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Adaptive neuro-fuzzy inference system to improve the power quality of variable-speed wind power generation system

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Abstract

In this study, an adaptive neuro-fuzzy inference system is designed for output voltage and frequency control of a variable-speed wind power generation system. Variable-speed wind power generation systems (VSWPGS) provide the opportunity to capture more power than fixed speed turbines. On the other hand, the variable-speed wind turbine output can be variable voltage and variable frequency for fluctuating wind speeds. The quality of output power can be improved if adequate controls are incorporated in the system. To bring the output voltage and frequency of system by means of control of blade pitch angle of wind turbine to a desirable value, an adaptive neuro-fuzzy inference system (ANFIS) is used in this paper. Based on the dynamic performance of VSWPGS, ANFIS is designed. Control and dynamic performance analysis of VSWPGS is made depending on various loading situations. Dynamic modeling, control and simulation study of the wind power generation system is performed with MATLAB/Simulink program. The simulation results obtained through various load situations and detailed analysis of so established simulation model is given in this study. As it can be seen in simulation results, the output voltage and frequency of ANFIS controlled variable-speed wind power generation system reach to desirable operation values in a very short time.

Key Words: *wind power generation system, adaptive neuro-fuzzy inference system, pitch angle control, power quality, Matlab/Simulink*

1. Introduction

In last 20 years, installation of wind power production systems and associate bennifits has greatly increased. Especially, in recent years, due both to a significant decrease in costs of wind power production and technological developments in wind tribune production, contribution of wind energy in the electricity power production systems has increased rapidly [1, 2].

The biggest problem faced during integration of the wind power production systems into existing power production systems is the quality of power. Different wind turbine types have various power quality characteristics. The power quality disturbances are power variances, vibrations and harmonics [2, 3]. Measurement of these disturbances is standardized by IEC 61000-4-30, which define the methods for power quality parameters in 50/60 Hz A.C. power supply systems. IEC 61400-21 provides a uniform methodology to ensure consistency and accuracy in-testing and assessment of power quality characteristics of grid-connected wind turbines [4-5].

Many studies have been conducted to analyze, develop and improve the quality of power from wind power production systems in literature. These analyses contain the system stability analysis, analysis of the converter of power electronics and stability analysis of output powers of generators in various types [6-8].

In Turkey, a study on the evaluation of power quality from wind power connected to the power system at the Alçatı substation was made. In this evaluation study, the phase voltage and phase current variations and active and reactive power measurements were obtained and compared to variables forecasted from the PsCAD simulation program [8]. For the power quality control of the wind-diesel power production system, hybrid intelligent controller was applied and the system performance was brought to desired values (voltage, frequency, active and reactive power) with regard to electrical operation [9]. In the fixed and variable speed wind power systems, by minimizing oscillations in the active power resulting from the wind speed changes through the Flywheel Energy Storage System (FESS) control connected to fuzzy logic supervisor, quality of the produced power was brought to desired value within some definite tolerances [10, 11].

In general, power quality and reliability in renewable systems are very important elements. One disadvantage of a wind energy system is that it exposes reactive power to the asynchronous generator from a network or capacitor groups. Constant speed energy systems operate in constant frequency and constant speed. As the wind speed is variable, the wind turbine speed changes depending on asynchronous generator and frequency of the system is continuously in oscillation position.

To obtain maximum benefit from the wind energy, variable speed wind turbines are being used in general. Variable speed wind turbine systems produce variable voltage and frequency when no controller element is used. In order to obtain output voltage and frequency in desirable values from variable speed wind generation systems, they must be operated together with the controller element [12].

Output power obtained from the wind turbine system changes throughout the day, depending on wind speed. In very large and powerful networks, changes and oscillations in wind output power is minimized or eliminated by controlling the frequency and voltage. In wind power generation systems isolated from networks, a power balance between generation and consumption within previously determined power limits must be ensured and voltage and frequency must be kept in desirable values.

In this study, dynamic modeling and simulation of the wind power generation system and control of blade pitch angle is performed by means of the Matlab/Simulink program. Behavior of the control system depending on dynamic performance of the wind power generation system (VSWPGS) is observed through the simulation study. The magnitude to be controlled in the wind turbine system is the blade pitch angle. The blade pitch angle must be checked for speed control and power limitation in wind turbine systems. In this study, the blade pitch angle is checked by the neuro-fuzzy controller and conventional PID controller separately. With control of blade pitch angle, control can be obtained over output voltage and frequency of the wind power generation system.

2. The wind turbine and dynamic model of mechanical system

The wind energy conversion system is a complex system that converts wind energy to mechanical energy and electric energy. Output power or moment of wind turbine is defined with basic factors such as wind speed, turbine shape and dimension. The dynamic model of a wind turbine must contain parameters defining the behavior of wind turbine. With operation of so established wind turbine, it is possible to control the performance of wind turbine to obtain desired characteristics. In respect to wind power generation, turbines having different characteristics play important role in power generation.

The air dynamic or wind turbine model is performed depending on the air dynamic power productivity coefficient $C_p(\theta, \lambda)$ or torque coefficient $C_q(\theta, \lambda)$, where θ is the blade pitch angle and λ is the speed rate. Output moment of the wind turbine model (air dynamic model) is determined depending on wind speed. In Figure 1, dynamic behavior model of wind turbine and mechanical system is given. Output power of wind turbine is multiplied by a definite gain coefficient (gear number) for stabile operation of the moment system produced depending on blade pitch angle and turbine rotor speed rate and so, shaft moment is kept in desirable value. As the shaft of wind turbine and shaft of asynchronous generator is coupled to each other, the generator can be operated in desired operation speed.

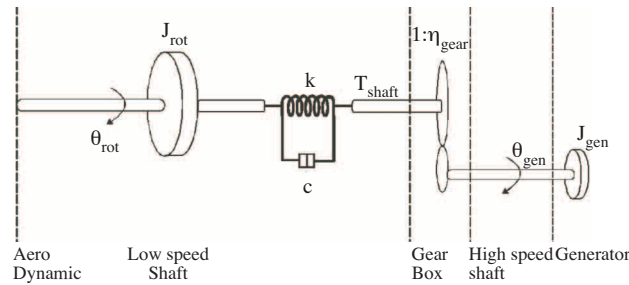


Figure 1. The wind turbine and dynamic behavior model of mechanical system.

Inputs and outputs of wind turbine are defined as follows:

- The wind speed is expressed as an independent input. It is defined as energy input to wind turbine.
- Specific (special) magnitudes of turbine are defined as input parameter.
- Magnitudes belong to turbine speed, rotor blade pitch and rotor blade gap angle form the transmission parameters of the wind energy conversion system.
- Wind turbine output magnitudes are defined as power and propeller moment.

With determination of input and output variables of the wind turbine, expressions relating input and output variables can be easily obtained. Equations defining relations between the obtained power and blade speed are related to the mechanical power in moving air flow and can be expressed as flow rate of kinetic energy per second:

$$P = \frac{1}{2}(\rho AV)V^2 = \frac{1}{2}\rho AV^3 \text{ Watt.} \quad (1)$$

Here, P is the mechanical power in the moving air (watt), ρ is air density (kg/m^3), A is area swept of the rotor blades (m^2), and V is velocity of the air (m/sc).

The mechanical power extracted by the blades is expressed as a fraction of the upstream as

$$P = \frac{1}{2} \rho \cdot A \cdot V^3 \cdot C_p \quad , \quad (2)$$

where C_p is the fraction of upstream wind power which is captured by the rotor blades and has a theoretical maximum value of 0.59. It is also referred as the power coefficient of the rotor or the rotor efficiency. The power coefficient of the rotor C_p is between 0.4 and 0.5 for two-blade high speed turbines. In low speed blade turbines with more than two blades, the power coefficient varies between 0.2 and 0.4 [12]. Turbine operation conditions and obtained mechanical power can be determined by means of productive area of rotor blades, wind speed and wind flow conditions in rotor. For this reason, turbine output power can be changed by means of change in flow conditions on rotor blades and productive area. The basis of controlling of wind energy conversion systems depends on controlling of flow condition and productive area.

