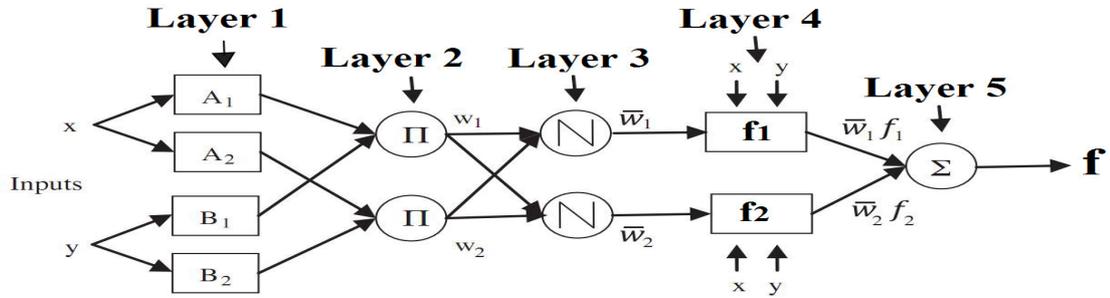


Fig. 2. ANFIS architecture of a 2-input first-order Sugeno fuzzy model with 2 rules

This structure has five layers. It can be seen that the nodes of the same layer have the same functions. The (i) output node in layer 1 is named as Q_{1i} . Layer 1: Every node in this layer consists of an adaptive node with a node function, and we have:

$$Q_{1,i} = \mu A_i(x), \quad \text{for } i = 1, 2 \quad (4)$$

$$Q_{1,i} = \mu B_{i-2}(y), \quad \text{for } i = 3, 4 \quad (5)$$

Where x (or y) is the input of node i and A_i (or B_{i-2}) is a fuzzy set related to that node. In other words, the output of this layer is membership value. Membership functions for A can be any appropriate parameterized membership function. Each parameter in this layer is regarded as a default parameter. Layer 2: Each node in this layer has been labeled with an “n” and the output of each node is the product of multiplying all incoming signals for that node. These nodes perform the fuzzy AND operation and the output of each node indicates firing strength of each rule.

$$Q_{2,i} = w_i = \mu A_i(x) \mu B_i(y) \quad \text{for } i = 1, 2 \quad (6)$$

Layer 3: each node in this layer has been labeled with an “N”. Nodes in this layer calculate the normalized output of each rule and we have:

$$Q_{3,i} = \bar{w}_i = \frac{W_i}{W_1 + W_2} \quad i = 1, 2 \quad (7)$$

Where W_i is the firing strength of that rule. The output of this layer is called the normalized firing strength. Layer 4: Each node in this layer is associated with a node function and we have: Where W_i is normalized firing strength of the third layer and $\{p_i, q_i, r_i\}$ are parameters sets of the node i . Parameters of this layer are called as “consequent parameters”.

$$Q_{4,i} = \bar{w}_i f_i = \bar{w}_i (p_i x + q_i y + r_i) \quad (8)$$

Layer 5: The single existing node in this layer is labeled as Σ that computes the sum of all its input signals and sends them to the output section. Where Q_{5i} is the output of the node (i) in the fifth layer. For this reason, first all existing rules will be established in the layer 1.

$$Q_{s,i} = \sum_i \overline{w_i} f_i = \frac{\sum_i w_i f_i}{\sum_i w_i} \quad (9)$$

In this paper, a hybrid learning algorithm has been used. The hybrid learning algorithm is a combination gradient descent and least squares methods. In this simulation, irradiance and temperature have been regarded as input and output will be optimal voltage (V_{mpp}) corresponding to the maximum power point (MPP) delivery from the PV system. Then the output voltage of PV module with ANFIS output voltage is deducted to obtain the error signal. Then through a PI controller, this error signal is given to a pulse width modulation (PWM) block. The block diagram of the proposed MPPT scheme is shown in the Fig.3.

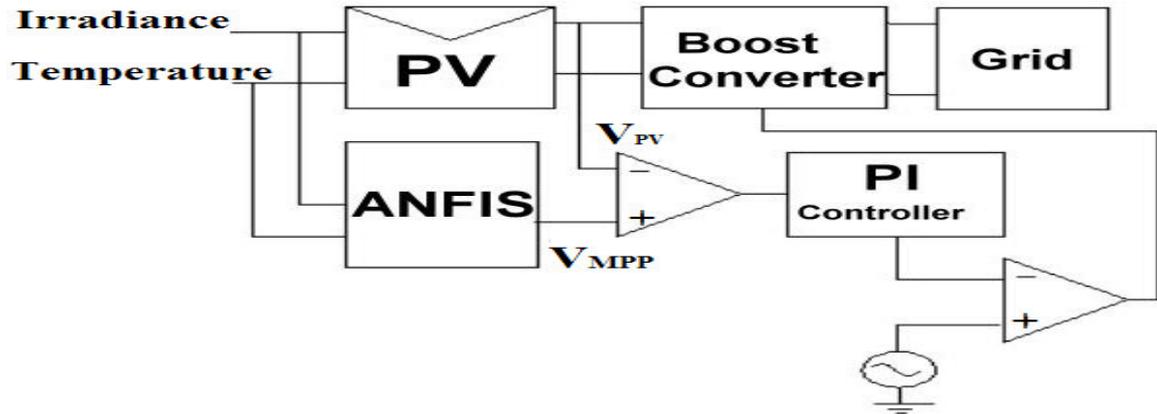


Fig. 3. Proposed MPPT scheme

The PV system is designed in order to obtain data. A set of 360 data has been put to temperature and irradiance as inputs which is shown in Fig.4a and the output will be V_{mpp} corresponding to the MPP delivery from the PV panels is depicted in Fig.4b. Then these optimum values will be utilized for training the ANFIS. By following Fig.4a, all input data are 360 data among which 330 and 30 data have been used for the network training and the network test, respectively. Input temperature ranges from 5 to 55 °C in steps of 5 °C and irradiance ranges from 50 to 1000 (W/m^2) in the steps of 32 (W/m^2).

