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Adaptive neuro-fuzzy inference system to improve the power quality of a split shaft microturbine power generation system

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ABSTRACT

This article presents design of adaptive neuro-fuzzy inference system (ANFIS) for the turbine speed control for purpose of improving the power quality of the power production system of a split shaft microturbine. To improve the operation performance of the microturbine power generation system (MTPGS) and to obtain the electrical output magnitudes in desired quality and value (terminal voltage, operation frequency, power drawn by consumer and production power), a controller depended on adaptive neuro-fuzzy inference system was designed. The MTPGS consists of the microturbine speed controller, a split shaft microturbine, cylindrical pole synchronous generator, excitation circuit and voltage regulator. Modeling of dynamic behavior of synchronous generator driver with a turbine and split shaft turbine was realized by using the Matlab/Simulink and SimPowerSystems in it. It is observed from the simulation results that with the microturbine speed control made with ANFIS, when the MTPGS is operated under various loading situations, the terminal voltage and frequency values of the system can be settled in desired operation values in a very short time without significant oscillation and electrical production power in desired quality can be obtained.

1. Introduction

Consumers want an economical and uninterrupted electric power. It is crucial to the industrial consumers and wholesalers who have to pay the penalty for a blackout, if power is disconnected for any reason. Recently, distributed generation (DG) has become an attractive method of providing electricity to consumers and retailers. In addition, from the viewpoint of economic feasibility, the costs of installing the generators and producing the electricity can be comparatively inexpensive using the DG method. Furthermore, electrical or thermal efficiency can also be improved if the utilities use co-generation or a combined heat cycle [1–3].

Gas turbines for distributed generation applications are an established technology in sizes from several hundred kilowatts up to about 300 MW. Gas turbines produce high-quality heat that can be used to generate steam for on-site use or for additional power generation (combined-cycle configuration) [1,4,5]. Gas turbines can be set up to burn natural gas, a variety of petroleum fuels or can have a dual-fuel configuration. Gas turbine emissions can be controlled to very low levels using water or steam injection, advanced dry combustion techniques, or exhaust treatment such as selective catalytic reduction (SCR). Maintenance costs per unit of power output are among the lowest of DG technology options. Low maintenance and high-quality waste heat make gas turbines an excellent match for industrial or commercial combined heat and power (CHP) applications larger than 5 MW [3]. Technical and economic improvements in small turbine technology are pushing the economic range into smaller sizes as well.

Microturbines are very small combustion turbines that are currently offered in a size range of 30–400 kW [5–8]. Microturbine technology has evolved from the technology used in automotive and truck turbochargers and auxiliary power units for airplanes and tanks. Several companies have developed commercial microturbine products and are in the early stages of market entry. A number of other competitors are developing systems and planning to enter the market within the next few years. In the typical configuration, the turbine shaft, spinning at up to 100,000 rpm, drives a high-speed generator. The generator's high-frequency output is converted to the 60 Hz power used by power electronic controls.

Microturbines are well suited for a variety of distributed generation applications due to their flexibility in connection methods, ability to be stacked in parallel to serve larger loads, ability to provide reliable power, and low-emissions profile. Potential applications for microturbines in power-only configuration include peak shaving, certain base load applications such as premium and remote power, and grid support [9–11].

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Microturbines generally have marginally lower electrical efficiencies (33–37%) than similarly sized reciprocating engine generators [7,12]. However, because of their design simplicity and relatively few moving parts, microturbines have the potential for simpler installation, higher reliability, reduced noise and vibration, lower maintenance requirements, and possibly lower capital costs compared to reciprocating engines [13].

The micro gas turbines used in power production plants are produced in two types; single-shaft and split-shaft. In single-shaft power production systems, the single expanding turbine moves the compressor and generator together. Such turbines can be both operated in high speeds and produce electric power in high frequency values. In a split-shaft model, one shaft drives the compressor and the other shaft drives the power turbine that is connected to the AC generator by means of a gear mechanism [8]. As the single-shaft gas turbines produce high frequency AC voltage; there must be an interface between the micro gas turbine power production system and load.

The control techniques for DG systems are designed depending on the situations whether they are connected to the network. Studies on dynamic performance of micro gas turbines under various operation conditions were made. In [14], a study was carried out to reduce the load and line current imbalance for operating the DG systems. A seamless transfer scheme for MTG system operation between grid-connected and intentional islanding mode was presented in [9]. The modeling of a single-shaft microturbine generation system suitable for power management in DG applications is considered in [13]. The model is good for both power only and CHP applications. In [15], multi objective genetic algorithm were analyzed as an alternative solution to the optimization problem for generating the switching pattern used to control three-phase PWM (pulse width modulation) inverter in microturbines.

The output voltage and frequency of power production systems that have different raw energy kinds must be adjusted to determined operation values. After the output voltage and frequency values of each power component are adjusted to the determined operation values (terminal voltage and frequency), interconnected connection may be realized. This desired voltage and frequency adjustment is realized with the AC–DC–AC power converter power electronic circuit elements. Besides, to realize the connection of MTPGS to the network or consumer, a power electronic converter interface is required. During realization of the power electronic interface circuit, MTPGS must be controlled according to any output variables (voltage, frequency, active and reactive power) or to the determined reference value of more variables. When MTPGS is connected to the distribution network, the reply of system in temporary situation, its stability, power quality, voltage and frequency regulation must be analyzed. For the control and analysis procedures, the detailed non-linear dynamic model of MTPGS is used. In ref. [2], the dynamic model of system and its power electronic converter interface control to ensure better performance of MTG (the microturbine generation) under various network operation conditions are presented. In ref. [16], the power electronic converter interface modeling for connection of MTG to the network for purpose of realizing bidirectional power flow between the MTG and network is presented. In this study, a PWM, depended on current control and the DC voltage control for the converter on network side were used. In ref. [17], with control of the wing inclination angle of the wind turbine within the tolerance limits determined by ANFIS, the variable speed wind has approached the power quality of power production system to the desired values.

In the study, to observe the dynamic behavior of MTPGS, the simulation block diagram of system components was realized by using the MATLAB/Simulink program and SimPowerSystems in it. In this study, a split-shaft model is used to determine the dynamic behavior of a microturbine. In ref. [8], the authors used the GAST model without speed control to simulate the split-shaft microturbine. The GAST model, which is developed by general electric (GE), is one of the most commonly used model to simulate gas turbines. If the terminal voltage and frequency of the system is tried to be preserved within desired or permitted tolerance limits in MTPGS, a stabile study can be realized. Under continuous operation status of MTPGS, for operation at desired electrical magnitudes (frequency, voltage and power), there exist two basic control unit. One of them is the gas turbine speed control and the second is the excitation circuit voltage control. In this study, the excitation circuit voltage is kept constant and for speed control of the gas turbine, conventional PID controller and adaptive neuro fuzzy inference system (ANFIS) are used. With the simulation study, it has been observed that the operation frequency of MTPGS and as well as oscillations in terminal voltage and the produced active power are within desired values in case the gas turbine speed control is made with ANFIS.

2. Microturbine power production system and its components

The microturbines used in power production plants are produced in two types: a single shaft machine and a split-shaft machine. In single-shaft microturbine systems, single extension turbine moves the compressor and generator together. Such turbines can be operated in high speeds and besides, they produce electric power in high frequency values of 1500–4000 Hz. In split-shaft model, one shaft drives the compressor and other shaft moves the power turbine connected to the AC generator by means of a gear box [8]. As single-shaft microturbines produce high frequency AC voltage, the microturbine power production system is connected to the load or network on AC–DC–AC power converter. In split-shaft microturbine power system, power converter is not required.

As it is seen in Fig. 1, a split-shaft micro gas turbine consists of air compression chamber and power turbine that drives the load and combustible matters [18–21]. As the cost of plant is low, the unit cost of produced energy is also low. As it is not convenient for continuous operation status, it is generally used when the power demand is high. They are mostly preferred because of the advantages of they do not have a complex structure in contrast to other diesel and steam power stations, their sizes are small and the cooling water problem is very less. The energy carrier in microturbines is the heat gas. Air is taken by means of the compressor and compressed in the combustion chamber. The gas heated with combustion of fuel in the combustion chamber gives its energy to the turbine. Then, it drives the generator to produce electric energy by means of power turbine.

The micro gas turbines can be operated in a manner connected to the electric network or in isolated manner from the network. In our study, the generator used to produce electric energy from the micro gas turbine power production system is the cylindrical pole synchronous generator. The synchronous generator is driven with gas turbine. To connect the MTPGS to the network or load, the output voltage and frequency values are adjusted to the determined operation values (voltage and frequency values of the network or load) and so, interconnected connection is realized. The power electronic interface (AC–DC–AC power convertor) required for connection of single-shaft MTPGS to the network or load is an important component. For connection of MTPGS to the desired network, power converters in various features were used. Some of these power converters are matrix converter [22], cycle-converter [23], and passive inverter and rectifier [24]. During realization of the power electronic interface circuit, MTPGS must be controlled according to any output variables (voltage, frequency, active and reactive power) or to the determined reference value of more variables.

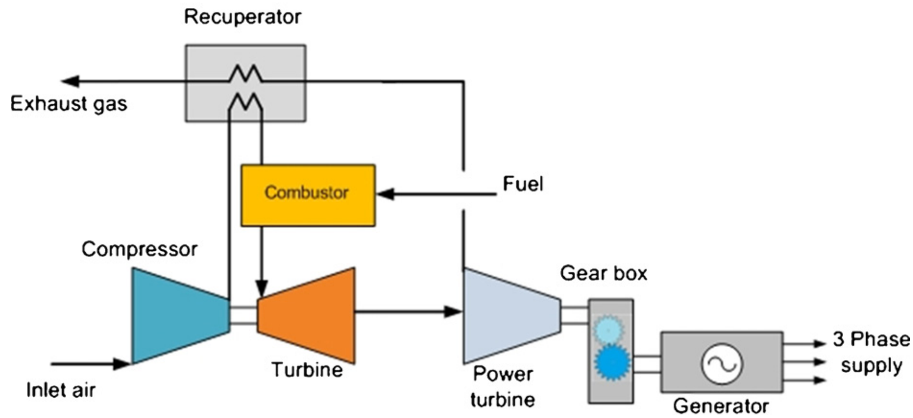

Fig. 1. Blok diagram of the split-shaft MTG system.

