Neuro-Fuzzy Tuning of PID Controller for Control of Gas Turbine Power Plant

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Abstract – The purpose of introducing Combined Cycle with gas turbine in power plants is to reduce losses of energy. Their main role lies in the utilization of waste heat that may be found in exhaust gases from the gas turbine or at some other points of the process to produce additional electricity. The efficiency of the plant increases reaching over 50 %, while the traditional steam turbine plants is approximately 35% 40% or so.

Up to date, the PID controller has been used to operate under such systems, but since the gain of PID controller manually has to be tuned by trial and error procedures. Getting an optimal PID gains is very difficult to tune manually without control design experience.

In this paper, we studied an acquiring of transfer function from operating data of Gun-san gas turbine in Korea and a new 2-DOF PID controller tuning by NFS is designed for the optimum control to Guns-san gas turbine's variables variety. Since the shape of a membership function in the NFS vary on the characteristics of plant. ANFIS based control method is effective for plant that their variables vary.

Its results are compared to the conventional PID, 2-DOF PID controller and represents satisfactory response. We expect this method will be used for another process because it is studied on the real operating data.

Key Words : Intelligent control, Neuro control, Fuzzy control, 2-DOF control, Gas turbine control

1. Introduction

The studies on the control of gas turbine have been a subject of interest for many years, since the gas-turbine engines have been widely adopted as peak load candidates for electrical power generation. Especially, the fully automatic start-up function and the fast run-up characteristic of gas turbine systems have made them particularly suitable for peak-load lopping and standby power supply purposes [1].

The start-up procedure for a modern gas turbine consists of the stages such as, warming up of main steam pipeline, warming up of turbine parts, turbine run-up, synchronization, and loading. So, the various studies about control in each step from start-up to loading need to have stability and safety because control procedure is very complicated.

Start-up and shutdown procedures are the most challenging problems for control applications to develop new control algorithms. They require the sequence of operations to be successfully performed leading a gas turbine and associated power plant components through a sequence of safe states. At the same time many variables must be monitored and checked to ensure safety of operation [2].

Moreover, minimum time and minimum energy losses during the star-up or run-up procedures would be desirable.

Additional problems are involved when starting-up or shutting down certain components within a bigger power station. This is especially difficult in case of Combined Cycle gas turbines because, in this case, interconnections between components occur not only through the electric network but also on the heat exchange side, i.e. flows of gases, and flows of steam [3].

An effective control is required to maintain system stability following a system disturbance. Failure to do so will cause an inevitable plant shutdown, from which a loss of production and considerable damage to the plant may result. There is an increasing demand for a more accurate gas-turbine control technology than those previously studied [1-3], to enable the system response be stabilized and improvements to the associated control system made.

In this paper, first of all, we designed the new 2-DOF PID controller to the operating data based transfer function of Gun-san gas turbine generation plant in Korea and studied an optimum tuning of a new 2-DOF PID controller designed using NF (Neural network Fuzzy System).

2. Gun-san gas turbine system

2.1 The structure and characteristics of Gun-San gas turbine

Generally, the model is composed of compressor, combustor, turbine, and fuel system with an arrangement shown in Fig. 1 [5~6]. The high-pressure compressor turbine powered by the exhaust gas from the combustion chamber drives the compressor.

The combination acts as a generator for the low-pressure free power turbine. The power turbine drives a generator through a gearbox. The gas generator is derived from single-shaft engine.

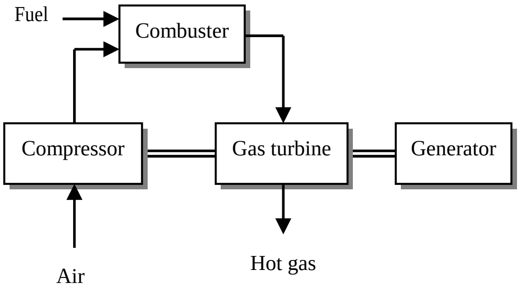


Fig. 1(a) Gas-turbine generating system

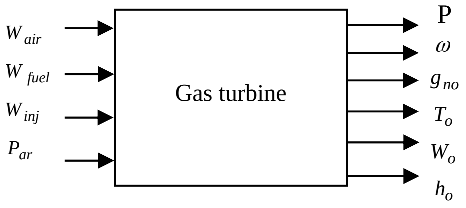


Fig. 1(b) The control variables of gas-turbine generating system

Where,

W_{air} =Air flow to the turbine
W_{fuel} =Fuel flow to the turbine
W_{inj} = Steam (water) injection flow
P_{ar} =Enthalpy, density, pressure and temperature of inlet air, temperature of injection liquid
P =Mechanical power
ω=Rotational speed
g_{no} = N_{ox} content in exhaust gas
T_o =Exhaust gas temperature
W_o =Exhaust gas flow
h_o =Exhaust gas enthalpy