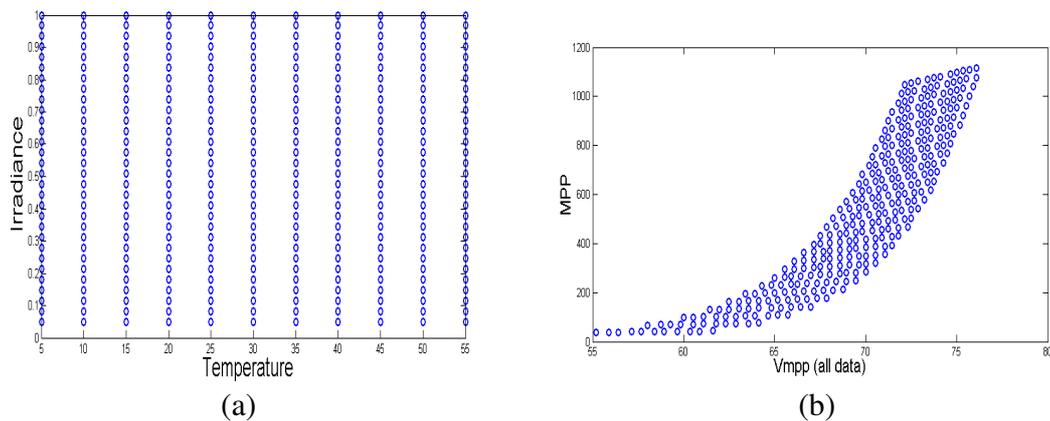


Fig. 4. Data : (a) Inputs data of irradiance and temperature; (b) (V_{mpp}) corresponding to (MPP)

ANFIS input structure is shown in Fig.5 which includes five layers. The two inputs represent irradiance and temperature both of which have 3 membership functions. The

structure shows two inputs of the solar irradiance and cell temperature, which is translated into appropriate membership functions, three functions for the solar irradiance is shown in Fig.7(a) and three functions for temperature is illustrated in Fig.7(b). They have 9 fuzzy rules in total which is shown in Fig.6; these rules have a unique output for each input.

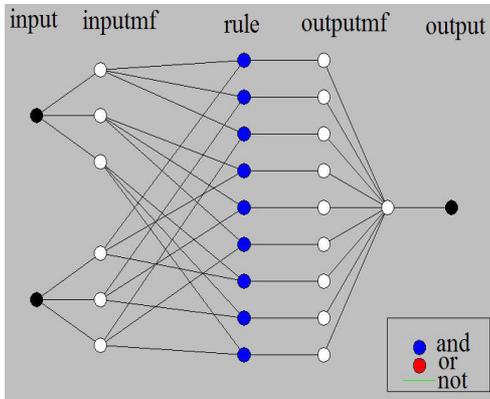


Fig. 5. ANFIS controller structure

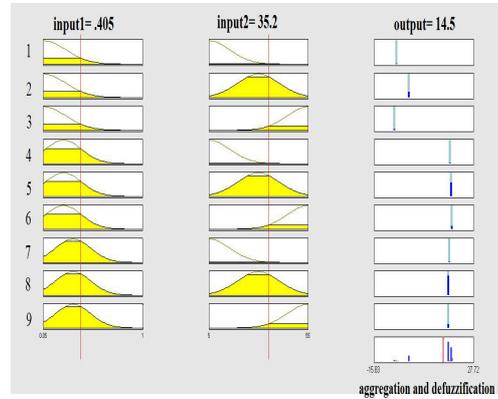
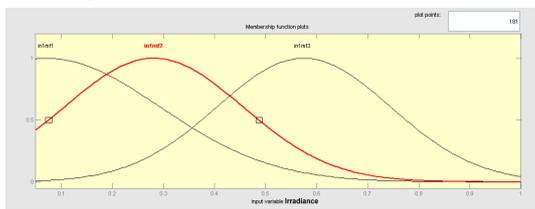
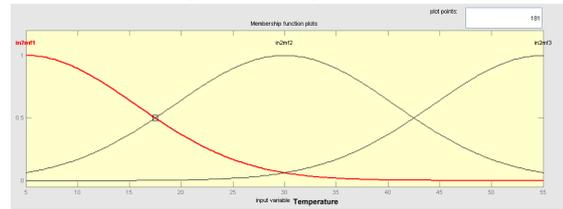


Fig. 6. Fuzzy rules



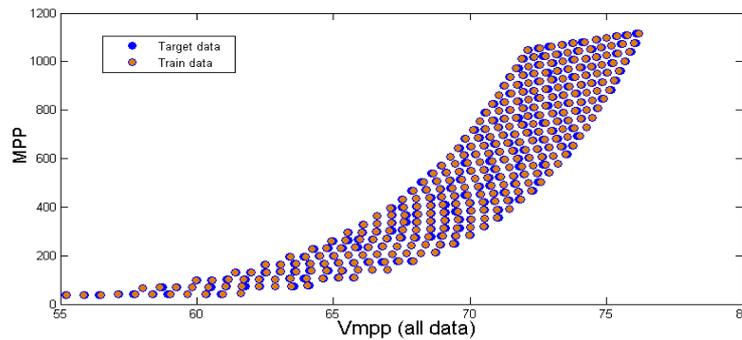
(a)



(b)

Fig. 7. ANFIS membership function : (a) Solar irradiance membership function; (b) Temperature membership functions

The network is trained for 30,000 epochs. After training process, the output of the trained network should be very close to the target outputs which are shown in Fig.8(a). According to Figs.8(b) and 8(c) V_{mpp} has been compared with the target value and in Figs.9(a) , 9(b) and 9(c) the output of ANFIS test has been compared with the target value that shows a negligible training error percentage of about 1.4%.