To connect the single-shaft MTPGS to the load or network, the AD–DC–Ac power converter consists of power electronic circuit elements as shown in Fig. 2 is used. The output voltage of system obtained from MTPGS is converted to DC power with rectifiers consist of six bridge connected diodes. Then, with IGBT inverter, the DC output power is converted to the AC power. Control of IGBT inverter is ensured with control of output voltage. Meanwhile, by using the current control and voltage control cycles together, power control cycle is realized. The AC–DC–AC power convertor is an important component that ensures desired voltage and frequency values (50 Hz–400 V) required for connection of the MTPGS to the load or network. If MTPGS is connected to the load or network in parallel, its control is ensured with controllers compatible with the system to keep the desired voltage and frequency values. Harmonics produced with IGBT inverter are filtered with LCL filter.

3. Modeling of the split-shaft microturbine power generation system for

3.1. Speed control

MTPGS consists of microturbine speed control, a split-shaft microturbine, cylindrical pole synchronous generator, and excitation circuit and voltage regulator. The block diagram of dynamic model related to the MTPGS is shown in Fig. 3.

A detailed split-shaft microturbine block diagram with a speed governor and a synchronous machine is shown in Fig. 4. The control block includes the speed control, the temperature control, the acceleration control, and the upper and lower fuel limits. The governor controls can be modified to either droop governor by adjusting the given parameters *W*, *X*, *Y* and *Z*. The signals for the speed governor are compared with the reference per unit signal and the speed per unit deviation as measured from synchronous machine block. To produce a fuel demands signal, V_{ce}, a low value select block compares signals coming from the speed governor and the temperature control.

In this study, a split-shaft model is used to simulate the microturbine. The model details and parameters are shown in Fig. 5 and Table 1, respectively [18,25]. In the split-shaft design, although there are two turbines, one is a gasifier turbine driving a compressor and another is a free power turbine driving a generator at a rotating speed; there is only one combustor and one gasifier compressor. This is largely different from the twin-shaft combustion-turbine, which has two combustors and two compressors [26]. So, it is more suitable to model this split-shaft turbine as a simple cycle, single-shaft gas turbine.

3.2. Simplified synchronous generator model

The simplified synchronous machine block models both the electrical and mechanical characteristics of a simple synchronous

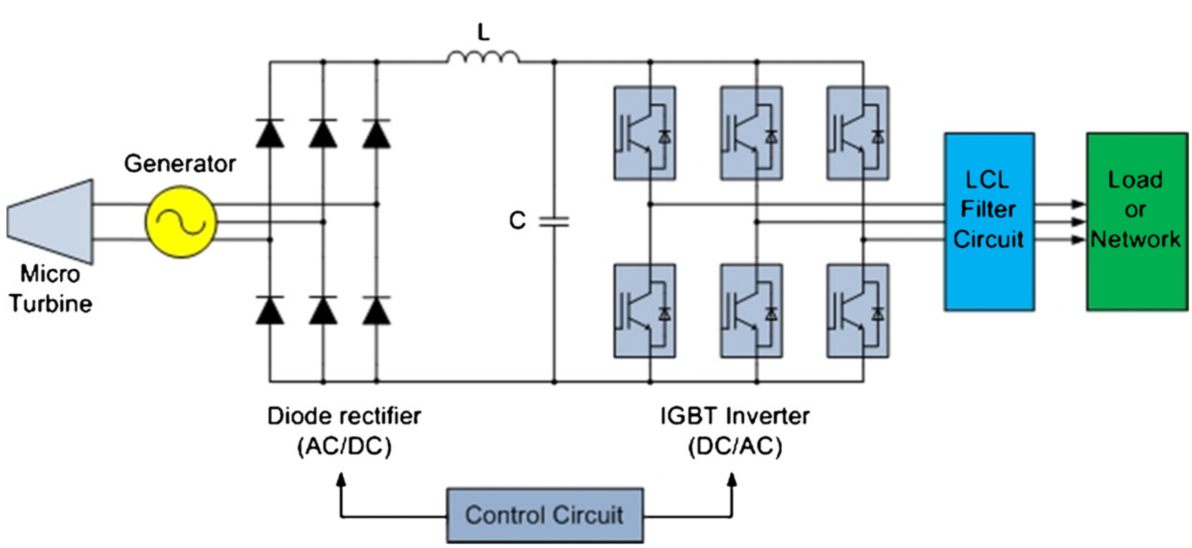

Fig. 2. MTPGS with AC–DC–AC power convertor.

Table 1
The split-shaft microturbine model parameters.

Parameter	Value
Rated power ($P_{rated\text{-}MT}$)	250 kW
Real power reference (P_{ref})	1.0 p.u.
Turbine damping ($D_{turbine}$)	0.03
Fuel system lag time constant (T_1)	10.0 s
Fuel system lag time constant (T_2)	0.1 s
Load limit time constant (T_3)	3.0 s
Load limit (L_{max})	1.2
Maximum value position (V_{max})	1.2
Minimum value position (V_{min})	−0.1
Temperature control loop gain (K_T)	1.0
Power control proportional gain (K_F)	0.1
Power control integral gain (K_i)	0.1
Speed control proportional gain (K_S)	1000
Speed control integral gain (K_k)	12.5
Speed reference (ω_{ref})	1.0

machine. The simplified synchronous machine block implements the mechanical system described by

$$\frac{2H}{\omega_b}\frac{d}{dt}(\omega_r) = p_T - P_e - D\omega_r \qquad (1)$$

$$\Delta\omega_r(t) = \frac{1}{2H}\int_0^t (P_T - P_e)dt - D\Delta\omega_r(t) \qquad (2)$$

Where H is an inertia time constant for a synchronous machine $\Delta\omega_r$, speed variation with respect to speed of operation; ω_b, a rated speed for a synchronous machine; ω_r, a rotor speed for a synchronous machine; P_T, a mechanical power input; P_e, an electrical power; D, damping coefficient.

In the simple model for a synchronous machine, P_T and P_e are assumed to be constant. All of the parameters are per unit systems. To simulate the synchronous machine, the authors used a

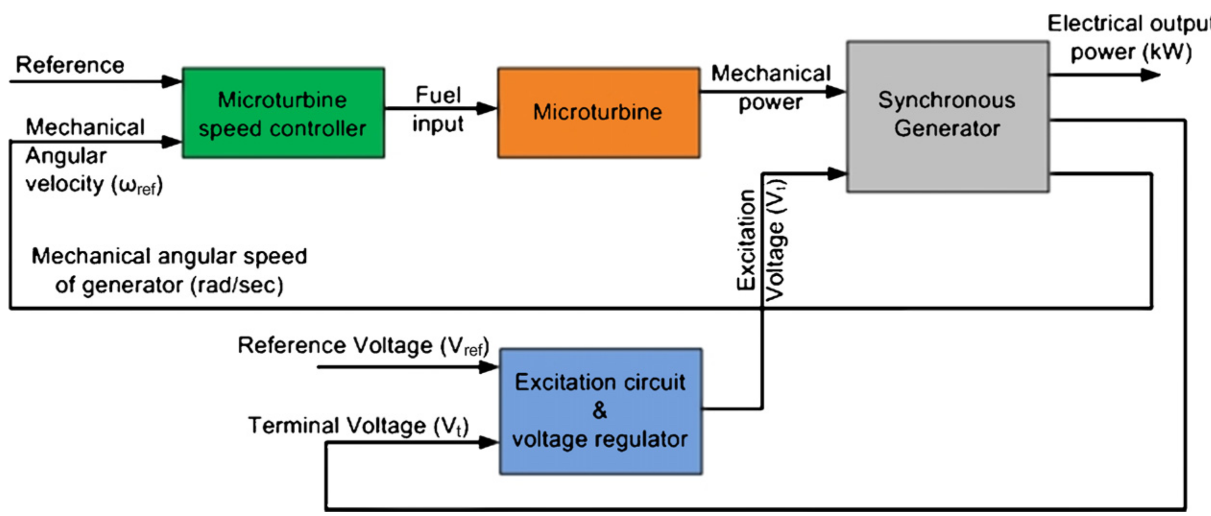

Fig. 3. The block diagram of dynamic model related to the micro turbine power production system.