The tip speed ratio λ is the proportion of linear speed at the tip of blade to free current wind speed and is defined as [13]

$$\lambda = \frac{\omega \cdot R}{V}, \quad (3)$$

where ω is rotor angular speed (rad/sn), and R is rotor blade radius(m). Maximum power is related to rotor speed rate wind turbine operation point. Maximum wind turbine output rises to the desired value for special tip speed ratio λ and blade gap angle β values. To keep the optimal level tip speed ratio λ at all times, the rotor must be rotated at high speed in high wind speeds, and at low speed at low wind speeds. For productive electricity generation from wind turbines, high proportional speed turbines must be preferred [14].

For modeling of dynamic behavior of wind turbines, if the power coefficient C_p that changes depending on the tip speed ratio and blade gap angle is placed in equation (1) and rearranged, the following equation is obtained:

$$P = \frac{1}{2} \rho \cdot A \cdot V^3 \cdot C_p(\lambda, \beta) \text{ (Watt)}. \quad (4)$$

3. Modeling and simulation of variable-speed wind power generation system inmatlab/simulink program

The wind turbine, detailed analysis of mechanical system and correlations defining dynamic behavior of the system are explained in detail in previous chapter. In the study performed for purpose of obtaining the dynamic behavior of the wind power generation system in real time, SimPowerSystems program involved in the Matlab/Simulink have been used. Before giving the simulation block diagram of the wind power generation system, a simplified block diagram of the system is given in Figure 2.

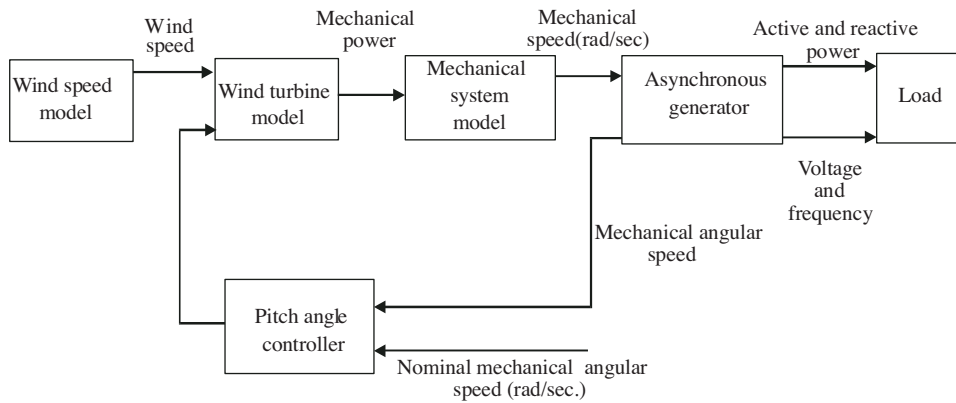


Figure 2. Simplified block diagram of the variable-speed wind power generation system.

In this diagram, output of the wind speed model is defined as kinetic energy or speed of wind. The wind speed is converted to mechanical power or moment by the wind turbine model. The obtained mechanical power or moment is the first input of the mechanical system (impulse system). Other second input of the mechanical system is the proportional speed of asynchronous generator. Output of the mechanical system is the wind turbine rotor speed and mechanical power. Inputs of the asynchronous generator model are mechanical energy obtained from the wind turbine, voltage at network or tips of load and frequency magnitudes. Outputs of asynchronous generator are network or active and reactive power values necessary for the load. Voltage and frequency of asynchronous generator can also be expressed as output magnitudes in the wind power generation systems that operate in isolation to electric networks.

In the study, data on MWT-300 kW variable speed and three-blade wind turbine manufactured by Mitsubishi heavy industry has been used. The wind speed of that wind turbine (m/s) and curve of produced output power is given in Figure 3 [15].

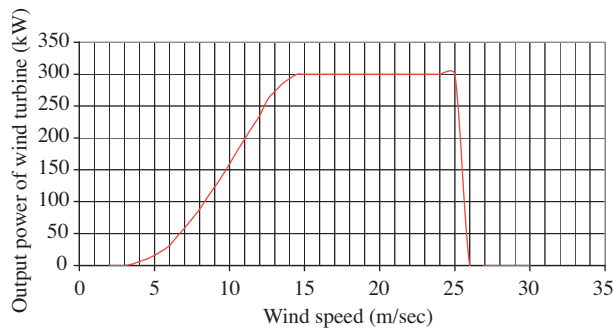


Figure 3. The curve of produced output power of MWT-300 kW wind turbine depending on wind speed.

In Figure 4 below, a simulation block diagram of the wind power generation system performed through Matlab/Simulink program is given. The wind power generation system consists of basic compounds such as squirrel cage asynchronous generator, synchronized condenser, variable speed wind turbine, load, frequency control unit, dump load, ammeter and voltmeter. As the equations and formulations related to dynamic modeling of the asynchronous generator and synchronized condenser that form the wind power production system will take a big place in this study, they are not given here. In the Matlab program, modeling of

the asynchronous generator and synchronized condenser is performed by means of formulas given in reference [16–23].

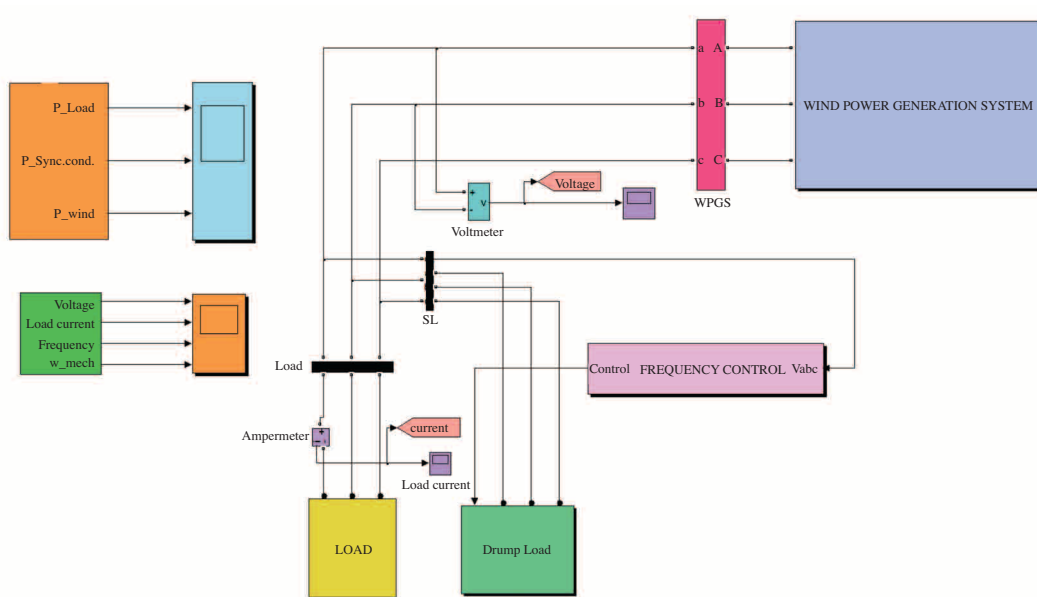


Figure 4. Simulation Block Diagram of the variable-speed wind power generation system without power converter obtained through Matlab/Simulink program [15].

In the block diagram of the wind power production system given in Figure 5, the output of the wind speed model is defined as the kinetic energy or speed of wind. The wind speed is converted to mechanic power or moment by the wind turbine model. The obtained mechanic power or moment is the first input of the mechanic system (of drive system). The other second input of the mechanic system is the proportional speed of the asynchronous generator. Inputs of the asynchronous generator are: mechanical energy obtained from the wind turbine, voltage and frequency magnitudes at ends of the network or load. Outputs of the asynchronous generator are the active and reactive power values required for the network or load. In the wind power production systems that operate in isolated manner from electric networks, voltage and frequency of the asynchronous generator can be expressed as output magnitudes.