(a)

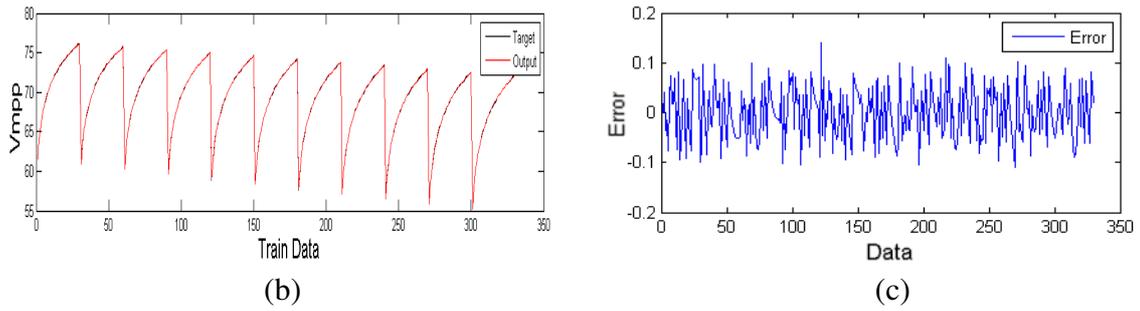


Fig. 8. The output of the ANFIS: (a) The output of the ANFIS with the amount of target data; (b) The output of ANFIS (V_{mpp}) with the amount of target data; (c) Percentage error of the (V_{mpp}) after training data;

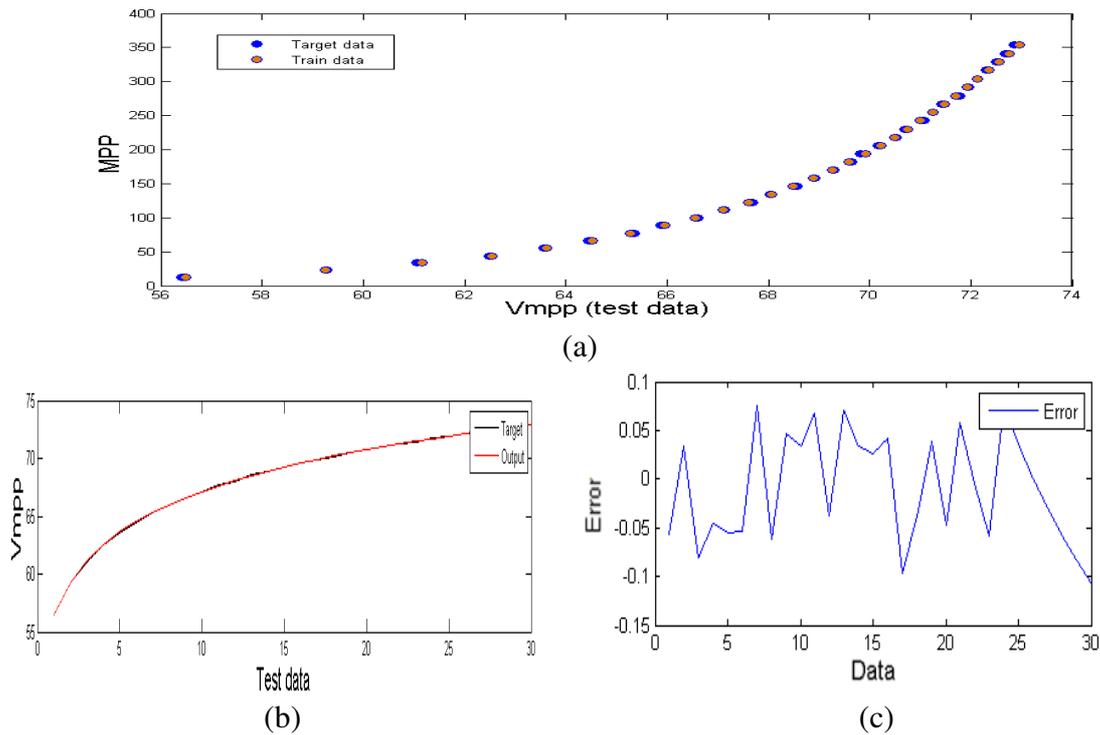


Fig. 9. The output of the ANFIS test: (a) The output of the ANFIS test with the amount of target data; (b) The output of the ANFIS test (V_{mpp}) with the amount of target data; (c) Percentage error of test data (V_{mpp}) after training data

3. Wind system configuration

The diagram of a wind energy system with the presence of PMSG integrated to grid is illustrated in Fig.10. Turbine output is rectified by using uncontrolled rectifier. Then dc link voltage is adjusted by PI controller until it reaches a constant value and then this constant voltage is inverted to AC voltage using sinusoidal PWM inverter. Inverter adjusts the dc link voltage and injected active power by d-axis and injected reactive power by q-axis using PQ control method. Furthermore, turbine output is regulated through pitch angle controller based on fuzzy logic in extra high wind speeds.

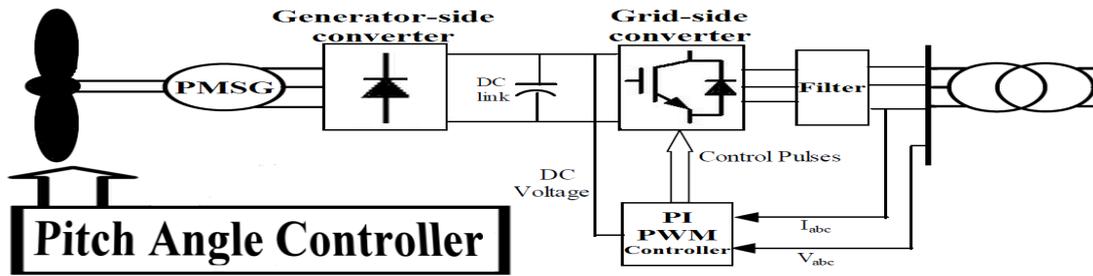


Fig. 10. The block diagram of system

3.1. Wind turbine and PMSG modeling

The amount of electricity that a turbine is able to produce depends on the speed of the rotor and the speed of the wind that propels the rotor [29, 30]. Aerodynamic wind power is calculated in equation (10):

$$P = 0.5 \rho A C_p(\lambda, \beta) V_w^3 \quad (10)$$

$$\lambda = \frac{W_m R}{V_w} \quad (11)$$

Where P , ρ , A , V_w , W_m and R are power, air density, rotor swept area of the wind turbine, wind speed in m/sec, rotor speed in rad/sec and radius of turbine respectively. Also, C_p is the power coefficient of rotor. PMSG voltage equations and other equation of wind turbine are presented in [28, 29].