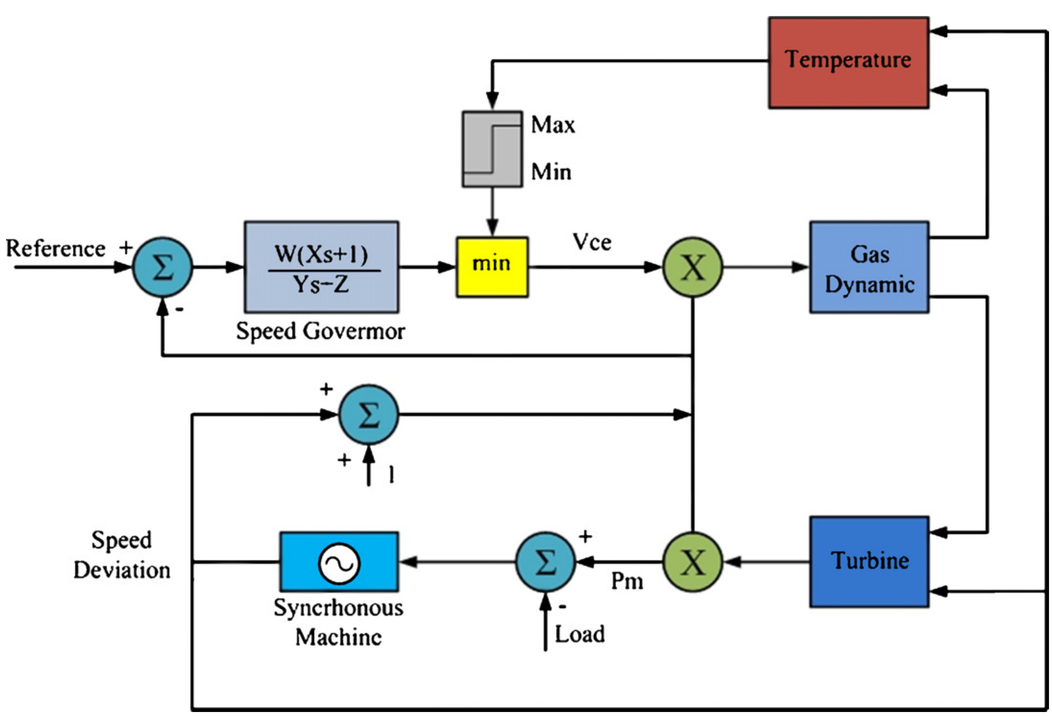

Fig. 4. The detailed block diagram for microturbine, speed governor, and synchronous machine.

Table 2
Synchronous machine model parameters for microturbine.

Parameter	Value
Rated power	250 kW
Rated line to line voltage	400 V
Frequency	50 Hz
Inertia constant (H)	0.1753
Friction factor	0.0157

predefined model existed in SimPowerSystems of the MATLAB software [27]. The model parameters are as shown in Table 2.

4. Simulation model for speed control of a split shaft microturbine power generation system

To ensure parallel operation of the MTPGS with other network or power production systems or to improve its power quality, its terminal voltage and frequency must be adjusted and maintained within the determined operation values. After the output voltage and frequency of each power production system is adjusted to determined values, interconnected connection can be realized between them. In this manner, electrical power in desired value is provided to consumers of MTPGS. In Fig. 6, the simulation block diagram of MTPGS realized with SimPowerSystems program included in the Matlab program is shown.

MTPGS' microturbine consists of cylindrical pole synchronous generator, excitation circuit, connection bars, load, switched load, frequency control unit, ampere meter, voltmeter and display showing electrical magnitudes. The detailed simulation block diagram of MTPGS given in Fig. 6 is shown in Fig. 7.

The detailed simulation block diagram of microturbine and excitation circuit included in MTPGS given in Fig. 7 is shown in Fig. 8.

4.1. Frequency control and dump load

Frequency of terminal voltage in the microturbine power production system is controlled with a frequency controller against the load changes externally form the speed control. As the frequency value changes depending on the rotor speed, no excessive fluctuation is seen in frequency when this controller is not used. Because, as the microturbine speed is under control with ANFIS, system frequency will also be put under control. However, to keep stability of the operation frequency of the system against to load changes by using a second controller, a frequency control unit is used.

The input of frequency controller is expressed with frequency of the input terminal. To measure the frequency of terminal input in MTGPS, the three-phase phase-switched cycle (PLL) included in SimPowerSystems is used. To obtain the frequency error of the system, by comparing the measured frequency value to the reference frequency value, the frequency error is obtained. The obtained error signal is integrated by being applied to discrete time integral element to obtain the phase. Then, the PD controller takes the derivative of the error signal.

As it is seen from Fig. 9, signal obtained from the PD controller is converted to 8-bit signal. Depending on the load situation, signals are sent to the dump loads. The output of the frequency control unit determines the desired lump load power. The dump load consists of parallel connection of 8 numbers 3-phase resistance to GTO (Gate-Turn-off) switches. The dump load operates according to the 8 bit binary number system. Each phase is controller with 8 switches. Consequently, there exists $2^8 = 256$ switching possibility. As a result of each switching possibility, load resistances have different values.

Operation principle of frequency control; the produced external load command signals are transmitted to the decoder. Pals decoder has one input signal, eight bit output signal and 256 different possibilities. The eight bit signal sampling goes to the signal block and that block produces 3-phase pals signals. Depending on the produced pals control signal, external resistances enter into/exit from circuit with switching (GTO) and so, the frequency of system is kept at desired (50 Hz) value. Dump loads are widely used in voltage and frequency control of power production systems in isolated manner from network or energy distribution systems.

5. Control strategy to improve the power quality of MTPGS

Microturbines are generally equipped with controls that allow the unit to be operated either in parallel with or independent of the grid, and they incorporate many of the grid- and system protection features required for interconnect. The controls usually also allow for remote monitoring and operation. Electronic components control all of the engine/generator operating and start-up functions. Power electronic converters can be operated with different control strategies in the grid, depending upon the operation mode of the microturbine units.

In the single-shaft microturbine operation, the high frequency AC is rectified to DC, inverted back to 60 or 50 Hz AC, and then

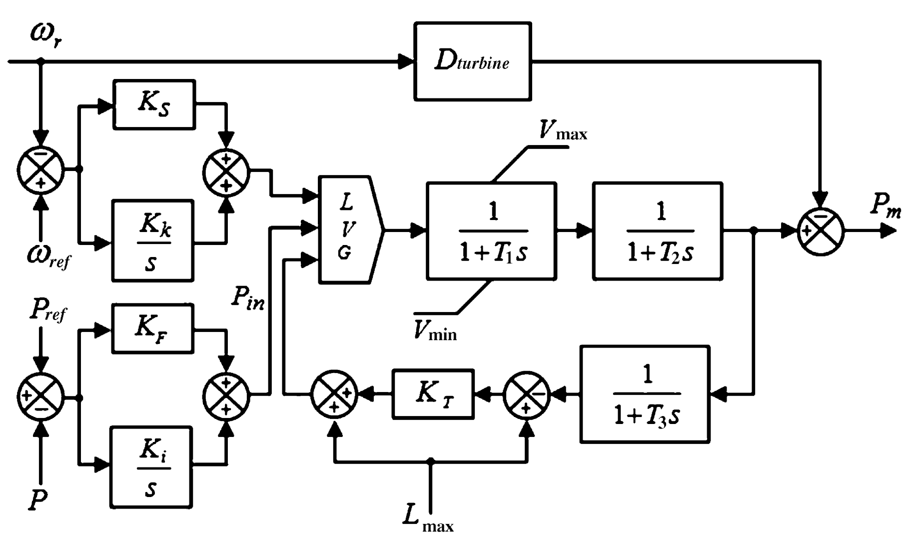

Fig. 5. A split-shaft microturbine system block diagram with speed and power control.

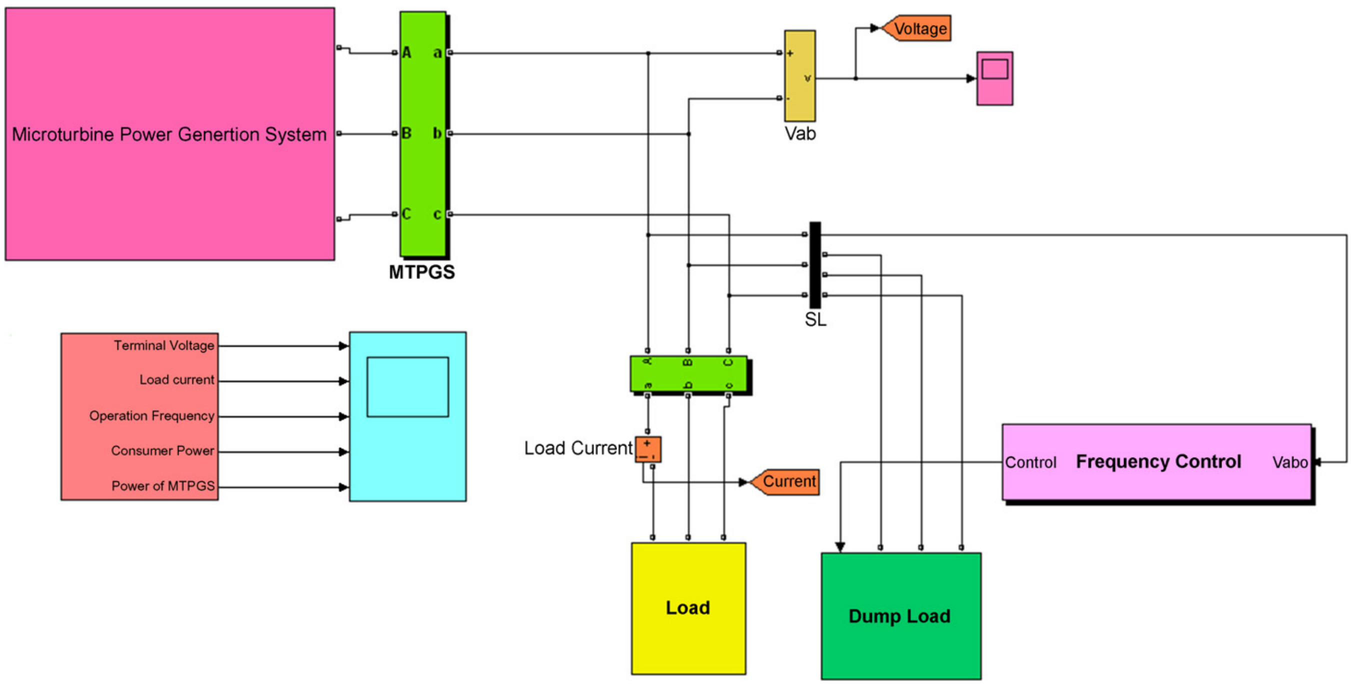

Fig. 6. Block diagram of a split-shaft microturbine power generation system.

filtered to reduce harmonic distortion. Power electronics are a critical component in the single-shaft microturbine design and represent significant design challenges, specifically in matching turbine output to the required load. Also, for the grid-connected mode of operation of a MTG, power electronic converters can adopt either an active and reactive power control scheme or control of active power and voltage [28,29].