The simulation block diagram performed in Matlab/Simulink program for dynamic operating situation of the wind power production system is shown in Figure 4. The wind power production system consists of basic components such as squirrel cage asynchronous generator, synchronized condenser, variable speed wind turbine, load, frequency control unit, dump-load, ammeter and voltmeter.

The detailed block model of the wind power production system given in Figure 4 above is shown in Figure 5 below. In this wind power production system, variations in frequency, output voltage and drawn power curves of the system are obtained individually by means of the simulation study without any controller element. Different power demands of consumers are expressed as 120 kW, 150 and 180 kW. The controller element (PID controller and ANFIS) is put into operation depending on variations in electrical magnitudes of the wind power production system in such loading situations. Amplitude of the voltage obtained from the system must be within permitted limits whatever the electric energy production system is used. It is known

that frequency of the system in other important magnitude is 50Hz in Turkey operating conditions. The system frequency in electric energy production stations is tried to be kept in 50Hz value. To obtain high quality power, the magnitude values of frequency and voltage must be kept in the desired range. The quality of obtained power may be brought to desired level by decreasing the undesired harmonic currents and voltages to minimum level. By considering the situation the wind power production system will operate with the network, the frequency and voltage value is adjusted according to the frequency and voltage values of the network.

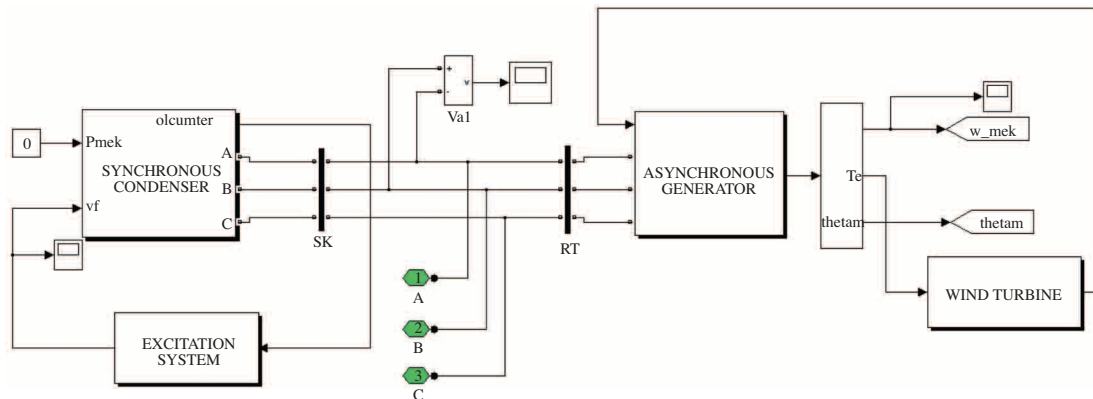


Figure 5. Simulation Block Diagram of Wind Power Generation System.

The wind power production system consists of asynchronous generator, synchronized condenser and wind turbine is given in Figure 5. The synchronized condenser is same with the synchronized machine we know. If it is operated as a condenser, its mechanic energy input is zero. In other words, it is not necessary to actuate it with a driving machine. The reactive power production is ensured by adjusting the DC excitation circuit. The reason why we use a synchronized condenser in the wind power production system is to obtain magnetic current or reactive power required in operation of asynchronous generator with wind turbine. Meanwhile, in order to be able to feel the effect of wind again, feeding of synchronized condenser with the active power produced by asynchronous generator is performed.

4. Control strategy in wind power generation system

Output power obtained from the wind turbine varies throughout day depending on variations in wind speed. Variations and oscillations in the wind output power can be decreased to minimum or eliminated completely by controlling the frequency and voltage in very big and powerful networks. In the wind power production systems isolated from electric networks, the power balance between production and consumption must be ensured and the frequency and voltage must be kept within previously determined power limits. In order the desired power can be in determined value and quality, the frequency and voltage values must be between the permitted lower and upper limits. The power produced by the wind power production system cannot always ensure the power balance between consumers. If the consumption power is less than that wind power production system, by putting into operation the spare load groups or dump-load circuit elements, the wind power is regulated and the frequency and voltage is performed in desired amplitude. In the study, the dump-load was used to control the frequency. Control strategy of the wind power production systems consists of two phases:

- Speed control, and
- Power limitation control.

The speed control is considered as the main parameter in the power optimization strategy. If the wind speed is lower than the rated wind speed, inclination angle is tried to be kept at its optimal value. In that situation, in order for the generator speed ω_{gen} to catch the maximum output power of wind, the wind turbine speed is adjusted by means of a controller.

In power limitation control, the blade pitch angle controller is made to equalize the nominal (rated) power with the produced power. In power limitation control loop, the error rate between the rated power value and measured power value is sent to the controller element. The controller produces the necessary reference the blade pitch angle. This reference the blade pitch angle is compared to the real reference the blade pitch angle. As a result of this, output of power limitation controller, inclination angle of wind turbine wings are determined.

In the study, depending on the real rotor speed value of the asynchronous generator in the wind power production system, it is aimed to control the turbine blade pitch angle. With control of the wing inclination angle, the power limitation control is also performed. With control of the wing inclination angle of the wind turbine, the voltage and frequency is kept in the desired value and so, the power balance is ensured and kept.

5. Adaptif neuro-fuzzy inference system

In recent years, fuzzy logic control has played an increasing and significant role in the development and design of real-time control applications. However, membership function type, number of rules and correct selection of parameters of fuzzy controller are very important to obtain desired performance in the system. Determination of membership function type and rule number of fuzzy controller and selection of parameters is made by means of trial and error method and by using the specialization knowledge [24, 25].

Adaptive Neuro-Fuzzy Inference System is the integration of artificial neural networks and fuzzy inference systems. ANFIS is formulated on three main elements: auxiliary, compatible and integrative [26]. ANFIS is also expressed as functional adaptive networks unit equivalent to fuzzy inference system. ANFIS is the combination of neural networks and fuzzy system to determine parameters of the fuzzy system. The main purpose of using the Neuro-Fuzzy approach is to automatically realize the fuzzy system by using the neural network methods. In ANFIS control system, Fuzzy Sugeno models are involved in framework of adaptive system to facilitate the learning and adaptation studies [24]. ANFIS permits combination of numerical and linguistic data. Besides, Neuro-Fuzzy systems have the ability to obtain fuzzy information from numerical data. [27–28].

In the adaptive neuro-fuzzy model, two basic learning algorithms are required. One of them is the structural learning algorithm to find suitable fuzzy logic rules and the second one is the parameter learning algorithm to adjust the membership functions and other parameters according to desired performance from the system. [27].

In this study, gradient- descent training algorithms from the neural networks area are used to obtain fuzzy system parameters. For this reason, the approach is generally expressed as Neuro-Fuzzy modeling. [28–30]. To express the ANFIS structure, two fuzzy if-then rules under Takagi-Sugeno (TS) model are given as follows:

Rule 1: If (x is A_1) and (y is B_1) then $f_1 = p_1x+q_1y+r_1$

Rule 2: If (x is A_2) and (y is B_2) then $f_2 = p_2x+q_2y+r_2$

Here, r_i, p_i and q_i are the design parameters determined during the period of training phase.

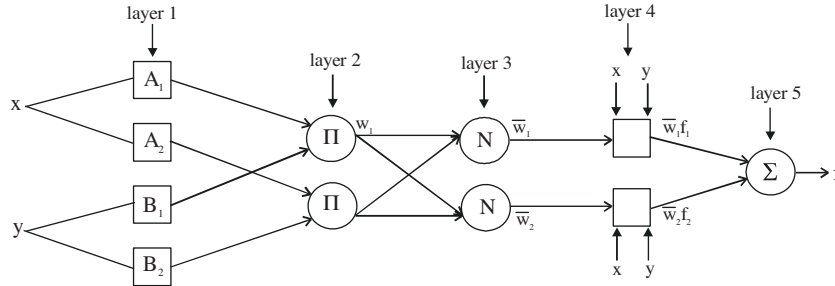


Figure 6. A general schematic diagram of ANFIS controller system.