3.2. Pitch angle based on fuzzy controller

Presented fuzzy controller is consisting of two input signal and one output signal. The first input signal is based on deviation between active power from the rated value in P.U and it's been mentioned as error signal. Thus, positive indicate shows turbine's normal operation and negative value shows the extra power generation during above rated wind speed. In this case, controller should modify in pitch angle degree which is done by increase the nominal value. The pitch angle degree is regulated on zero in a normal condition, the whole wind energy can be converted to mechanical energy and when the pitch angle start to increase from zero value, the wind attach angle to blades will be increase that lead to aerodynamic power reduction and consequently the output power will draw down. Besides, the second signal taken from anemometer nacelle [29, 30].

Controller's response is so faster when wind speed is used as an input signal comparing to the time that inputs are rotor rotational speed or active power in large turbines with high moment of inertia [25-27]. However, mechanical erosion in large and high speed turbines will diminish by adjusting this fuzzy controller. Designing of pitch angle controller based on fuzzy logic for wind turbine power adjustment in high wind speeds, is being proposed. Three Gaussian membership functions are considered in this article. Also Min-Max method is used as a defuzzification reference mechanism for Centroid. Given membership functions are shown in Fig.11.

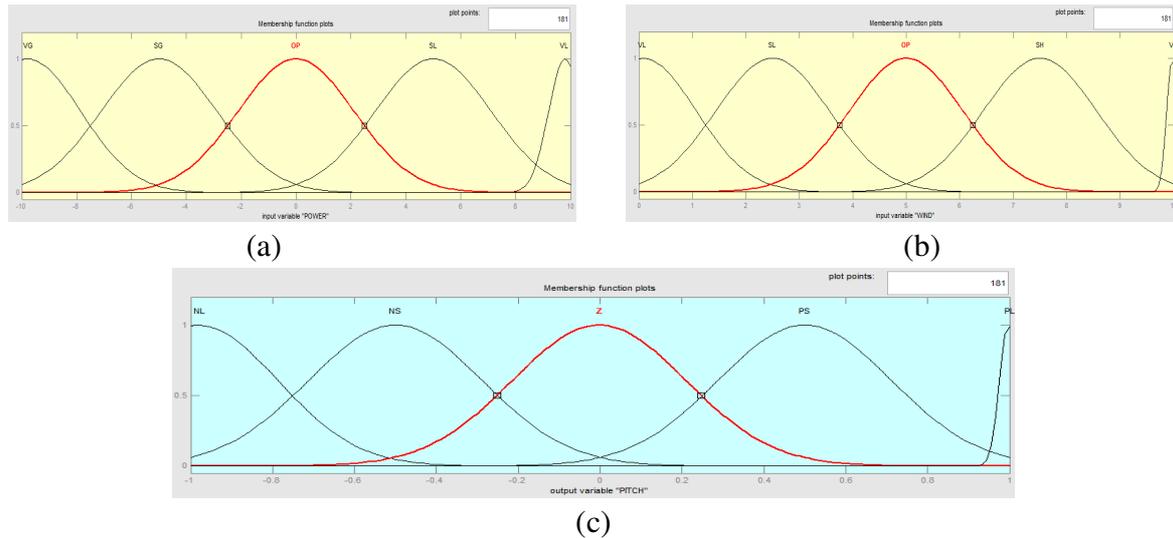


Fig. 11. The membership function of fuzzy logic: (a) Membership functions of Active power (error signal); (b) Membership functions of wind speed; (c) Membership functions of Output (β)

Moreover, the rules were implemented to obtain require pitch angle are shown in Table2. Where the linguistic variables are represented by VG(very great), SG (small great),OP (optimum), SL (small low),and VL (very low) for error signal and VL (very low), SL (small low), OP (optimum), SH (small high) and VH (very high) for wind speed signal and for output signal NL (negative large), NS (negative small), Z (zero), PS (positive small) and PL (positive large), respectively.

Table 2: Fuzzy rules

PITCH COMMAND		ACTIVE POWER(Error)				
		VG	SG	OP	SL	VL
WIND SPEED	VL	PL	PS	Z	Z	Z
	SL	PL	PS	Z	Z	Z
	OP	PL	PS	Z	Z	Z
	SH	PL	PS	PS	PS	PS
	VH	PL	PL	PL	PL	PL

4. Control strategy (P-Q)

Inverter control model is illustrated in Fig.12. The goal of grid side controller is keeping the dc link voltage in a constant value regardless of production power magnitude. Internal control-loop which control the grid current and external control loop which control the voltage. Also, internal control-loop which is responsible for power quality such as low Total harmonic distortion (THD) and improvement of power quality and external control-loop is responsible for balancing the power. For reactive power control, reference voltage will be set same as dc link voltage. In grid-connected mode, hybrid system must supply local needs to decrease power from the main grid. One the main aspects of p-q control loop is grid connection and stand-alone function. The advantages of this operation mode are more reliability and high power quality [31]. The THD is the summation of all harmonic components of the voltage or current waveform compared against the fundamental component of the voltage or current wave, the formula below shows the calculation for

THD on a voltage signal. The end result is a percentage comparing the harmonic components to the fundamental component of a signal.

$$I = \frac{\sqrt{(I_2^2 + I_3^2 + I_4^2 + \dots + I_n^2)}}{I_1} * 100\% \tag{12}$$