Despite significant advances in the field of control systems engineering, proportional integral derivative (PID) controller is still the most common control algorithm for industrial applications used today. In the MTG system, the control block includes the speed control, the temperature control, the acceleration control, and the upper and lower fuel limits [30]. The output of these control function blocks are the inputs to a least value gate (LVG), whose output is the lowest of the three inputs and results in the least amount of fuel to the compressor-turbine.

Speed and acceleration control: Speed control operates on speed error between reference speed and micro gas turbine system machine rotor speed; control block used generally lead-lag transfer function or PID control. There are two types of work modes for lead-lag control: slope control mode and synchronous control mode. In this paper, slope control mode is used, which input signal is speed error between reference speed and rotor speed. Acceleration control is used primarily during turbine startup to

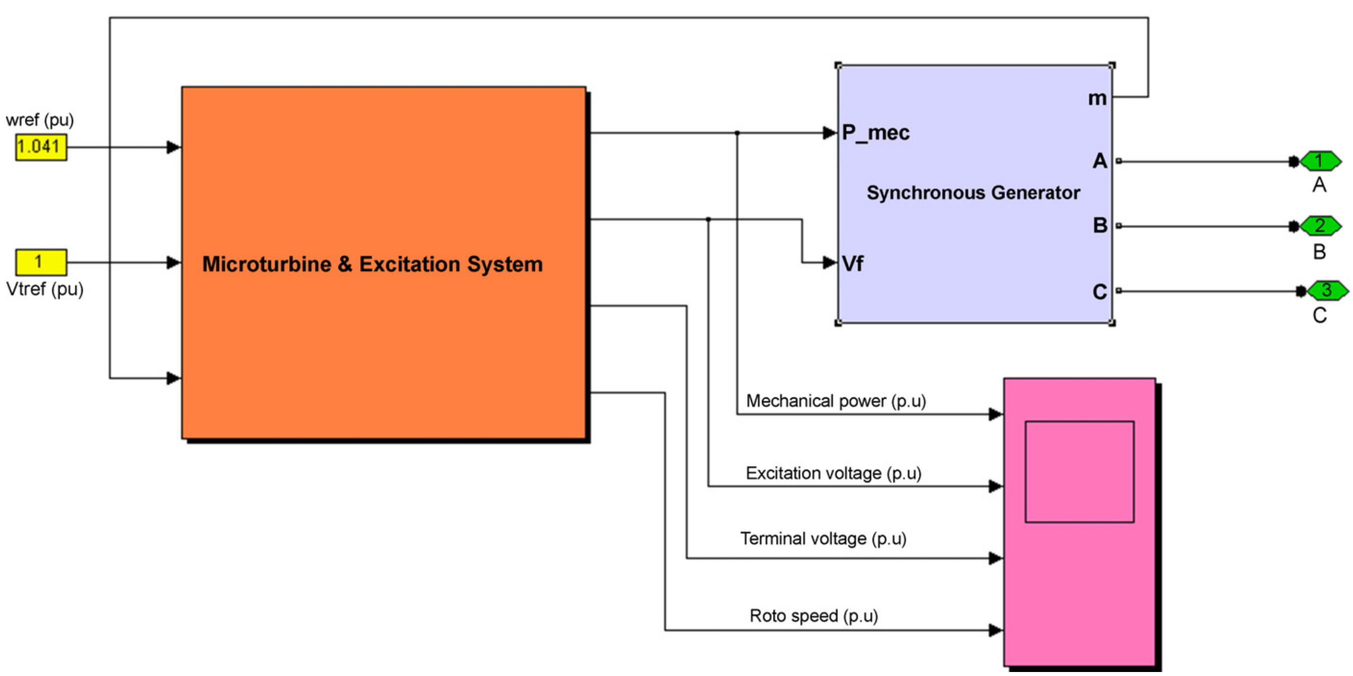

Fig. 7. Simulation block diagram of MTPGS including microturbine, excitation circuit and synchronous generator.

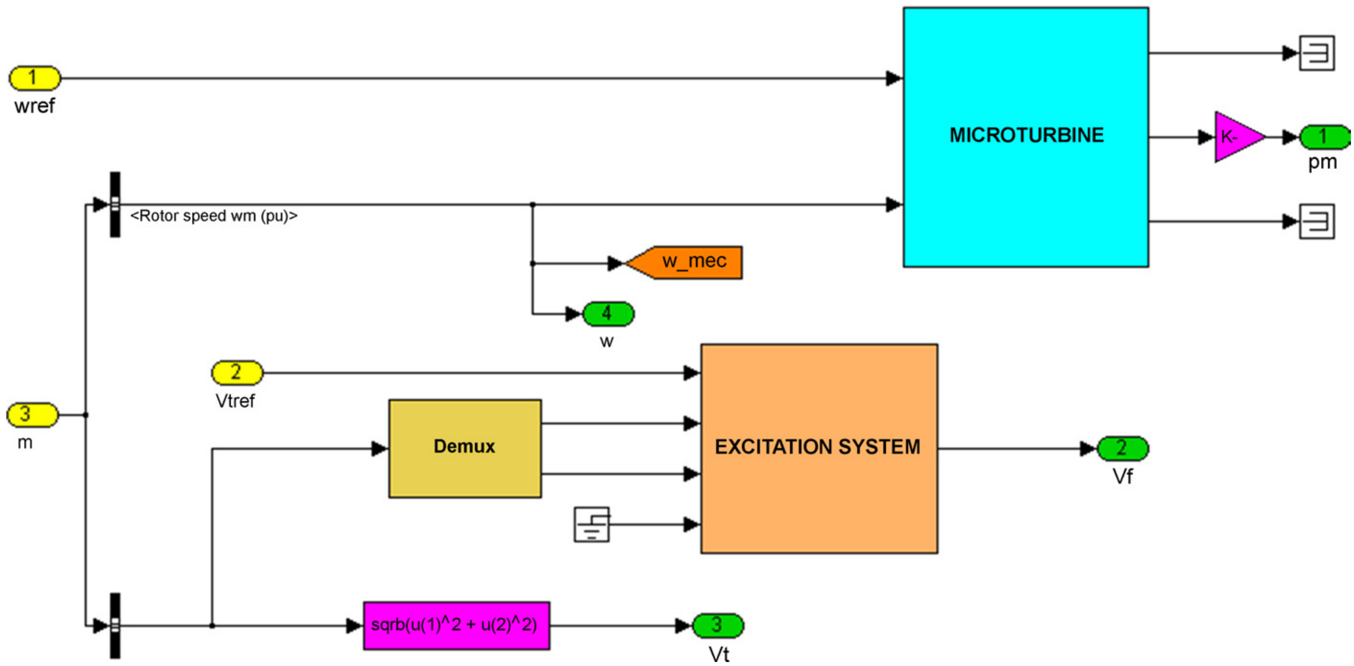

Fig. 8. The detailed simulation block diagram of microturbine and excitation circuit of MTPGS.

limit the rate of the rotor acceleration prior to reaching operating speed.

Temperature control system limits output power of turbine which does not exceeds limited value by limiting input quantity of fuel; fuel system includes valve locator and fuel regulator, which are represented by first-order inertia plant.

In the microturbine power production system, the excitation circuit voltage of synchronous generator is constant and the second magnitude applied to the generator input adjusts the mechanic energy input, and frequency of the system and as well as the oscillations in voltage are put under control. The speed control element is responsible for ensuring the convenient fuel flow (gas) or air rate for the synchronous generator. While the speed controller element and gas turbine system ensure mechanic power required for the synchronous machine, two important situations are considered. First of them is the power requirement for consumers and the second one is keeping of the terminal voltage and frequency within permitted limits. If these two situations are observed, reliability, productivity of the operating place and quality of the produced power will be higher.

The second input magnitude of synchronous generator driven with a microturbine is the excitation circuit current or voltage. With adjustment of the excitation circuit current, magnitude of output voltage of synchronous generator is put under control. Meanwhile, adjustment of reactive power produced by synchronous generator and excitation current is realized. In the study, the initially produced active power control was made with control of mechanical energy input of the generator with the speed controller element (speed governor). The mechanical energy input of synchronous generator was adjusted and simultaneously, oscillations in voltage, frequency and produced electrical power were put under control.

In case the power production system of microturbine is operated in parallel to the network or as long as changes occur in the consumer load fed from the system, frequency of the system will begin to deviate from 50 Hz value permitted by the plant. The frequency range desired by electric plants and networks in Turkey is in 50 Hz ± 1% value. To keep the frequency value of system in desired frequency range, by controlling the gas input or flow, the mechanical power produced by microturbine is brought to acceptable desired value for the synchronous generator. This control process is realized with the speed controller element (speed governor). In this study, the production power of MTPGS, its frequency and oscillations in voltage were put under control with traditional PID controller and ANFIS we used as a speed governor.

6. Adaptive neuro-fuzzy inference system

In recent years, fuzzy logic controller has played a significant role in increasing number, 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. Today,

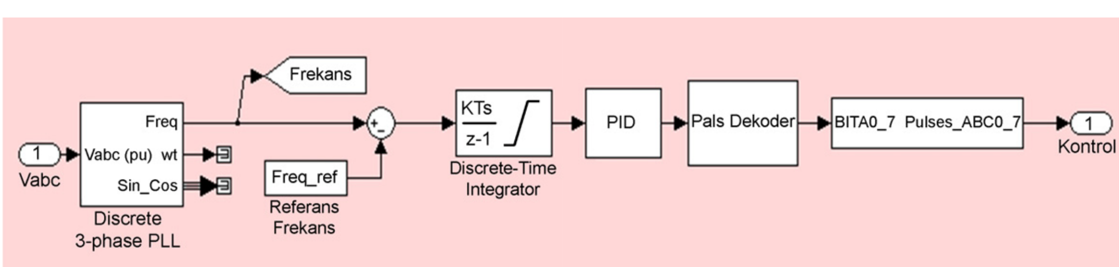

Fig. 9. Simulation Block Diagram of frequency control.