The general block diagram of ANFIS controller system performed for two-rule fuzzy system is given in Figure 6. The ANFIS controller system realizes TS rules in 5 layers by using multi-iteration learning procedure and hybrid learning algorithm [30].

In the block structure of ANFIS given in Figure 6, there are two adaptive layers (Layers 1 and 4). Layer 1 has three adjustable parameters related to input membership functions (a_i, b_i and c_i). These parameters are pioneer parameters. Layer 4 has three adjustable parameters (r_i, p_i ve q_i) related to first degree polynomial. These parameters are called result parameters [24].

The duty of learning or training algorithm for ANFIS is to change all the adjustable parameters to compare ANFIS output with trained data. a_i, b_i and c_i membership function parameters define the center of sigma, slope and bell type membership function respectively. Each period of training is divided into two phases. In the first phase, the result parameters are adjusted with Least-squares method and in the second phase, the pioneer parameters are adjusted with gradient descent (back propagation) method. If these parameters are fixed, ANFIS output is expressed with the correlation

$$\begin{aligned}
 z &= \frac{w_1}{w_2+w_2} z_1 + \frac{w_2}{w_1+w_2} z_2 \\
 &= \bar{w}_1(p_1x + q_1y + r_1) + \bar{w}_2(p_2x + q_1y + r_2) \\
 &= (\bar{w}_1x)p_1 + (\bar{w}_1y)q_1 + (\bar{w}_1)r_1 + (\bar{w}_2x)p_2 + (\bar{w}_2y)q_2 + (\bar{w}_2)r_2
 \end{aligned}
 \tag{5}$$

In equation (3), the output of Sugeno Fuzzy system z is linear in the result parameters p, q and r . ANFIS output is a linear combination of adjustable parameters. For this reason, a combination of gradient descent and least squares methods can easily define optimal values for the result parameters p, q and r . However, if parameters of membership function are not fixed and permit changing, the area to be trained becomes wider and convergence of training algorithm slows down. In such cases, the hybrid learning algorithm with combination of gradient descent and least- squares gives more effective results. [31].

6. ANFIS for blade pitch angle control of variable-speed wind power generation system

After wind power generation system is commissioned, electrical output magnitudes become very important with regard to system productivity and reliability. If the power obtained from the wind power generation system

is desired to be high quality, output voltage and frequency must be within operation limit values. For this purpose, to obtain electrical power in desired quality from the said power generation system, operation voltage and frequency has been controlled with ANFIS.

The pitch angle control is made to control wind flow around the turbine blades by controlling the moment spent on the turbine shaft. If the wind speed is lower than the rated speed of wind turbine, pitch angle is constant in its optimum value. It must be considered that the pitch angle can be changed in limited rate. This rate may be completely low because of rotor blade dimension. The maximum change rate for blade gap angle is about ± 10 degree/s. By means of blade pitch angle control, in speeds of rotor above slow and nominal values, no problem may occur with respect to the structure of the wind turbine. [32]. As long as the wind turbine output power is lower than that for the rated speed of wind turbine, the error signal will have a negative value and gap angle will be have optimum value. But, if the turbine output power is above the reference value, the error signal will be positive and gap angle will be replaced with a new value in limited rate.

While controlling the blade pitch angle of the wind turbine, attempt is made to keep the mechanical angular rate of the asynchronous generator at rated value. Frequency of the system is put under control of the pitch angle control, thereby controlling the electronic output frequency and voltage at specified values.

To develop operational performance of the wind power generation system and obtain power in desired quality and value, an adaptive neuro-fuzzy inference system (ANFIS) has been designed to regulate the blade pitch angle of variable speed wind turbine. As frequency of output voltage of VSWPGS is direct proportional to the speed of asynchronous generator, frequency adjustment can be made at the same time.

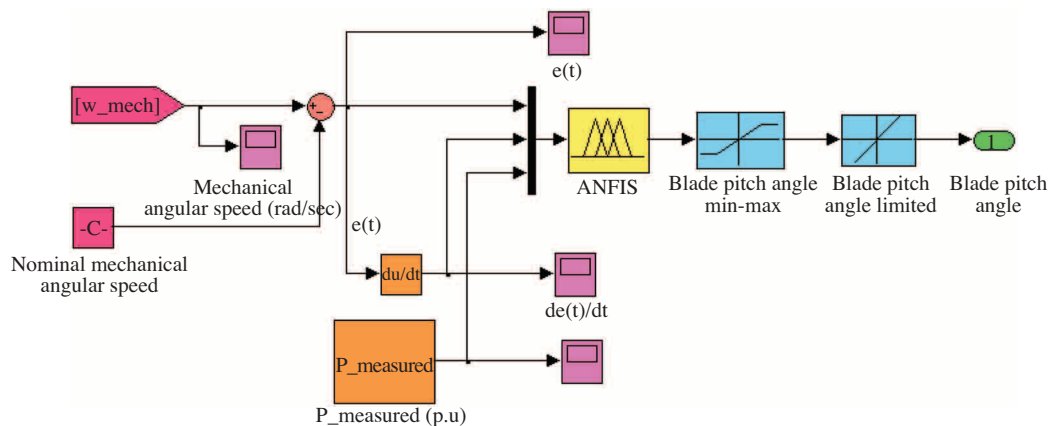


Figure 7. Simulation block diagram of controlling with ANFIS of blade pitch angle of variable-speed wind turbine.

The simulation block diagram of controlling of blade pitch angle of VSWPGS with ANFIS is given in Figure 7. The difference between mechanic angular speed of asynchronous generator and nominal mechanic angular speed gives an error signal. As the squirrel cage asynchronous generator used in simulation study has 4 poles, nominal mechanic angular speed is calculated

$$\omega_{mek_nominal} = \frac{2 \cdot \pi \cdot n_s}{60} = \frac{2 \cdot \pi \cdot 1500}{60} = 157.0796 \text{ rad/s.}$$

Here, n_s is synchronized speed or rotational speed of asynchronous generator. First of three input signals of ANFIS is the error signal $e(t)$, the second one is the changing of error signal depending on time $de(t)/dt$ and is expressed with correlations as

$$e(t) = \omega_{mek} - \omega_{mek_nominal} \tag{6}$$

$$\frac{de(t)}{dt} = \frac{\omega_{mek} - \omega_{mek_nominal}}{dt}. \quad (7)$$

The third input signal of ANFIS is the value $P_{measured}$ (p.u) calculated as per-unit value of power drawn according to tip voltage and load current values of the load fed from output ends of VSWPGS. The output signal of controller element is the value of blade pitch angle determined in maximum level. This maximum level value is applied to inlet of blade turbine system by passing through the circuit element limiting min-max gap of blade pitch angle and blade pitch angle limiter. As a result, the blade pitch angle in value desirable for stable operation of the system is applied to inlet of the turbine system.

In order we can control the variable speed wind turbine with ANFIS, firstly we had to know the system or analyze it very well. If we do not analyze the behavior of system well, we can not control the process. In this study, the aim is to regulate the output frequency and voltage by adjusting the rotor blade pitch by adjusting the blade pitch angle of the wind turbine system. Our prior purpose in this study is to bring frequency and voltage of the system to a desirable point by realizing the speed control.

The error signal in uncontrolled situation of VSWPGS ($e(t)$), changing signal in error signal $de(t)/dt$ and measured power P measured signal data are recorded individually. In controlling of blade pitch angle of VSWPGS with ANFIS, the total data number to be used in establishment of the ANFIS data base and fuzzy inference system is 64654 for three different load situations. Then, these recorded data are entered in *anfisedit* software of Fuzzy Logic Toolbox in MATLAB program. To automatically establish the fuzzy inference system with ANFIS, the membership function type, linguistic variable number and by making how many iteration, the hybrid learning algorithm will be applied are determined. In Figure 8, the view is given after the controller input and output data are transferred to the ANFIS editor in Matlab/Simulink. After data transfer to ANFIS editor is completed, for controlling of blade pitch angle of VSWPGS, triangle membership function, four linguistic variables and four iterations (trial) for training of hybrid learning algorithm and data are applied.