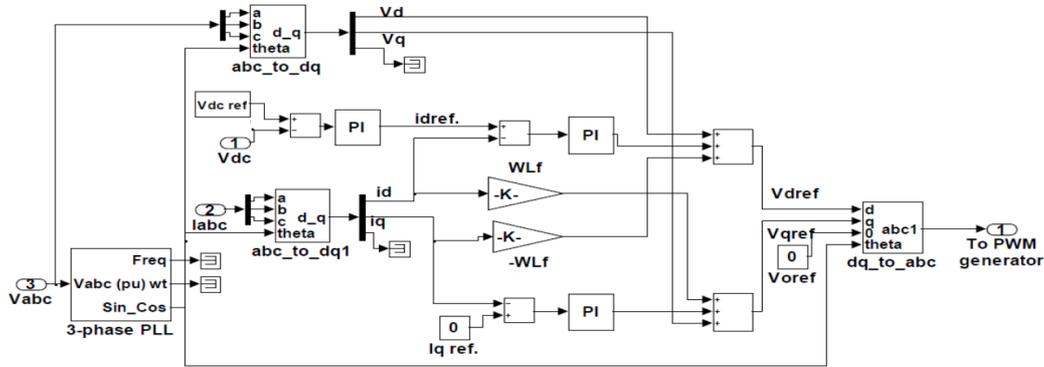


Fig. 12. The inverter control model

5. Simulation results

In this section, simulation results under different terms of operation in hybrid system using Matlab/Simulink are presented. In Figs.13 and 14 PV and wind system connected to grid by applying PQ controller in grid side inverter are shown. System block diagram is shown in Fig.15.

The grid voltage and frequency are 220 V and 60 Hz respectively. Photovoltaic parameters: output power= 1.08 kW Carrier frequency in PWM generator (V_{MPPT}): 4 kHz and in grid-Sid controller: 6 kHz, boost converter parameters: $L= 0.071H$, $C= 85 \mu F$, PI coefficients in grid-side controller: $K_{pVdc}= 3$, $k_{iVdc}= 14$, $K_{pId}= 15$, $K_{iId}= 630$, $K_{pIq}= 15$, $K_{iIq}=630$. PMSG parameters: Stator resistance per phase: 2.87Ω , inertia: $0.9e^{-3} \text{ kg}\cdot\text{m}^2$, torque constant $12N\cdot\text{M}/\text{A}$, Pole pairs: 8, output power= 88kW, Nominal speed: 12 m/s, $L_d = L_q = 9.2 \text{ mH}$. Grid parameters: X/R: 7, and other parameters, DC link Capacitor: $5530 \mu F$, DC link voltage: 1050, type of load: Inductive. Now, two cases are investigated for the simulation study based on the variation of wind speed, irradiance and load circumstances.

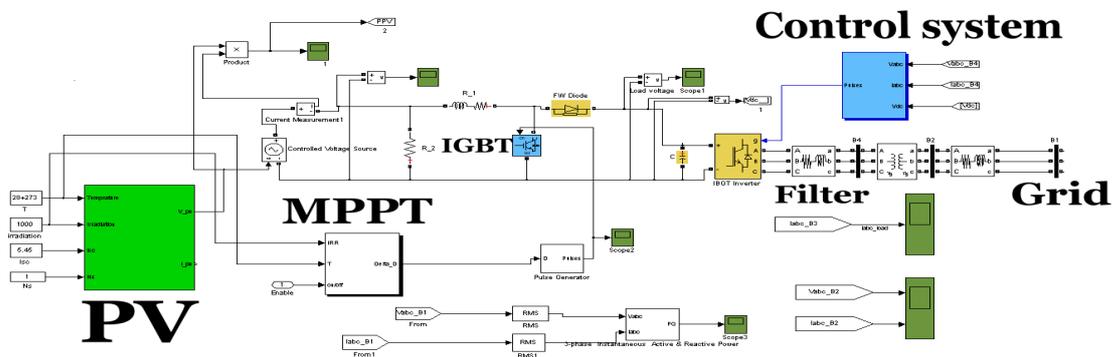


Fig. 13. PV in grid-connected mode and applying grid-side controller

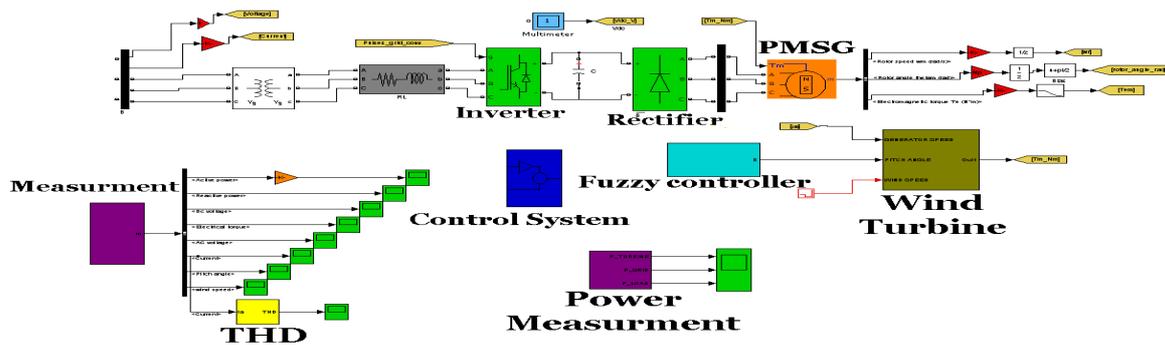


Fig. 14. Wind in grid-connected mode and applying grid-side controller

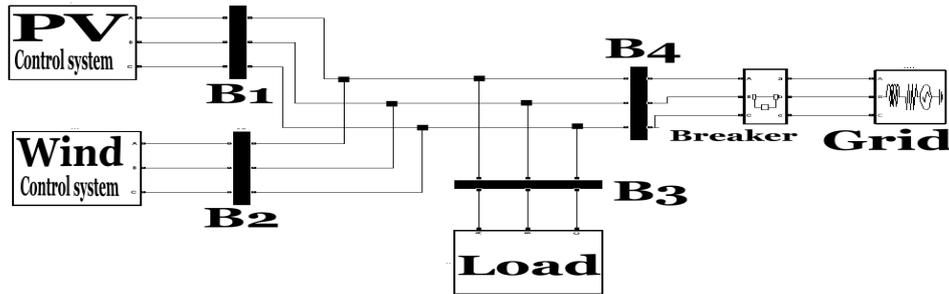
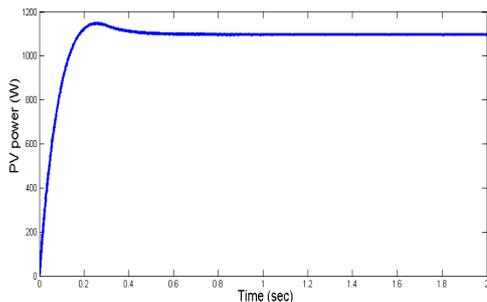