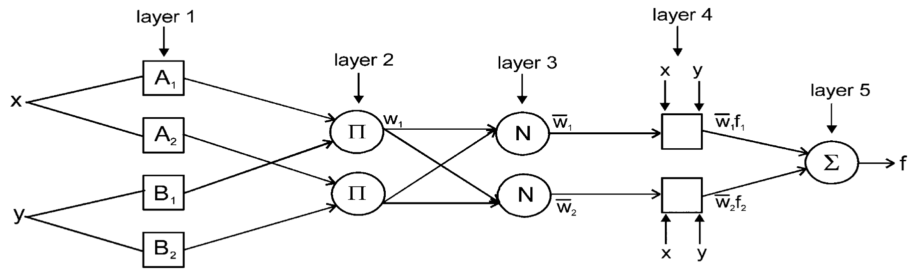

Fig. 10. A general schematic diagram of ANFIS controller system.

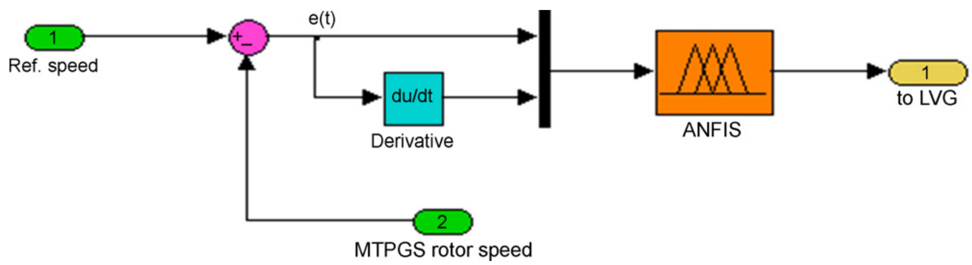

Fig. 11. Simulation block diagram of microturbine speed control with ANFIS.

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 [31,32].

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 [33]. 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 [31]. ANFIS permits combination of numerical and linguistical data. Besides, Neuro-Fuzzy systems have the ability to obtain fuzzy information from numerical data [34,35].

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 [34].

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 [35–37]. 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.

The general block diagram of ANFIS controller system performed for two-rule fuzzy system is given in Fig. 10. The ANFIS controller system realizes TS rules in 5 layers by using multi-iteration learning procedure and hybrid learning algorithm [37].

In the block structure of ANFIS given in Fig. 10, 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 and q_i) related to first degree polynome. These parameters are called as the result parameter [31].

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

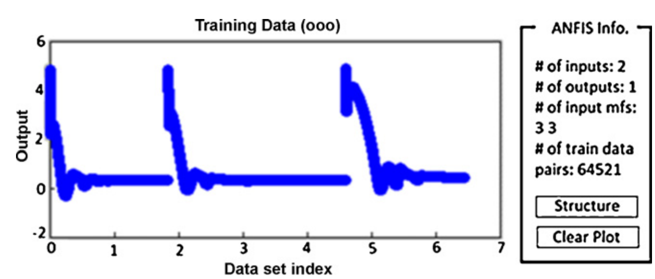

Fig. 12. Image of transferring of input and output data of controller to the ANFIS editor to make the speed control of MTPGS with ANFIS.

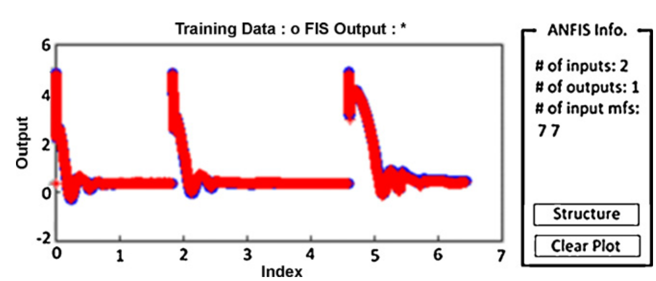

Fig. 13. The image of controller output signal obtained as a result of application of the hybrid learning algorithm to the data base of ANFIS used for microturbine speed control.

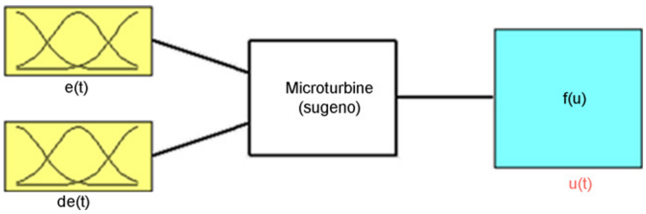

Fig. 14. For microturbine speed control, structure of Sugeno type Fuzzy Inference System consists of three input and one output signals.

gradient descent (back propagation) method. If these parameters are fixed, ANFIS output is expressed with the following correlation;

$$\begin{aligned} z &= \frac{w_1}{w_2+w_2} z_1 + \frac{w_2}{w_1+w_2} z_2 \\ &= \bar{w}_1(p_1 x + q_1 y + r_1) + \bar{w}_2(p_2 x + q_1 y + r_2) \\ &= (\bar{w}_1 x)p_1 + (\bar{w}_1 y)q_1 + (\bar{w}_1)r_1 + (\bar{w}_2 x)p_2 + (\bar{w}_2 y)q_2 + (\bar{w}_2)r_2 \end{aligned} \quad (3)$$

It is seen from Eq. (3) that 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 [38].

7. Adaptive neuro-fuzzy inference system for the microturbine speed control

As the gas flow in MTPGS increases, mechanical power obtained from output of the turbine also increases and depending on this, rotor speed of synchronous generator raises. Both amplitude and frequency of the voltage produced depending on the rotor speed of synchronous generator raise above the value of plant. When this situation is considered in respect to synchronous generator, generator in high speeds subject to mechanical forces and causes big financial loss. When we consider it in respect to consumer, machines, especially the rotating area machines, operated in high frequency and voltage are damaged dramatically. When the gas flow in MTPGS realizes under the desired value, as the speed of synchronous generator will be below rated speed, the frequency and voltage value will be low in the same rate. Consequently, in such operating situations, the biggest damage will be on part of consumers. The power production energy plants are also affected from these negative operating conditions.

One of the most important conditions for high quality power produced in MTPGS is that; the magnitude of terminal voltage must be within determined tolerances and the second is that the frequency must realize within 50 Hz ± 1% for the network frequency. In other words, when the operating frequency is between 49.5 Hz and 50.5 Hz, it is not possible to meet with any negative situation. On the other hand, the tolerance limit range determined in voltage is 400 V ± 5%. The voltage value at the ends of network voltage or load terminal can vary between 360 V and 420 V. When we consider the plants operating with electric energy of our daily life, mostly it is impossible to see the effective vale of voltage in standard 380 V.

The turbine speed control depending on the adaptive neuro-fuzzy inference system was designed to develop operating performance of MTPGS and obtain electrical output values (terminal voltage, frequency and production power) in desired quality and value. The adaptive neuro-fuzzy inference system is explained in detail in Section 6. By making the control of turbine speed with ANFIS in MTPGS, electrical magnitudes (voltage, frequency and power) within limits permitted by the plant were obtained.

Instead of the speed governor shown in Figs. 4 and 5 above, traditional PID controller and ANFIS were used for the microturbine speed control. ANFIS has two input signals. First of them is the error signal [$e(t)$] that is the difference between the reference speed and speed of synchronous generator in operation (p.u). The second is the change of error signal depending on time [$de(t)/dt$]. These two signals are expressed with equations below;

$$e(t) = \omega_{ref}(p.u) - \omega_{mek}(p.u) \quad (4)$$

$$\frac{de(t)}{dt} = \frac{\omega_{ref} - \omega_{mek}}{dt}(p.u) \quad (5)$$

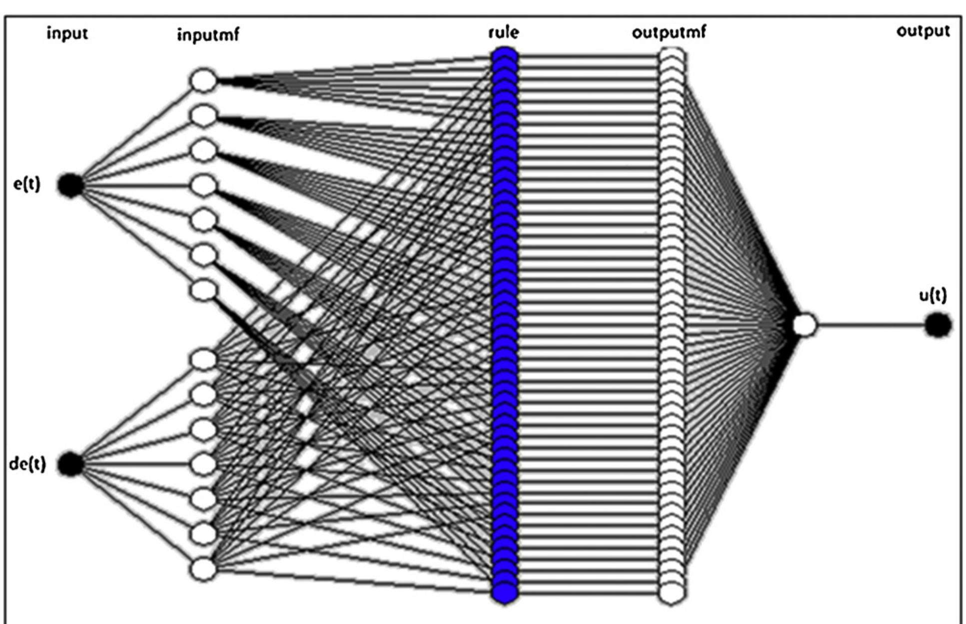

Fig. 15. Structure of ANFIS designed for microturbine speed control.