Air at atmospheric pressure enters the compressor inlet. After compression of the air to achieve the most favorable conditions for combustion, fuel gas is mixed with the air in the combustion chamber, combustion takes place and the hot exhaust gases are expanded through the turbine to produce mechanical power. So, if we want to model, a gas turbine generation plant can be represented by a linear model which is devised assuming that the engine can be represented as a collection of multi-variable functions, which can be linearized by writing them in a total differential form. This approach method has been extensively used in gas-turbine control studies up to now [2-3]. But it is not easy for us to model and control.

In a gas-turbine engine, the fuel flow is a true independent variable with respect to the engine. The engine speed is an independent variable with respect to the thermodynamic cycle but a dependent variable in the inertia/speed relationship. The dependent variables chosen are the compressor discharge pressure, the exhaust gas pressure, the exhaust gas temperature and the exhaust gas power [5, 6].

2.2 Control system of Gun-san gas turbine plant

Fig. 2 represents a simplified block diagram for a single-shaft Gun-san gas turbine generation plant. The control system includes speed control, temperature control, acceleration control, and upper fuel and lower fuel limits.

Speed control is suitable for either droop or isochronous control and operates on the speed error formed between a reference made up of one per unit speed plus the set-point, compared with actual system or rotor speed. A droop governor is a straight proportional speed controller in which the output is proportional to the speed error [5,6].

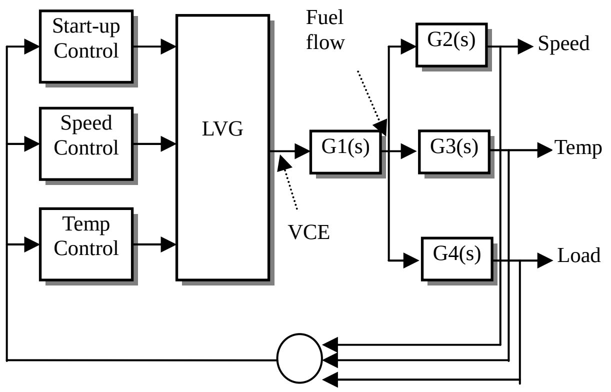
Temperature control is the normal means of limiting gas turbine output at a predetermined firing temperature, independent of variation in ambient temperature or fuel characteristics.

Acceleration and deceleration fuel schedules are basic control requirements for maintaining the gas-turbine engine to operate within its safe margin during steady state or transient conditions.

Acceleration control is used primarily gas turbine startup to limit the rate of rotor acceleration prior to reaching governor speed, thus ameliorating the thermal stresses encountered during startup. This control serves a secondary function during normal operation, in that it acts to reduce fuel flow and limit the tendency to over-speed in the event that the turbine generator separates from the system [8].

These three control functions, speed governing under part load conditions, temperature control acting as an upper limit, and acceleration control to prevent over-speeding, are all inputs to a low value selector. The output of the low value selector, which is called VCE, is the lowest of the three inputs, whichever requires the least fuel. Transfer from one control to another is bumpless and without any time lags. The output of the low value selector is compared with maximum and minimum limits. The minimum limit is the more important. This is because the minimum limit is chosen to maintain adequate fuel flow to insure that flame is maintained with the gas turbine combustion system [8].

Gas turbine fuel systems are designed to provide energy input to the gas turbine in proportional to the product of the command signal (VCE) times the unit speed. This is analogous to the actual mode of operation of the fuel system. since liquid fuel pumps are driven at a speed proportional to turbine rotor speed. Gas fuel control is accomplished in two stages with the output pressure of the first stage being proportional to rotor speed [5~8].



VCE=fuel flow signal, G1(s)= transfer function of fuel system, G2(s)=transfer function of between fuel flow and turbine speed, G3(s)=transfer function of between fuel flow and turbine exhaust gas temperature, G4(s)=transfer function of between fuel flow and generator output

Fig. 2 Control system of Gun-san gas-turbine generating system

The fuel gas control system consists of two valves in series, the first of which controls the pressure between the two valves as a function of speed. The second valve has a linear characteristics versus lift range and is aerodynamically designed so that sonic velocities are attained at the controlling area with flange-to-flange valve pressure ratios as low as 1.25. If valve position is maintained proportional to the VCE signal, the actual result is a flow rate of fuel gas, which is proportional to the produce of gas turbine speed [7].