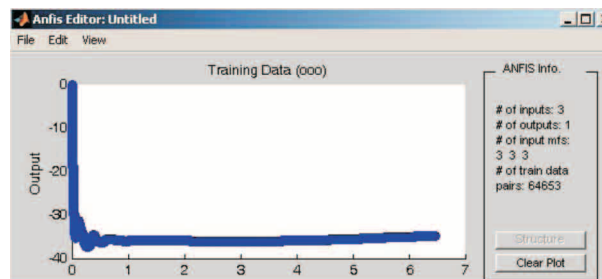


Figure 8. A view of input and output data via the ANFIS Editor. Here, blade pitch control via VSWPGS.

As a result of four iterations, the input signals at operation phase of the system are trained depending on the controller output we previously determined for the stable operational of the system. To obtain electrical magnitude values expected from VSWPGS, the desirable control output we previously determine and control output we obtain as a result of training must override. Figure 9 shows that the desired situation has performed as a result of hybrid learning algorithm.

As a result of training of data performed in ANFIS editor, Sugeno type Fuzzy Inference System having three input and one output signal is obtained automatically in Figure 10. Also, ANFIS structure for blade pitch angle control of VSWPGS is given in Figure 11.

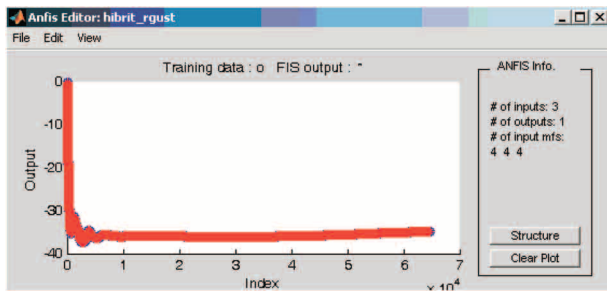


Figure 9. Final situation of output signal after hybrid learning algorithm is applied to ANFIS data base used to control the blade pitch angle.

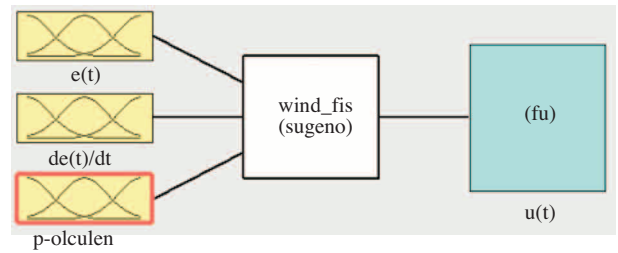


Figure 10. For VSWPGS, structure of Sugeno type Fuzzy Inference System consists of three input and one output signals.

The triangle type membership functions of inputs of this fuzzy inference system are given in below together with their value gaps. As output of Sugeno type ANFIS consists of real numbers, marking such as input signal membership function is not made. As the output variable consists of 64 real numbers, the value gap is -42.79 and $3.5 \cdot 10^{-9}$.

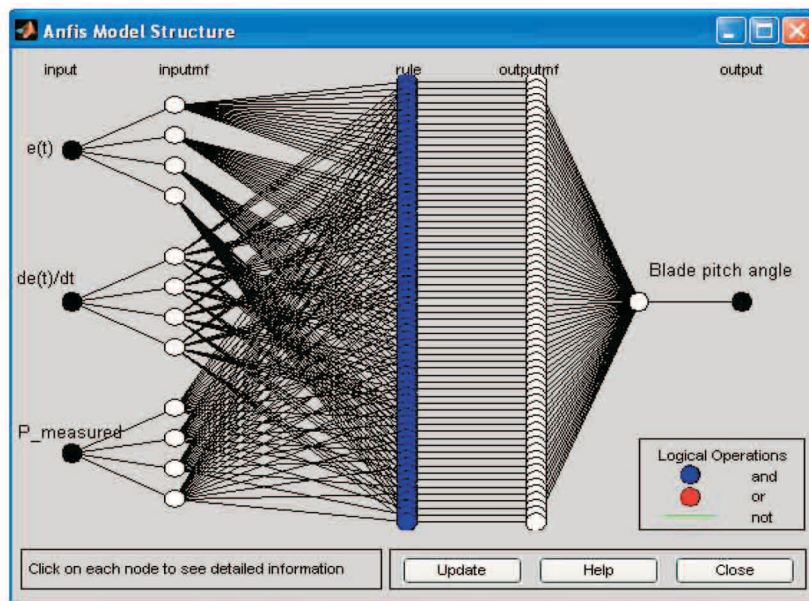


Figure 11. ANFIS structure for blade pitch angle control of VSWPGS.

Membership functions, linguistic variables and value gaps of input variables of ANFIS are given in Figure 12 and Figure 13. The rule base of obtained fuzzy inference system consists of 64 rules. The linguistic variables of error signal $[e(t)]$, one of the input variables of ANFIS, are: very large negative (VLN), large negative (LN), medium negative (MN) and negative (N). The linguistic variables of change in signal $[de(t)/dt]$, the second input variable, are: large negative (LN), medium negative (MN), medium positive (MP) and large positive (LP). The linguistic variables of the third input variable, measured power change (P measured) are: positive (P), medium positive (MP), large positive (LP) and very large positive (VLP).

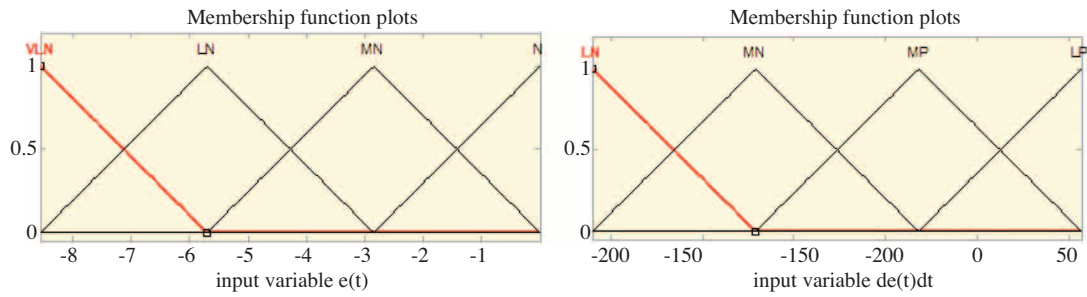


Figure 12. Membership functions and value gaps of error $[e(t)]$ and change in error $[de(t)/dt]$ of the input variables of ANFIS.

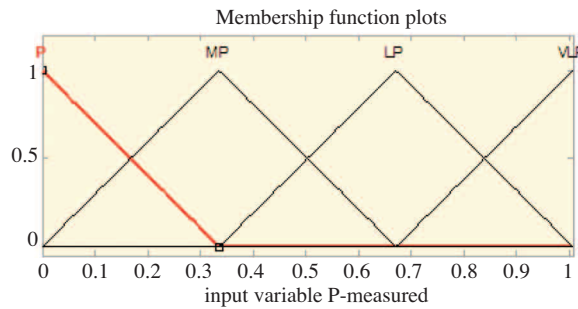


Figure 13. The membership function and value gap of the third input variable of ANFIS, the measured power change $[(P_{\text{measured}} (p.u))]$.

64 rules in the rule base of ANFIS are obtained by using a logical operator between the input and output signals of system with (**if, then**) words. The input variables of ANFIS are combined with “**and**” conjunction. 64 rules obtained through *anfisedit* software of Matlab/Simulink program, Fuzzy Logic Toolbox are given in Table 1.