Table 3
The rule table of ANFIS designed for speed control of microturbine.

e/de	N	NM	ZE	PS	PM	P	PB
ZE	−1.4183	−0.1891	0.2788	0.9937	6.9969	5.9750	5.6801
PVS	−0.3245	0.1611	0.7505	1.3862	1.8386	2.5508	3.4426
PS	0.1619	1.5614	2.8003	2.2806	2.4241	2.5811	3.5343
PM	0.9075	1.0506	1.8104	2.0824	2.8305	3.8041	4.4284
P	2.4539	1.6221	2.1877	2.8484	3.6771	4.5025	4.2814
PB	2.9684	2.7305	3.0599	3.7629	4.5735	5.2850	0.0000
PLB	1.1256	3.3932	3.8962	4.5868	5.1834	0.0000	0.0000

The simplified block diagram of the micro speed control made with ANFIS is seen in Fig. 11. For stabile operation of MTPGS with ANFIS, first of all, we have to know or analyze the system very well. In this study, by making the control of microturbine speed against the reference speed value, fuel input to the system was realized in controlled manner. Though the control of turbine speed was ensured, it was aimed that the voltage obtained from the output terminals and active power drawn by consumers to be stabile continuously and in desired value. Our top priority aim in that study was to bring the system's frequency and oscillations in voltage because of change in speed to the desired point by realizing the speed control.

While the operation frequency, voltage and produced power quality in MTPGS were in desired quality, values of output signal of speed control were determined. These values constituted the output magnitude of ANFIS. In this study, the power demanded by three consumer loads of 50 kW, 150 KW and 250 kW of MTPGS were met and the system's frequency and voltage was protected in some definite rates. However, for loading situations of MTPGS in range of 50–250 kW, ANFIS designed for turbine speed control can be easily used.

The error signal ($e(t)$) of MTPGS in uncontrolled situation and change in error signal ($de(t)/dt$) were recorded individually. The values of controller output signal ($u(t)$) according to the desired voltage and frequency values for three different loading values are determined by the user. While determining the values of controller output signal, the data on error determined for each loading and change in error signal are considered. Then, with the recorded data, ($e(t)$, $de(t)/dt$ and $u(t)$), the design of fuzzy logic controller is realized by using the *anfisedit* software in the MATLAB program. These data are passed from training by using of the hybrid learning algorithm given in Section 5 and the values of output signal of ANFIS are determined. The values and current of controller's output signal obtained by using of the hybrid learning algorithm are compared to the output magnitudes of speed controller determined by the user and their overlapping is ensured. If there is a dramatic difference between the output signal determined by the user and the controller's output signal obtained as a result of training made in the *anfisedit* software, we cannot talk about a stabile operation of the system.

In making of turbine speed control of MTPGS with ANFIS, the data number used for each input-output signal related to three different loading situations in establishment of data base and fuzzy inference system of ANFIS is 64,521. A total of 64,512 data are transferred to the *anfisedit* software in the Matlab program. By using that software, to automatically establish the fuzzy inference system, the membership function type, linguistic variable number and how many iteration will be made to apply the hybrid learning algorithm are determined by the user.

In Fig. 12 above, the image after the input and output data of controller are transferred to the ANFIS editor are given. The image of controller output signal determined by the user according to the values of controller input signals for three loading situations of MTPGS is given in Fig. 12.

After the data transfer to the ANFIS editor was completed, for the speed control of MTPGS, the type of membership function was applied as triangle, linguistic variable as seven and five iterations (trial) for hybrid learning algorithm and training of data were applied. As a result of the five iterations, for stabile operation of the system, the input signals of the system according to the controller output signal determined by the user (by us) were trained. The control output signal determined by the user and the controller output signal obtained as a result of training of the input-output signals of controller must be overlapped to obtain the electrical magnitude values expected from MTPGS. The desired situation was realized as a result of the hybrid learning algorithm and this is shown in Fig. 13.

The curves of controller output signal indicated in blue color (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.) in Fig. 12, determined by the user for speed control of MTPGS, and curves of controller output signal indicated in red color, obtained as a result of application of the hybrid learning algorithm to the data base of ANFIS, are overlapped as clearly shown in Fig. 13. This indicates that the applied hybrid learning algorithm gives a good result.

As a result of the training made in the ANFIS editor, the Sugeno type fuzzy inference system having two input and one output signals was automatically obtained as shown in Fig. 14. As the output of Sugeno type ANFIS consists of real numbers, it cannot be marked as like the input signal membership function. The ANFIS output signal consists of 49 real numbers and its value range is −1.4183 and 5.2850 (Table 3).

The general structure of ANFIS in Fig. 15 consists of five layers as stated in Section 6. While establishing the rule base, the "*and*" operator from logical operations was used. The membership functions of input variables of ANFIS, linguistic variables and value ranges are given in Figs. 16 and 17.

The linguistic variables of error signal [$e(t)$] from input variables of ANFIS are; zero (ZE), positive very small (PVS), positive small (PS), positive medium (PM), positive (P), positive big (PB) and positive very big (PLB). The linguistic variables of change signal in error [$de(t)/dt$] as a second input variable are; negative (N),

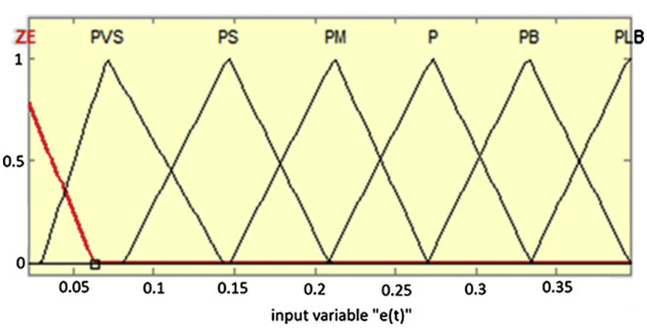

Fig. 16. Membership functions and value ranges of error [$e(t)$] of the input variable of ANFIS.

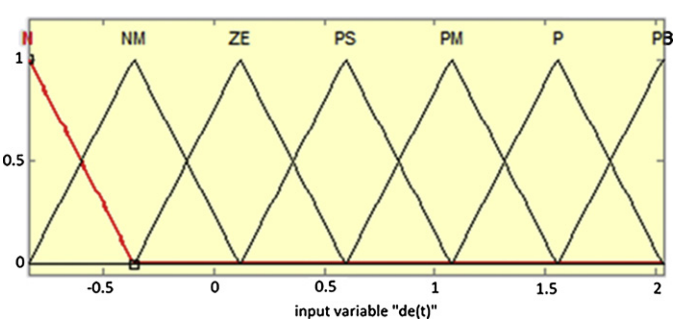

Fig. 17. Membership functions and value ranges of change in error [$de(t)/dt$] of the input variable of ANFIS.

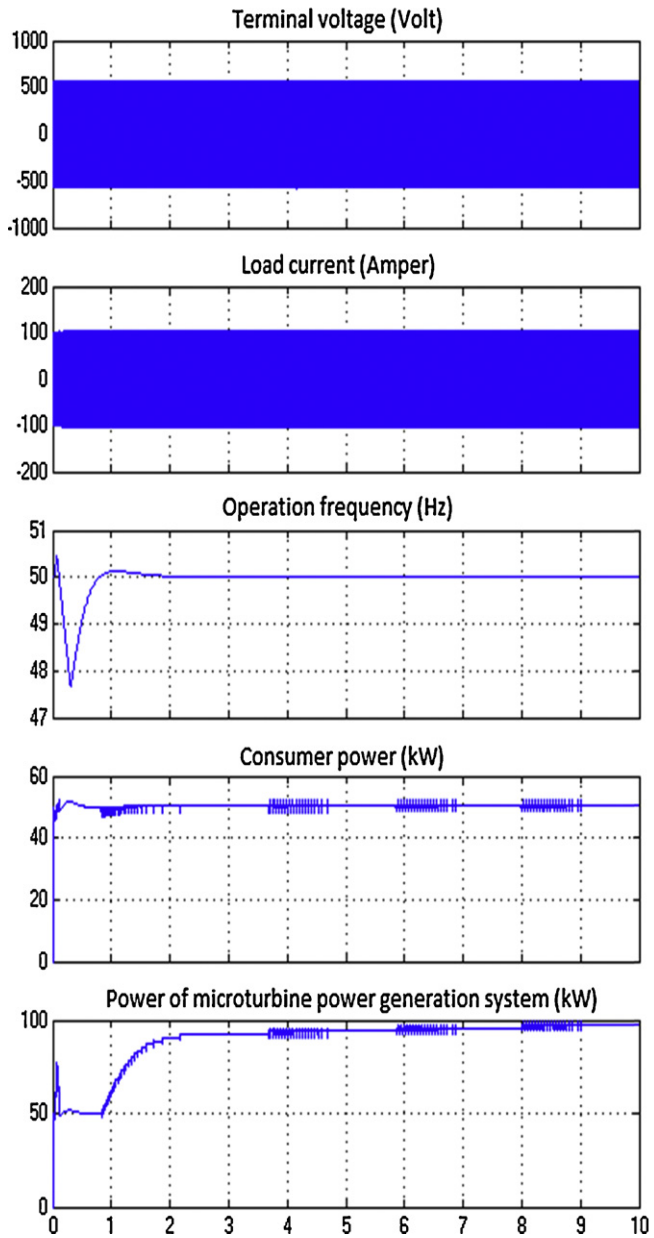

Fig. 18. Variation curves in electrical output magnitudes of MTPGS with traditional speed controller when it is loaded with 50 kW consumer load.