Both the torque and exhaust temperature characteristics of the single-shaft gas turbine are essentially linear with respect to fuel flow and turbine speed over the 95~107% design rating. The exhaust temperature equations are somewhat less accurate at part load; however, since temperature control is only active at the design point, the impact of the part load inaccuracy is negligible to the overall simulation.

An ideal acceleration control allows the engine to accelerate at a reasonably fast rate without the engine being driven into the surge region or overheating, the engine components. Following load rejection, a rapid reduction of fuel flow is required to limit the maximum speed rise.

There is a minimum level to which the fuel flow can be reduced without causing a flameout problem. A deceleration fuel schedule is required to minimize the turbine speed rise on load rejection, but not the flaming-out of the engine [5~8].

3. PID controller in gas turbine

The three-mode PID controller is widely used in plants due to ease of control algorithms and tuning in the face of plant uncertainties. However, the response of those depends on the gain P, I, and D [7].

Nevertheless, the linear PID algorithm might be difficult to deal with processes or plant with complex dynamics, such as those with large dead time, inverse response and highly nonlinear characteristics.

Up to date, many sophisticated tuning algorithms have been used to improve the PID controller work under such difficult conditions, since the control performance of the system depends on the parameter gains. However, most control engineers can tune manually PID gains by trial and error procedures in many cases. So, PID gains are very difficult to tune manually without control design experience [5~8].

4. A feed-forward 2-DOF controller for gas turbine

4.1 Filler parameter separated type 2-DOF PID controller

The parameter of target filter is designed into separate two part α, β. The transfer function of between process value PV(s) and settling value SV(s), process value PV(s) and disturbance D(s) is given as the following equations:

$$G_{PVSV}(\mathrm{s}) = \frac{PV(s)}{SV(s)}$$

$$= \frac{K_p(1+1/T_i s)\alpha\{a/(T_i s+b)\}}{1+(K_p+s/T_i)-T_d sG(s)} \qquad (1)$$

$$G_{DVSV}(\mathrm{s}) = \frac{DV(s)}{SV(s)}$$

$$= \frac{G(s)}{1+(K_p + s/T_i) - T_d sG(s)} \qquad (2)$$

In equation (1), the process value PV(s) depends on the two degree parameter α , filter parameter T_f , a, and b..

But numerator is the same as that of conventional PID controller

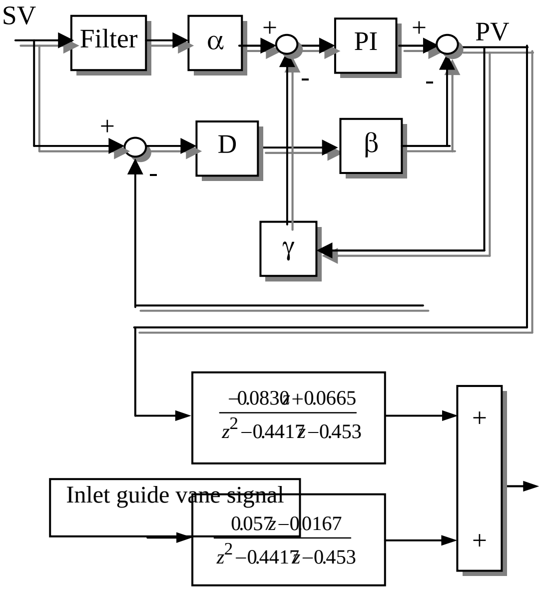


Fig. 3 2-DOF PID controller with NFS for Gun-san gas turbine

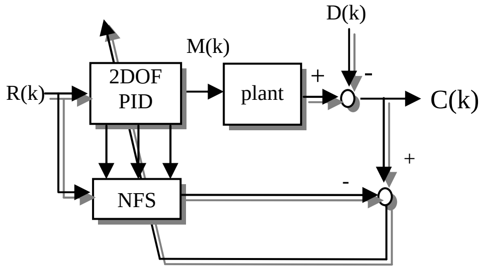


Fig. 4 The structure of a 2-DOF PID controller for Gun-san gas turbine

The proportional gain is also affected by the filter parameter a and two degree parameter α .