7. Simulation results and discussions

In the simulation study, conventional PID controller and ANFIS are used to obtain electrical output values of VSWPGS in desirable quality and value. Controlling of blade pitch angle of variable speed wind turbine of VSWPGS is made through conventional PID controller and ANFIS. Adjustment of the wind turbine blade pitch angle depending on rotor (shaft) speed of asynchronous generator in VSWPGS is made. Because, power obtained from the wind turbine system varies depending on blade pitch angle (θ) and rated speed (λ) of wind turbine.

In simulation study, controlling of blade pitch angle of VSWPGS is performed through conventional PID controller and ANFIS, separately. Nominal operation power of VSWPGS is 300 kW and maximum loading is limited with that value. Power produced by VSWPGS is consumed by power consumers and synchronized condensers. While the power generation system meets power demand between 0–300 kW, output electrical magnitudes of the system are obtained separately as a result of the simulation study. The simulation results obtained for three individual consumer loads—120 kW, 150 kW and 180 kW—are shown in graphics. While consumer loads are fed by conventional PID controlled VSWPGS, voltage at load ends, load current, voltage

frequency at load ends, generation power of VSWPGS, power consumed by consumers and simulation results belong to consumption power of synchronized condenser are given in Figure 14, Figure 16 and Figure 18 respectively. In case ANFIS controller VSWPGS is loaded with consumer loads, the simulation results belong to changes in generation and consumption powers are given in Figures 15, 17 and 19, respectively.

Table 1. The rule table of ANFIS designed for blade pitch angle control of VSWPGS.

Rule No	IF			THEN	Rule No	IF			THEN
	e(t)	de(t)/dt	P_measured (p.u)	Controller output		e(t)	de(t)/dt	P_measured (p.u)	Controller output
1	VLN	LN	P	0	33	MN	LN	P	-12,694
2	VLN	LN	MP	0	34	MN	LN	MP	-14,266
3	VLN	LN	LP	-42,788	35	MN	LN	LP	-14,257
4	VLN	LN	VLP	-19,733	36	MN	LN	VLP	-14,207
5	VLN	MN	P	0	37	MN	MN	P	-1,411
6	VLN	MN	MP	-42,796	38	MN	MN	MP	-14,263
7	VLN	MN	LP	-42,788	39	MN	MN	LP	-14,263
8	VLN	MN	VLP	-42,788	40	MN	MN	VLP	-14,260
9	VLN	MP	P	0	41	MN	MP	P	0
10	VLN	MP	MP	-42,778	42	MN	MP	MP	-13,662
11	VLN	MP	BP	-42,789	43	MN	MP	LP	-14,263
12	VLN	MP	VLP	-42,789	44	MN	MP	VLP	-14,255
13	VLN	LP	P	0	45	MN	LP	P	0
14	VLN	LP	MP	0	46	MN	LP	MP	0
15	VLN	LP	LP	-42,789	47	MN	LP	LP	0
16	VLN	LP	VLP	-42,789	48	MN	LP	VLP	0
17	LN	LN	P	0	49	N	LN	P	0,529
18	LN	LN	MP	-28,524	50	N	LN	MP	-0,000383
19	LN	LN	LP	-28,534	51	N	LN	LP	0,00581
20	LN	LN	VLP	-28,556	52	N	LN	VLP	0,00584
21	LN	MN	P	0	53	N	MN	P	-5,8288
22	LN	MN	MP	-28,522	54	N	MN	MP	-0,0017
23	LN	MN	LP	-28,526	55	N	MN	LP	-0,0245
24	LN	MN	VLP	-28,526	56	N	MN	VLP	-0,10153
25	LN	MP	P	0	57	N	MP	P	-4,153
26	LN	MP	MP	-28,537	58	N	MP	MP	0
27	LN	MP	LP	-28,526	59	N	MP	LP	0
28	LN	MP	VLP	-28,525	60	N	MP	VLP	0
29	LN	LP	P	0	61	N	LP	P	-2,342
30	LN	LP	MP	0	62	N	LP	MP	0
31	LN	LP	LP	-28,526	63	N	LP	LP	0
32	LN	LP	VLP	-28,526	64	N	LP	VLP	0

When output electrical magnitudes of the power generation system are examined, it can be seen that the operational frequency reaches to desirable $50\text{Hz} \pm \%1 \cdot f_{isl}$ value between about 1 second and 1.5 seconds time gap. The operational frequency acceptable for Turkey is (f_{isl}) 50 Hz. The value of

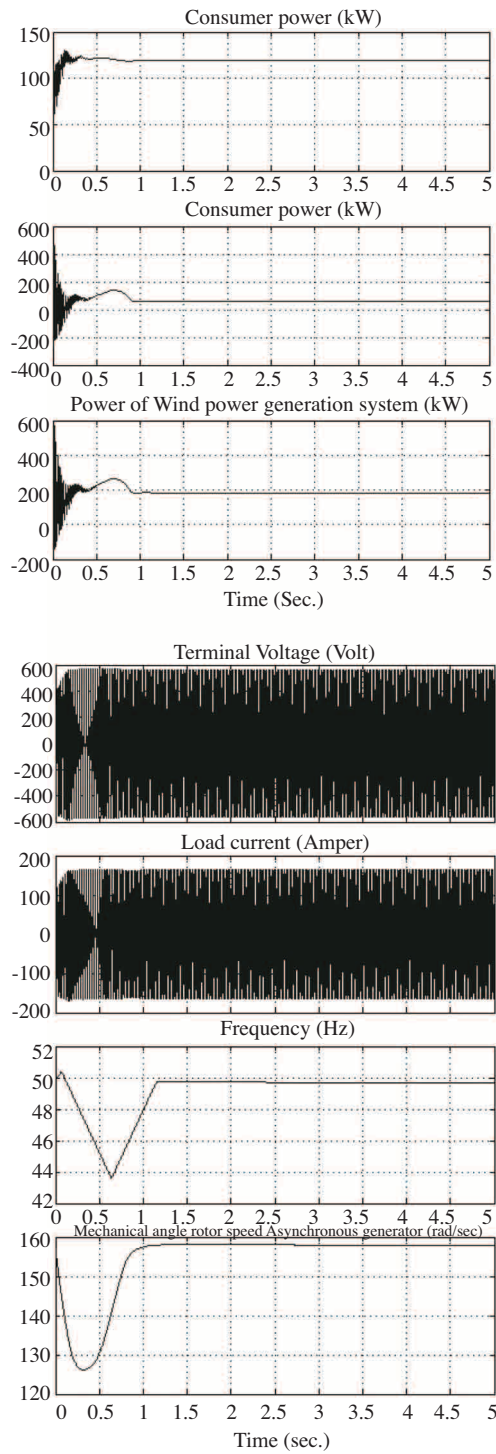


Figure 14. Changing curves in electrical output magnitudes of conventional PID controlled VSWPGS when it is loaded with 120 kW consumer load.