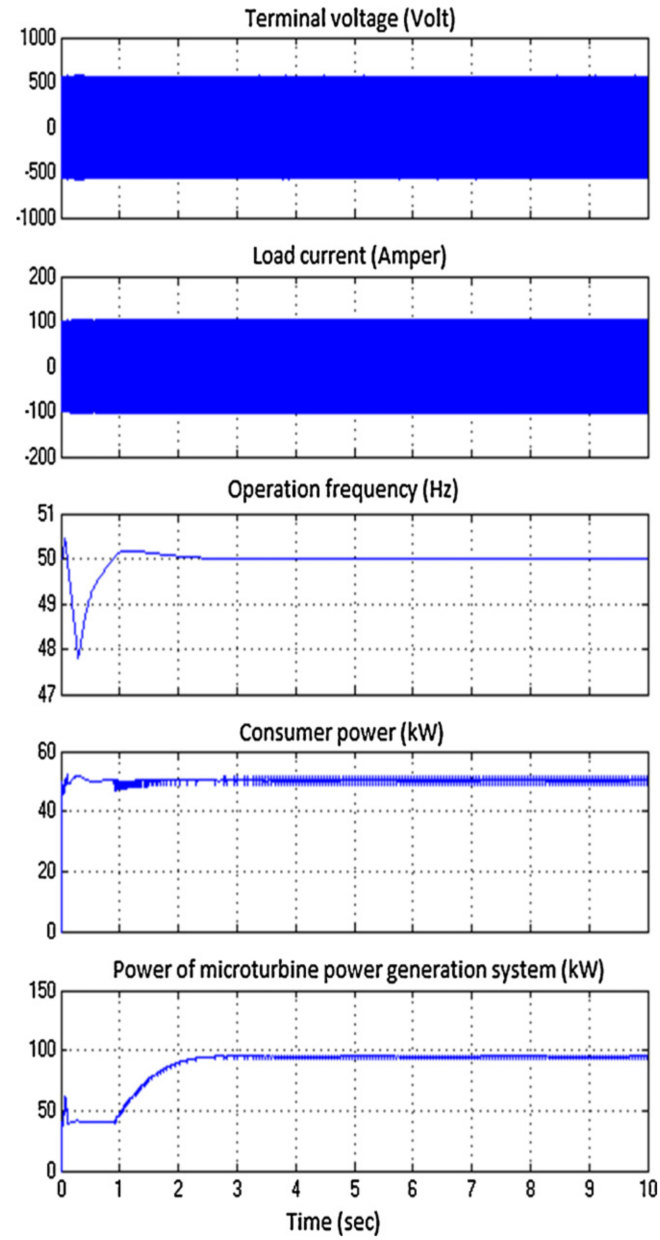

Fig. 19. Variation curves in electrical output magnitudes of MTPGS with ANFIS speed controller when it is loaded with 50 kW consumer load.

negative medium (NM), zero (ZE), positive small (PS), positive medium (PM), positive (P) and positive big (PB).

49 rules established in the rule base of ANFIS were obtained by using the logical operator between the input and output signals of the system with words of "*If*", "*Then*". The input variables of ANFIS were combined with "*and*" conjunction. 49 rules obtained for the microturbine speed control are given in Table 1.

8. Simulation results and discussions

In this study, conventional PID controller and ANFIS are used to obtain electrical output values of MTPGS in desirable quality and value. Speed control of the microturbine of MTPGS is made through conventional PID controller and ANFIS. Adjustment of the microturbine speed depending on rotor (shaft) speed of synchronous generator in MTPGS is made. Because the power was obtained from the MTPGS depending on the speed of the microturbine.

In simulation study, controlling of microturbine speed of MTPGS is performed through conventional PID controller and ANFIS separately. Nominal operation power of MTPGS is 250 kW and maximum loading is limited with that value. Power produced by MTPGS is consumed by consumers. While the power generation system meets power demand between 0 and 250 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 – 50 kW, 150 kW and 250kW – are shown in graphics. While consumer loads are fed by conventional PID controlled MTPGS, voltage at load ends, load current, operating frequency at load ends, generation power of MTPGS, power consumed by consumers and simulation results are given in Fig. 18, Fig. 20 and Fig. 22 respectively. In case ANFIS controller MTPGS is loaded with consumer loads, the simulation results belong to changes in generation and consumption powers are given in Fig. 19, Fig. 21 and Fig. 23 respectively. Voltage curve shown at the Fig. 24 with terminal voltage curves shown in Figs. 18–23 are the same. But time

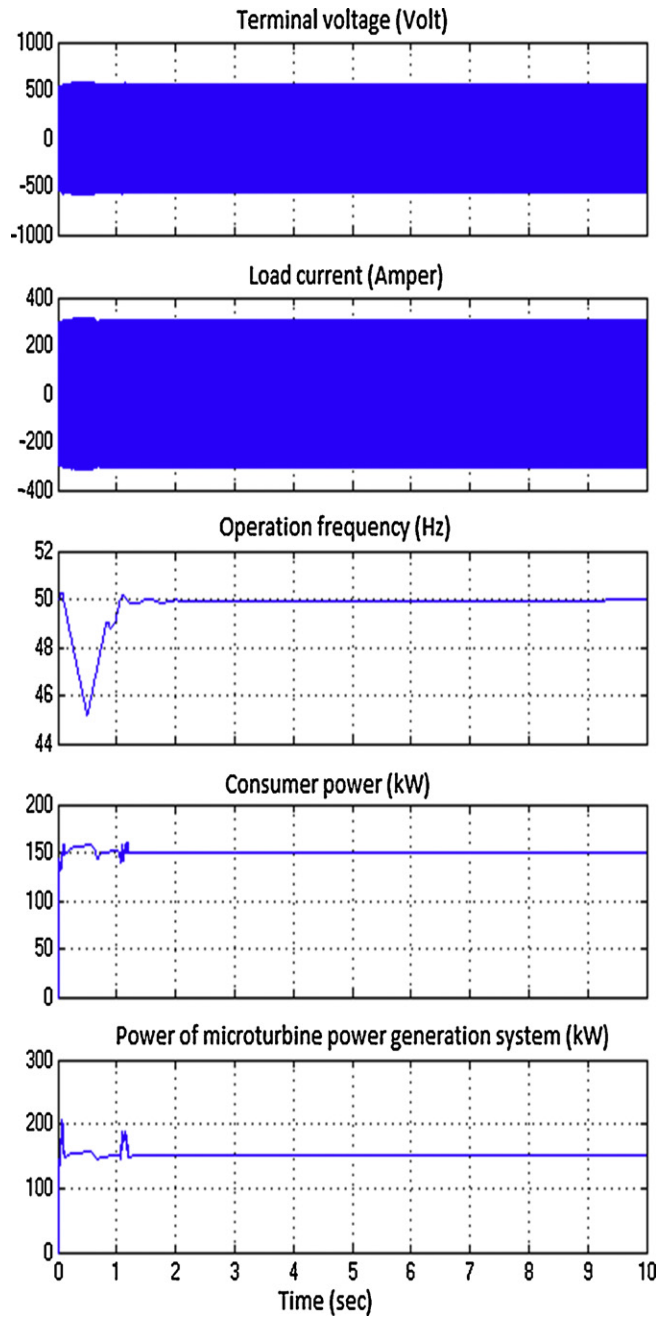

Fig. 20. Variation curves in electrical output magnitudes of MTPGS with traditional speed controller when it is loaded with 150 kW consumer load.

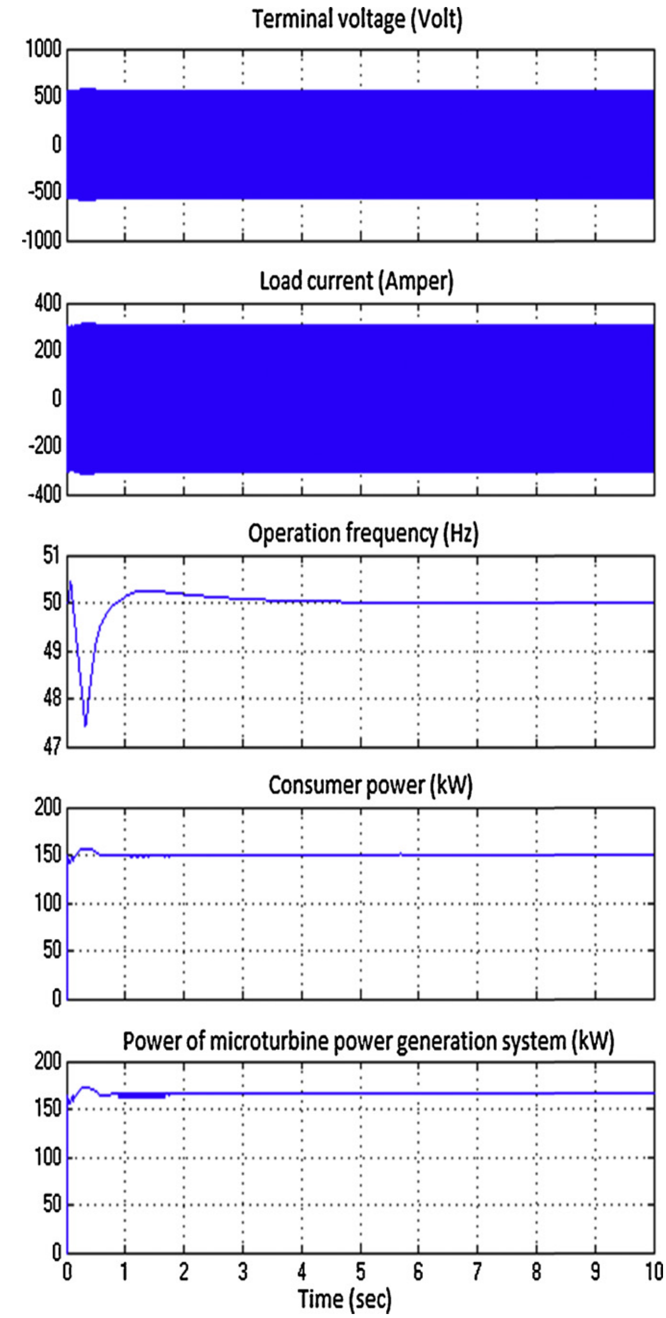

Fig. 21. Variation curves in electrical output magnitudes of MTPGS with ANFIS speed controller when it is loaded with 150 kW consumer load.

range is 0–10 s in Figs. 18–23, shape of the signal could not be seen in full. Harmonic effects and disorder of voltage curve cannot be seen properly, terminal voltage and load current curve is shown in Fig. 24 again.