Fig. 15. Case study system

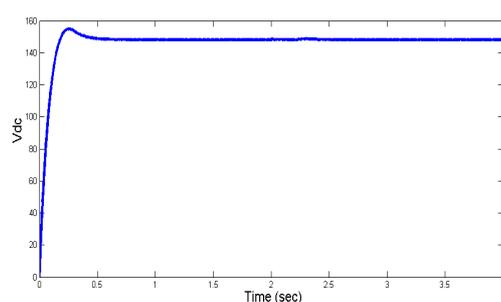
5.1. Case study 1

The hybrid system here is connected to the main grid that including 1080W photovoltaic system and 88kW wind turbine system .The system controlled by p-q technic and load is 75kW, which can be seen in Figs.16 and 17. The grid voltage is 220V. Simulation is done under “standard laboratory conditions” where irradiance intensity is 1000 [W/m²], temperature is 25 °C. Controller’s responses for grid voltage waveform, grid current waveform and photovoltaic module have been shown in Fig.16. Also, during 0 < t < 6 sec the load power is 75kW and at t= 6, it has %55 step increase in load. Moreover wind speed is 11 m/s which at t= 2 reduced to 8 m/s, at t= 3 increased to 10 m/s and also at t=4 increased to nominal speed (12 m/s). Fig.17 show the simulation results for active powers, inverter output voltage, grid current, DC link voltage, Reactive power and THD % .

It’s been clear that grid with cooperation of wind and PV system can easily meet the load demand. One of the most important aspects of using distributed generation (DG) sources and connecting them to grid is keeping the THD in minimum of its value. According to IEEE Std.1547.2003 it should be around 5%, which in THD curve it’s been around 5% to 7%. According to reduction of wind speed, the turbine torque decrease and based on this active power output from wind system and inverter current declined. In order to meet the load demand, power shortage will be supplied by grid.



(a)



(b)

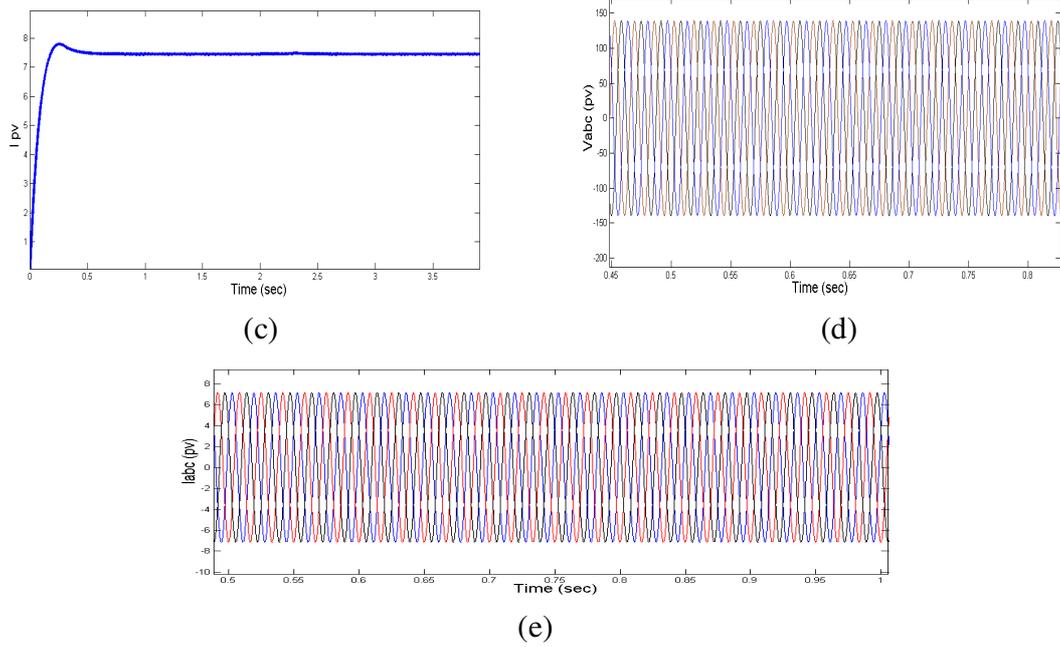


Fig. 16. Simulated result for PV system in case 1: (a) Output power of PV; (b) Output voltage of PV; (c) Output current of PV; (d) Output voltage of PV (after filter); (e) Output current of PV (after filter)