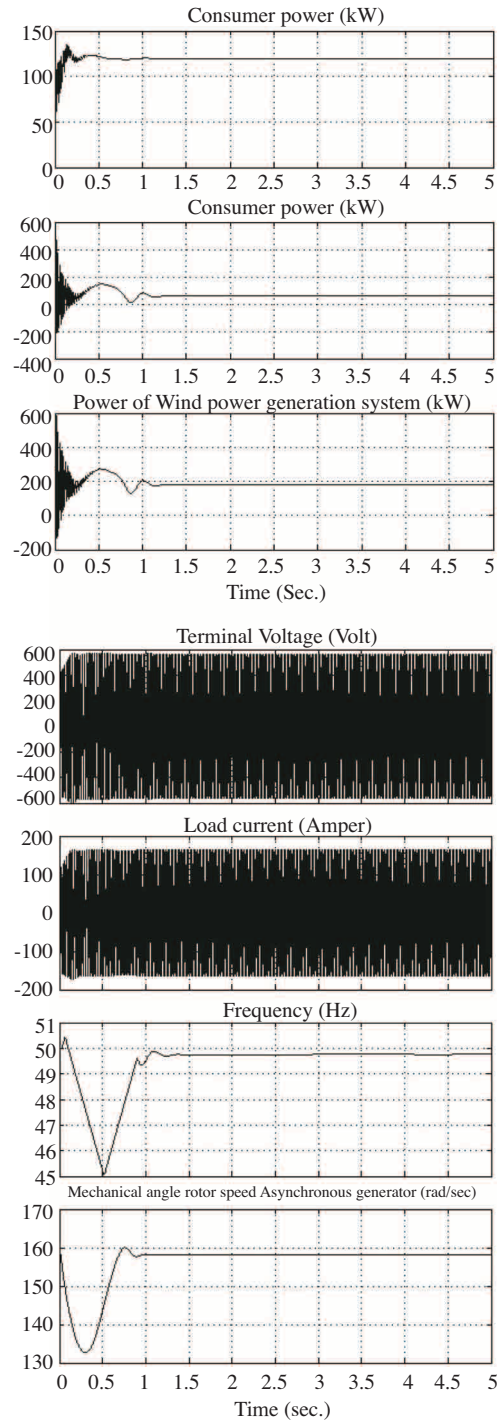


Figure 15. Changing curves in electrical output magnitudes of ANFIS controlled VSWPGS when it is loaded with 120 kW consumer load.

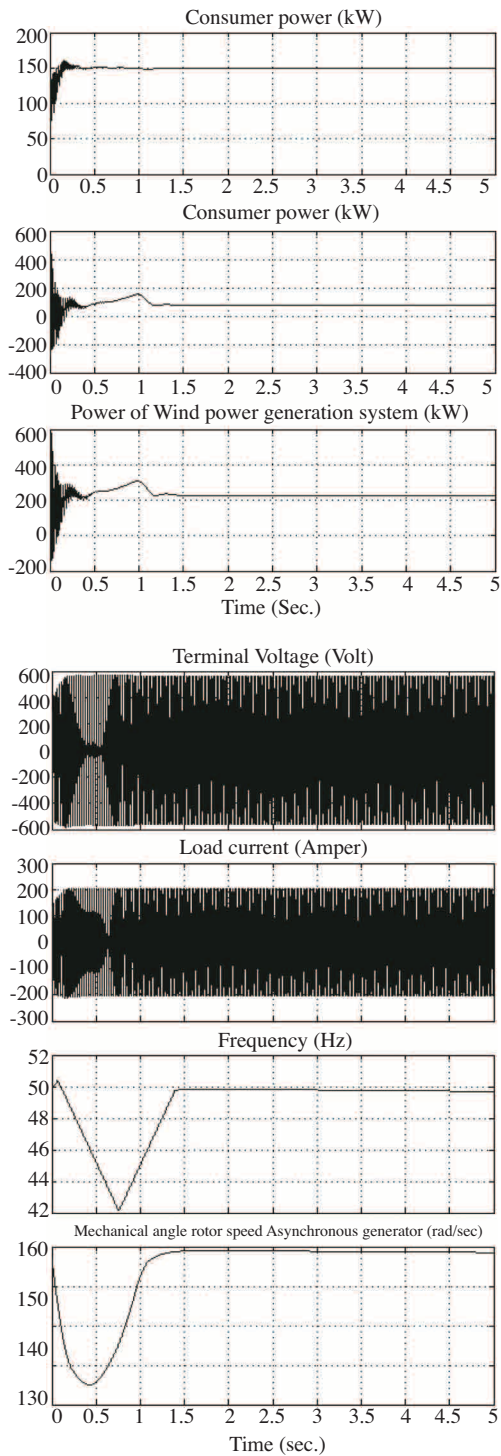


Figure 16. Changing curves in electrical output magnitudes of conventional PID controlled VSWPGS when it is loaded with 150 kW consumer load.

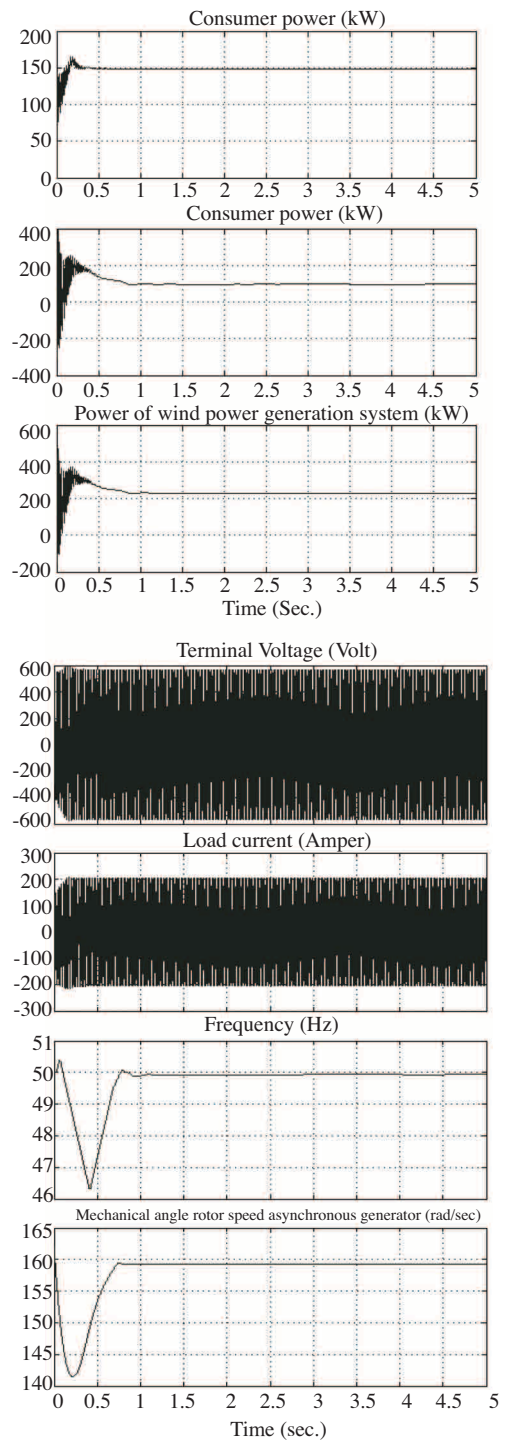


Figure 17. Changing curves in electrical output magnitudes of ANFIS controlled VSWPGS when it is loaded with 150 kW consumer load.

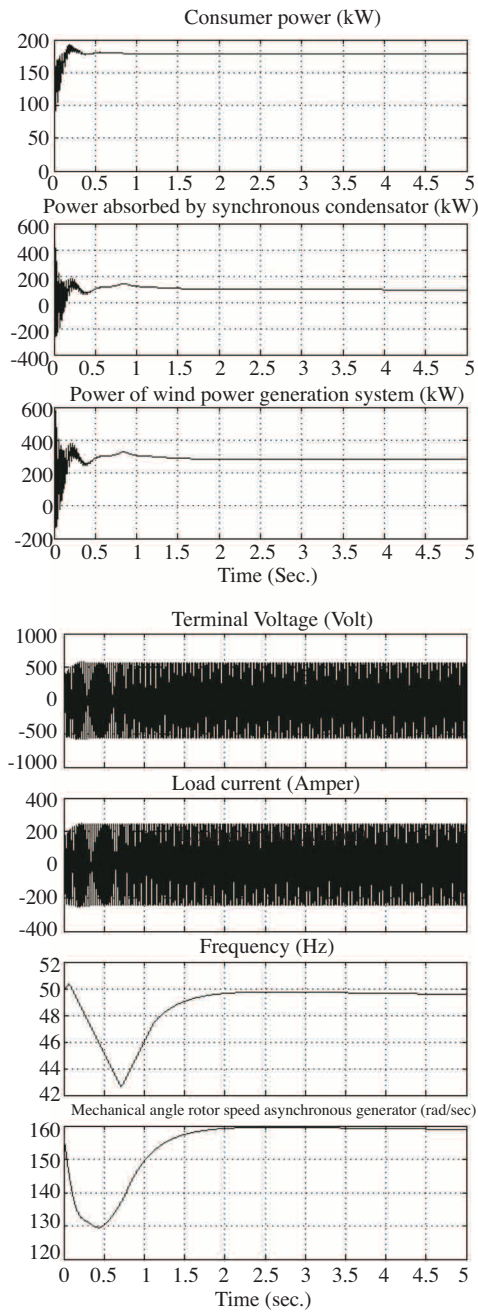


Figure 18. Changing curves in electrical output magnitudes of conventional PID controlled VSWPGS when it is loaded with 180 kW consumer load.