When output electrical magnitudes of the power generation system are examined, it can be seen that the operational frequency reaches to desirable 50 Hz ± 1% value between about 1 second and 1.5 s time gap. The operational frequency acceptable for Turkey is (f_{opr}) 50 Hz. The value of voltage obtained in the simulation study is maximum (peak) value. Nominal voltage value is 400 v. The maximum value of this voltage is obtained from the simulation study as $U_{max} = U \cdot \sqrt{2} = 400 \times \sqrt{2} = 565$ 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 MTPGS on the said simulation curves, we can see that they reach to stable operation situation in desirable values within 1–1.5 s. 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 and K_D) of conventional PID controller used in the study are readjusted in every changing load phase to keep voltage in 565 Volt 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

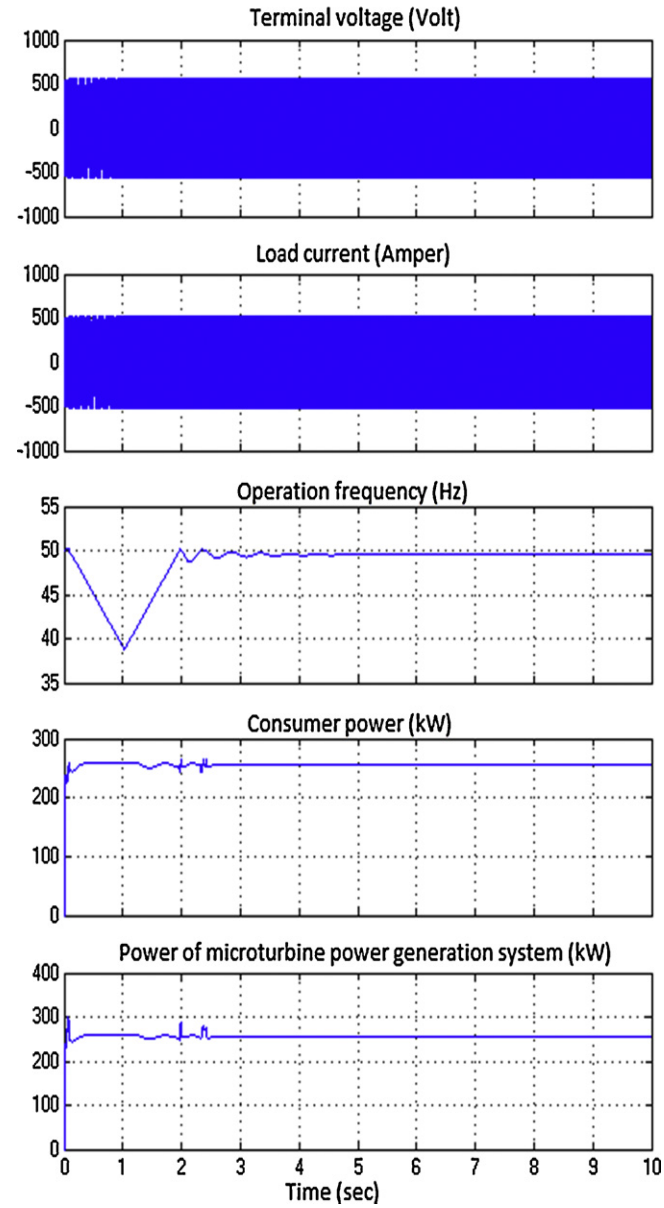

Fig. 22. Variation curves in electrical output magnitudes of MTPGS with traditional speed controller when it is loaded with 250 kW consumer load.

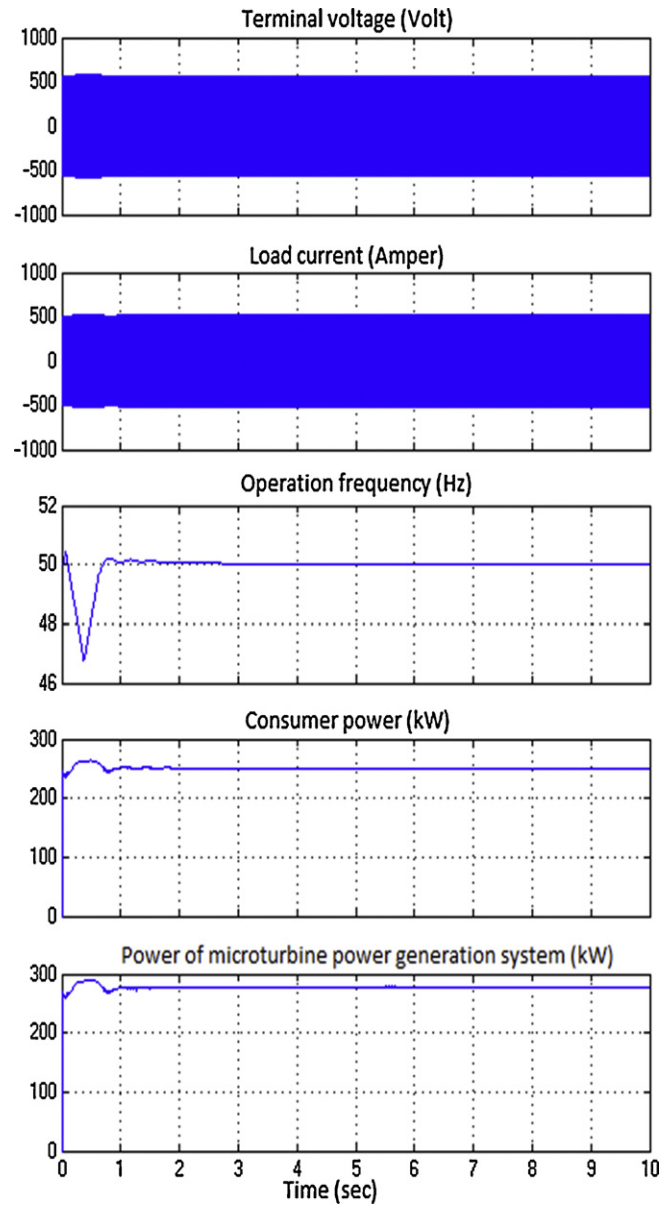

Fig. 23. Variation curves in electrical output magnitudes of MTPGS with ANFIS speed controller when it is loaded with 250 kW consumer load.

controller, the gain parameters of PID controller can be automatically adjusted within operation condition determined adaptively.

The output voltage and frequency in MTPGS changes depending on the microturbine speed. Meanwhile, generation power of the system also depends on changes in this 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 microturbine speeds, terminal voltage and frequency of MTPGS must be within permitted tolerances. For this purpose, ANFIS is designed for MTPGS. When MTPGS 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 MTPGS. 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.

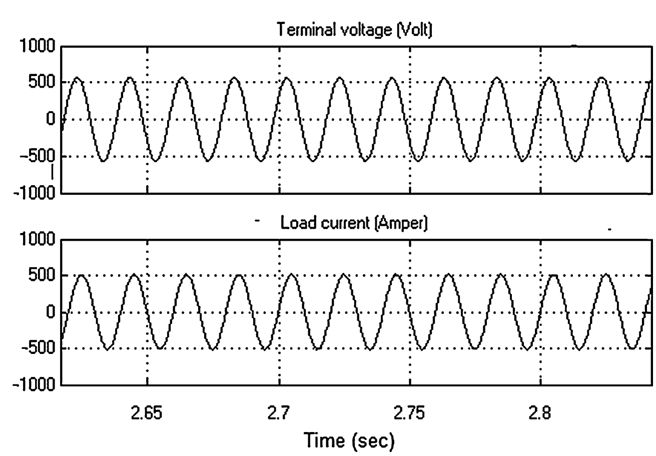

Fig. 24. Variation curves in the terminal voltage and load current magnitudes of MTPGS with ANFIS speed controller when it is loaded with 250 kW consumer load at 0.25-s time interval.

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 microturbine speed control of MTPGS. The error values between the data obtained from the simulation study and the desired data are defined as [18]:

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

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 microturbine speed control of MTPGS are within 0.0711%. As expected, the proposed ANFIS model provides highly accurate estimation of the microturbine speed control for the different operation situations of MTPGS.

In the study, the microturbine speed of MTPGS is controlled with ANFIS and output voltage and frequency of the system is tried to be kept within determined tolerance limits. The turbine speed is adaptively adjusted with ANFIS depending on changing consumer load situations under the determined operational conditions of MTPGS. In this study, controlling of the microturbine speed between 50 kW and 250 kW consumer load values is automatically performed with ANFIS. As it can be seen in Figs. 19, 21 and 23, the operational frequency, 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 MTPGS, 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.

9. Conclusions

For terminal voltage and frequency control of the split-shaft microturbine power generation system, ANFIS is designed and is used in simulation block diagram of MTPGS performed in Matlab/Simulink program. For purpose of obtaining high quality power from MTPGS, the effective value of output voltage must be in 400 V and frequency in 50 Hz operational limit values. For this purpose, power limitation or speed control of the microturbine is performed by means of controlling of microturbine speed. For controlling of the microturbine speed, the conventional PID controller and ANFIS are used separately. As a result of controlling of the microturbine speed, it is determined from the simulation results that the output electrical magnitudes of MTPGS (voltage, current, frequency and power) reach to desirable values within 1–1.5 s. 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 MTPGS 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 microturbine speed 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 the microturbine speed of MTPGS 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 MTPGS has been experienced. In contrary, electrical output magnitudes in desirable quality and output have been obtained.

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