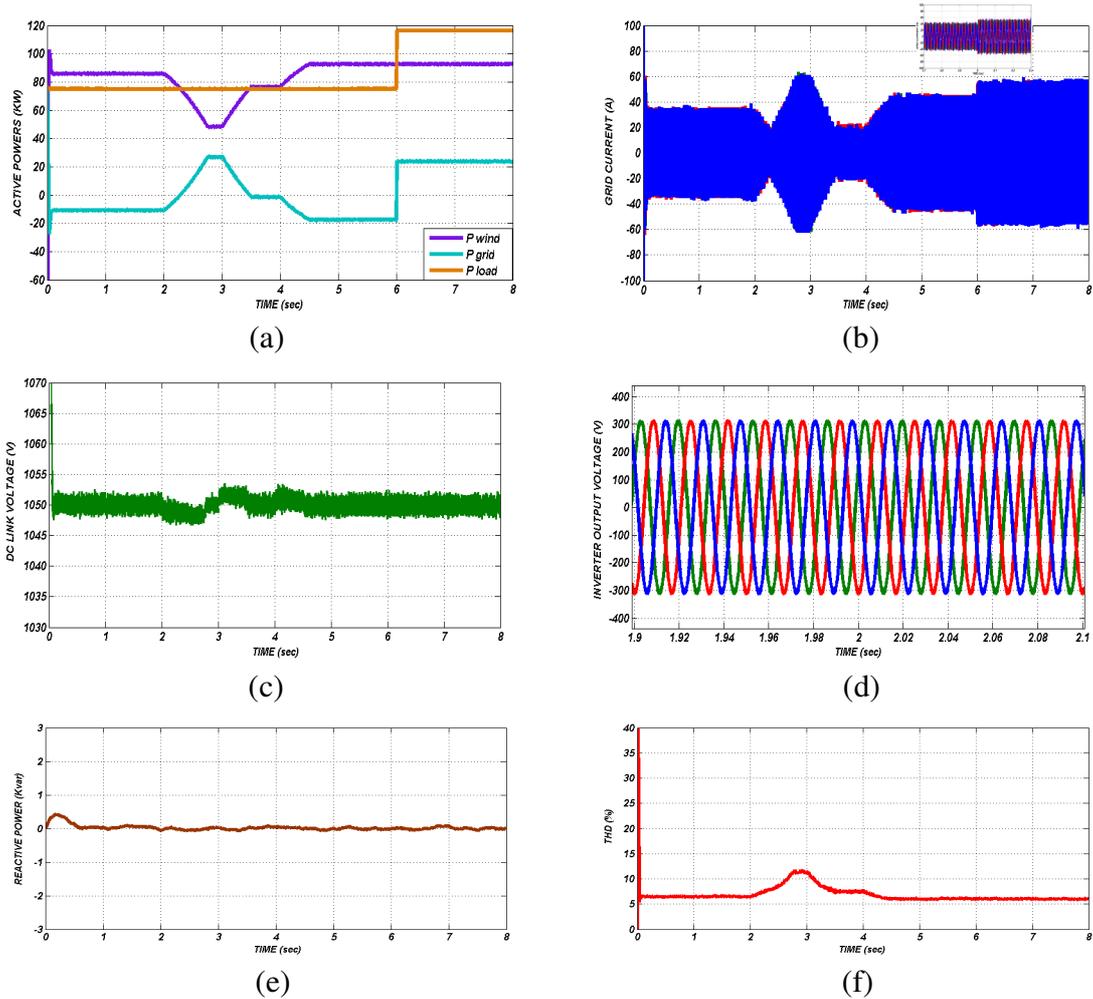


Fig. 17. Simulated result for wind system in case 1: (a) Active powers; (b) Grid current; (c) DC link voltage; (d) Inverter output voltage; (e) Reactive power; (f) THD %

5.2. Case study 2

A 75 kW load has been connected to the hybrid system in different irradiance level according to Fig.18 (a) has been evaluated the system's performance. It can be seen, the hybrid system can track maximum power and active power exchange between grid and DGs. The simulation results for PV are shown in Fig.18. Also, in this case wind speed during $0 < t < 1$ is 11 m/s and at $t = 1$ sec it reduces to 9 m/s and load is 75 kW constant. Then during $1 < t < 2$, wind speed is 9 m/s and after that at $t = 2$, it's extremely increase to 16m/s. Through designing fuzzy controllers when wind speed is more than nominal (12 m/s), turbine output power is increased by extremely increasing wind speed, however without controller the power is constant in high level and with presence of fuzzy controller, its reduced to nominal power and make it smoother that lead to prevent mechanical fatigue to generator. Fig.19 (a) shows the wind speed that has been used. Figs.19 (b) and 19(c) show active power of wind turbine with absence and presence of fuzzy logic controller according to wind speed. Figs 19(d) and 19(e) show inverter output current with absence of controller and presence of controller respectively. Fig.19 (f) shows the variation of pitch angle with presence of controller which in normal situations, pitch angle is set as zero. Figs.19 (h) and 19(g) show effect of fuzzy controller on active powers and absence of this controller.