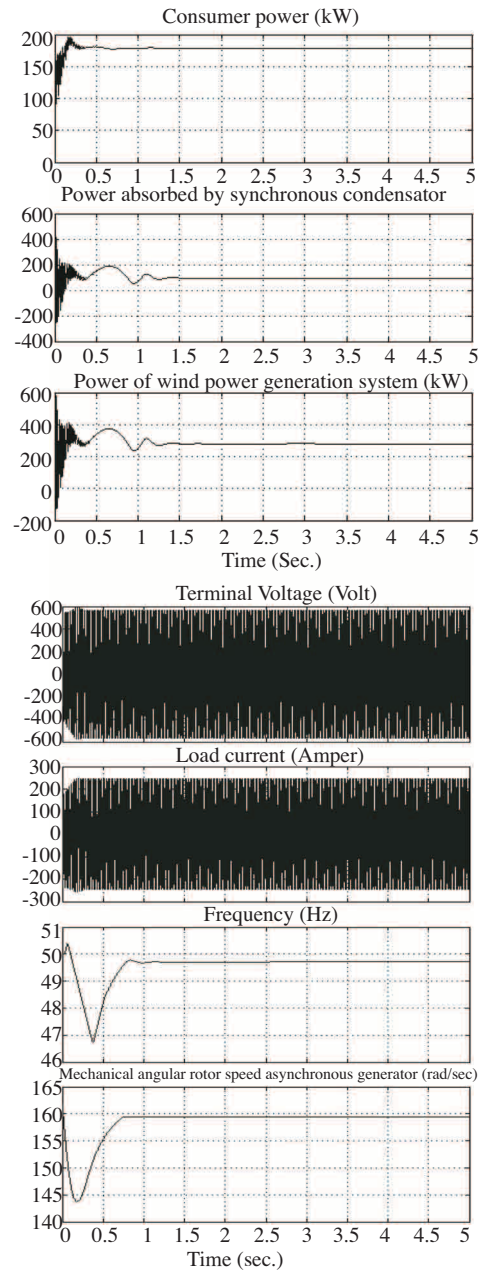


Figure 19. Changing curves in electrical output magnitudes of ANFIS controlled VSWPGS when it is loaded with 180 kW consumer load.

voltage obtained in the simulation study is maximum (peak) value. Nominal voltage value is 400 volt. The maximum value of this voltage is obtained from the simulation study as $U_{\max} = U \cdot \sqrt{2} = 400 \times \sqrt{2} = 565 \text{ V}$. When the induced voltage value is in its maximum value, accordingly, the drawn current will be in its maximum value. If we examine the output electrical magnitudes of VSWPGS on the said simulation curves, we can see

that they reach to stable operation situation in desirable values within 1–2 seconds. If continuous situation error in the power generation systems is close to zero within the said short time, we can say that the operation has the best operating performance.

The gain coefficients (K_P , K_I ve K_D) of conventional PID controller used in the study are readjusted in every changing load phase to keep voltage at 565 V and frequency in 50 Hz. The adjustment of gain coefficients is performed with trial method. If we consider the conventional PID controller for a single operation point, we can say that it is a very good controller. However, as it is difficult to readjust the gain parameters of the conventional PID controller in cases of different load or operation situations, an advance level controller that automatically adjusts gain coefficients is developed. For instance; with Fuzzy-PID controller and Neuro-Fuzzy-PID controller, the gain parameters of PID controller can be automatically adjusted within operation condition determined adaptively.

The output voltage and frequency in variable speed wind power generation system changes depending on wind speed. Meanwhile, generation power of the system also depends on changes in wind speed. However, in order consumers can be fed with high quality electric energy, the produced power must be in desirable performance. In case of changing load situations or changing wind speeds, terminal voltage and frequency of VSWPGS must be within permitted tolerances. For this purpose, ANFIS is designed for VSWPGS. When VSWPGS is controlled with conventional PID controller and ANFIS separately, very big differences between the simulation results occur. However, gain parameters of conventional PID controller must be readjusted in every changing load situation of VSWPGS. To eliminate that disadvantage of conventional PID controller and to ensure controlling of variable speed wind turbine blade pitch angle between the upper and bottom limit loading situations determined adaptively, ANFIS is used.

The data obtained from the simulation study are used to train and verify the proposed ANFIS model. The training data set is used to train the ANFIS, whereas the testing data set is used to verify the accuracy and effectiveness of the trained ANFIS model for the blade pitch angle control of VSWPGS. The error values between the data obtained from the simulation study and the desired data are defined as

$$\varepsilon = \frac{1}{D} \sum_{k=1}^D \frac{p_a(k) - p_e(k)}{p_a(k)} \cdot 100\%, \quad (8)$$

where p_a and p_e refer to the data obtained from the simulation study and the desired data from the trained ANFIS model, respectively, D is the number of training data. The average percentage errors (APEs) for both the training data set and the testing data set are calculated. All APEs of the proposed ANFIS model for the blade pitch angle control of VSWPGS are within 0.0279%. As expected, the proposed ANFIS model provides highly accurate estimation of the blade pitch angle for the different operation situations of VSWPGS.

In the study, the blade pitch angle of VSWPGS is controlled with ANFIS and output voltage and frequency of the system is tried to be kept within determined tolerance limits. The turbine blade pitch angle is adaptively adjusted with ANFIS depending on changing consumer load situations under the determined operational conditions of VSWPGS. In this study, controlling of turbine blade pitch angle between 40kW and 180kW consumer load values is automatically performed with ANFIS. As it can be seen in Figures 15, 17 and 19, frequency of terminal voltage and other electrical output magnitudes reach to desirable operational value within as 1 second. When the simulation results are assessed in respect to operational performance of VSWPGS, electrical output values of the system are within the permitted tolerance values. Besides, the simulation results

show that the desired value is obtained within a short time without subjecting to excessive voltage and frequency oscillations that may negatively affect consumers.

8. Conclusions

For terminal voltage and frequency control of the variable speed wind power generation system, ANFIS is designed and is used in simulation block diagram of VSWPGS under the Matlab/Simulink program. To obtain high quality power from the wind power generation system (VSWPGS), the effective value of output voltage must be at 400 volt and frequency in 50 Hz operational limit values. For this purpose, power limitation or speed control of the variable speed wind turbine is performed by means of controlling of turbine blade pitch angle. For controlling of blade pitch angle, the conventional PID controller and ANFIS are used separately. As a result of controlling of the wind turbine blade pitch angle, it is determined from the simulation results that the output electrical magnitudes of VSWPGS (voltage, current, frequency and power) reach to desirable values within 1.5 seconds. When the simulation results are examined, it is observed that continuous situation error is close to zero in continuous operation. However, as the load of consumers fed from VSWPGS differs in every hour of a day, coefficients of the conventional PID controller must be readjusted depending on changing load situations. For this reason, in case of changing consumer load situations, the turbine blade pitch angle is adaptively adjusted to keep the terminal voltage and frequency within permitted tolerance values.

When simulation curves of electrical output magnitudes obtained as a result of controlling of blade pitch angle of VSWPGS with ANFIS are examined, it is seen that operational performance of the system is within a very good value. Meanwhile, no problem about compatibility of ANFIS with VSWPGS has been experienced. In contrary, electrical output magnitudes in desirable quality and output have been obtained.

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