The disturbance is controlled by gains K_p, T_i, T_d . The structure of new 2-DOF PID controller tuning by ANFIS suggested in this paper is represented as Fig. 4 and Fig. 5 [4].

4.2 Tuning of 2-DOF PID controller by NFS

Up to now, ultimate method, Z&N method has been used for tuning of 2-DOF PID controller. Instead of that in this paper, we used NFS (Neural Fuzzy System) for tuning [4, 9, 10].

We used Neural-Fuzzy based on the architectures and learning rules of adaptive networks have been studied in reference [5]. In NFS, if-then rules structure for tuning is applied by a first-order Sugeno fuzzy model as the follows:

Rule 1: If x is Al and U is Bl, then fl=Plx+q1y+rl,
Rule 2: If x is A2 and w is Bl, then f2=p2+q2y+r2.

Every node, that is, Layer 1 Layer 3 of Fig. 6 have meaning as described in reference [5].

Fig. 6 is an NFS architecture that is functionally equivalent to a three-input first order Sugeno fuzzy model with seven rules, where each input is assumed to have three associated MFs.

Here, we denote the output of the i^{th} node in layer *l* as $L_{l,i}$ and each node can be described as the following:

Fig. 6 The structure of NFS for a new 2-DOF PID controller of Gun-san gas turbine system

1) Layer 1

All nodes i in this layer are adaptive nodes with a node function

$$L_{1,i} = h_{A_i}(x) \text{ , for } i = 1, 2, \qquad (4)$$

where x is the input of process (gas turbine) to node *i* and A_i is a linguistic label such as, “BIG or ZERO” associated with this node to process. That is, $L_{1,i}$ is the membership grade of a fuzzy set A_i (A_1, A_2, B_1, B_2).

Here the membership function for A is given as the following bell function:

$$h_A(x) = \frac{1}{1+\left|\frac{x-c_i}{a_i}\right|^{2b}} \qquad (5)$$

where each parameter a_i, b_i, c_i decides the shape of bell to exhibit various forms of membership functions for fuzzy set A.

Parameters in this layer are referred to as premise parameters as reference [5]

2) Layer 2

The function of every node is a fixed node and output is the product of all the incoming signals:

$$L_{2,i} = w_i = h_{A_i}(x)h_{B_i}(y),\ i = 1,\ 2\,. \qquad (6)$$

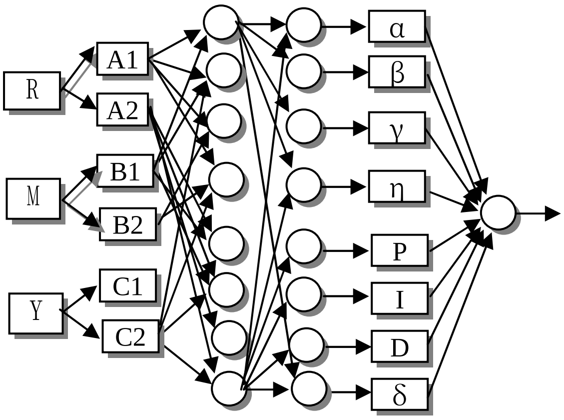


Fig. 5 The structure of NFS for 2-DOF PID controller of Gun-san gas

3) Layer 3

Nodes in this layer are fixed node and the i^{th} node in this layer calculates the ratio of the i^{th} rule's firing strength to the sum all rules' firing strengths:

$$L_{3,i} = \overline{w_i} = \frac{w}{w_1 + w_2},\ i = 1,\ 2. \qquad (7)$$

3) Layer 4

Every node i of this layer has an adaptive behavior with

α $L_{4,i} = \overline{w_i} f_i = \overline{w_i}(p_i x + q_i y + r_i)$, (8)

where $\overline{w_i}$ is a normalized firing strength from layer 3 and $(p_i + q_i + r_i)$ is the parameter set of this node.

4) Layers 5

As a fixed node, which computes the overall output as the summation of all incoming process signals:

$$\text{Overall output} = L_{5,1} = \sum_i \overline{w_i} f_i = \frac{\sum_i w_i f_i}{\sum_i w_i} \qquad (9)$$

We can make an adaptive rules to process because the assignment of node functions and the network configuration are arbitrary, as long as each layer perform meaningful and modular functionalities [10].

5. Simulation and discuss

5.1 PID and conventional 2-DOF PID controller in Gun-san gas turbine system

To compare the characteristics of these controllers such as, PID, the conventional 2-DOF PID, new 2-DOF PID, we adapted these controller to transfer function based on the operating data of Gun-san turbine.