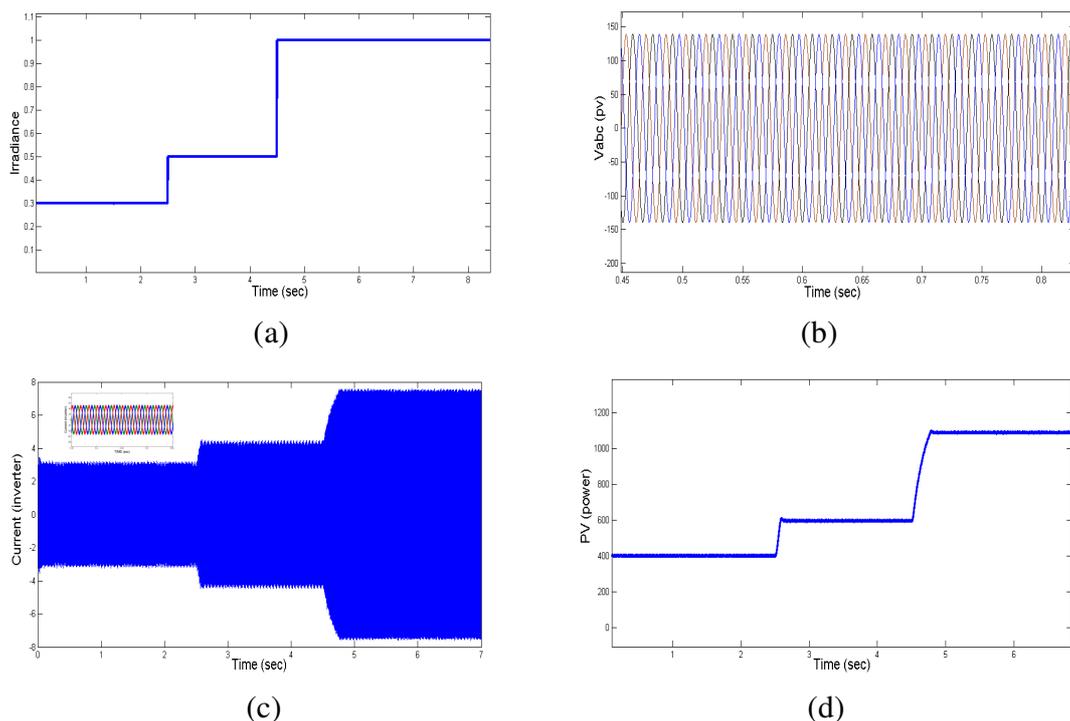


Fig. 18. Simulated result for PV in case 2 : (a) Irradiance ; (b) Output voltage of PV (after filter) ; (c) Output current of PV (after filter) ; (d) PV power

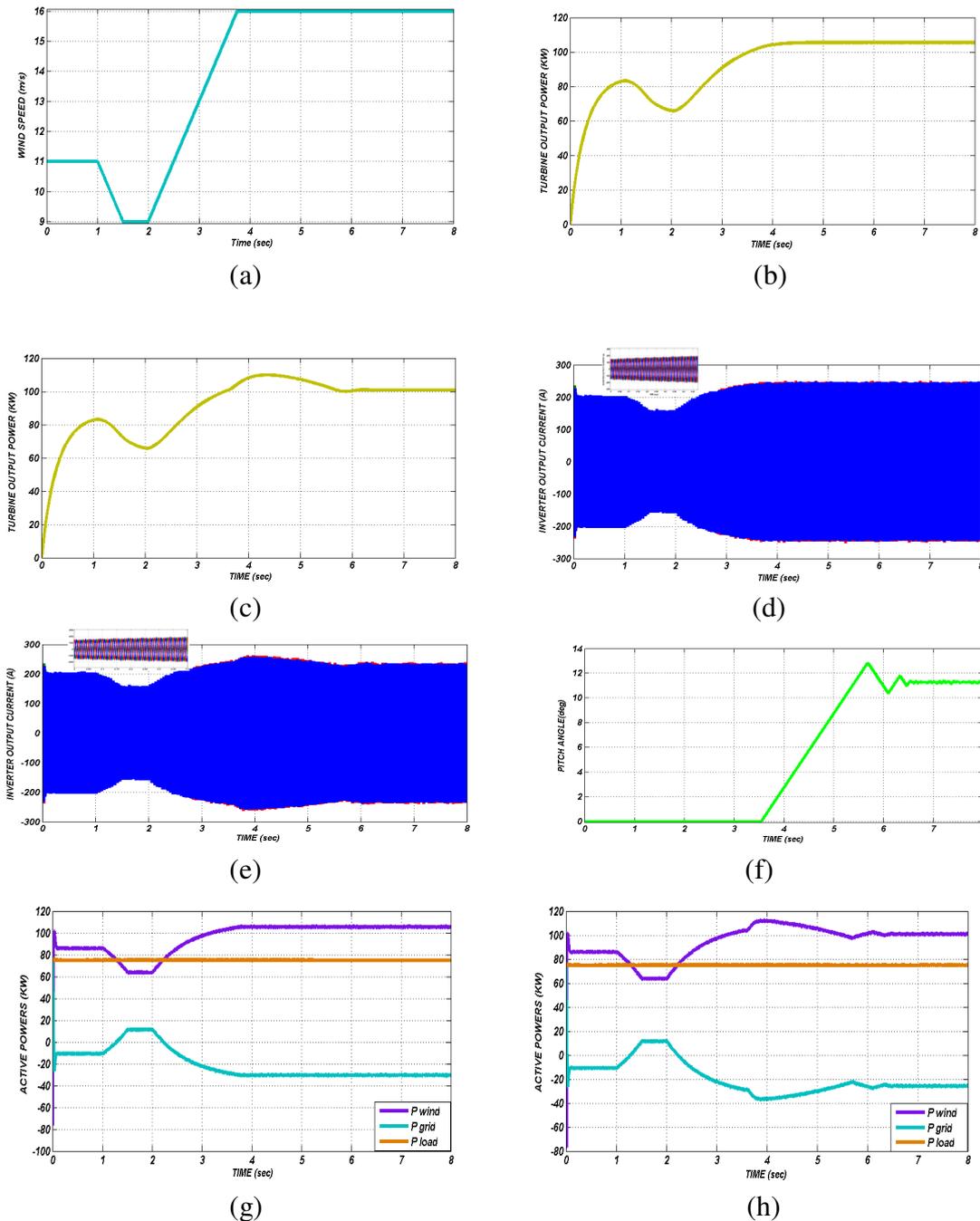


Fig. 19. Simulated result for wind system in case 2: (a) Wind speed; (b) Active power of turbine with absence of controller; (c) Active power of turbine with presence of fuzzy controller; (d) Inverter output current with absence of controller; (e) Inverter output current with presence of controller; (f) Variation of pitch angle with presence of fuzzy controller; (g) Active powers with absence of fuzzy controller; (h) Active powers with presence of fuzzy controller

6. Conclusion

The presented study is modeling and analysis of grid connected wind turbine using PMSG and photovoltaic source (hybrid system), under load circumstances, variations of wind speed and irradiance.

The simulation results show that using ANFIS controller can dramatically reduce the disadvantages of previous approaches. In fact, this research suggests that, in grid-connected mode using ANFIS controller can decrease oscillations of power output around the

maximum power point and can increase convergence speed to achieve the maximum power point. Presented controller in wind system by adding wind speed as an input signal of fuzzy logic will have faster and smoother response in large wind turbines. The benefit of this controller is that it keeps the turbine output in admissible value and it can prevent more mechanical erosion and fatigue and also dynamic performance of PMSG will more improve. Finally, by applying the appropriate controller, the hybrid system in grid-connected mode can meet the need of load assuredly.

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