Fig. 7　8 illustrate the response in case of application PID controller to gas turbine control system.

In Fig. 7, in case of fuel loop feedback control FF is having a stable shape against FS's disturbance and stable but in case of temperature feedback loop, FGT do not follow FF well in running part. So, if we use PID controller in start-up and running of gas turbine, we figure out that we can not control satisfactorily by PID controller.

Fig. 8 is the response of applying PID controller in case of P=1.24, I=0.01, D=0.0 to a temperature loop of gas turbine control system. Fig. 8 is response of total loop (fuel flow signal, gas temperature signal, and guide vane signal) in case of P=5, I=0.5, D=0. In Fig. 10, FF is having a stable shape against FS's disturbance but FGT do not follow well in running part. So, if we use PID controller in start-up and running of gas turbine, we figure out that we can not control satisfactorily

Fig. 9 show the results of the conventional 2-DOF PID controller in Gun-san gas turbine. In Fig. 9, between flow signal FS and flow rate FF is not matching exactly from 2seconds point.

Fig. 9 represents the response of total loop feedback of 2-DOF PID controller. There are many disturbances in flow signal FS but FF signal is very smooth. In Fig. 9, FF is not controlled by FS.

5.3 A new 2-DOF PID controller tuning by ANF in Gun-san gas turbine

Fig.10　12 illustrate the response in case of application a new 2-DOF PID controller to gas turbine control system.

From figure 10　11, even if parameter values P, I, D, α, β, γ, η change, the response of fuel flow is very stable in spite of the disturbance of fuel signal.

So, we can see a new 2-DOF PID controller that we proposed in this paper is having a good characteristic against the PID and the conventional 2-DOF PID controller.

6. Conclusion

Up to date, the PID controller has been used to operate under such difficult conditions in this system, but since the gain of PID controller manually has to be tuned by trial and error procedures. Getting an optimal PID gains is very difficult to tune manually without control design experience.

In this paper a new 2-DOF PID controller method has been suggested using NFS tuning.

Tuning method used in this system is NFS and this method is a good response without prior knowledge of the process. Also, Resulting by this method is more good response than the conventional PID or 2-DOF PID controller. This control method is very useful to apply process control system.

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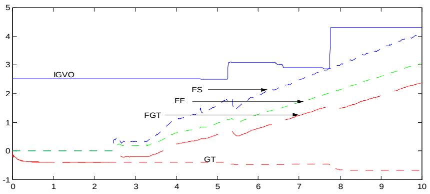


Fig. 6 A varying characteristics of each parameter Start-up process of Gun-san gas turbine.

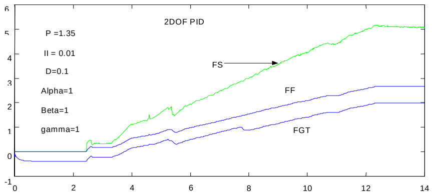


Fig. 7 A varying characteristics of each parameter in start-up process of PID controller.

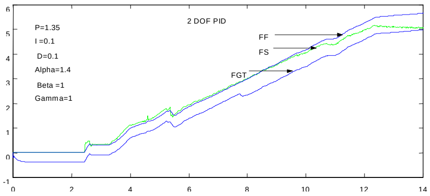


Fig. 8 Temperature feedback loop control by PID controller.

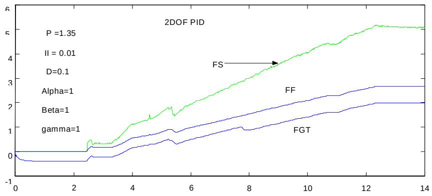
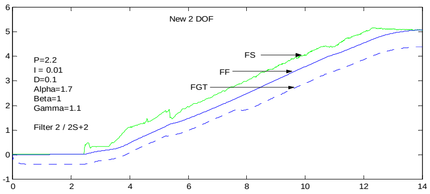


Fig. 9 Temperature feedback loop control by conventional2-DOF PID controller.

Fig. 10 Fuel feedback loop control



by NIF tuning 2-DOF PID controller.

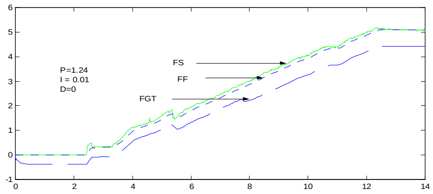


Fig. 11 Temperature feedback loop control by NIS tuning 2-OF PID controller.

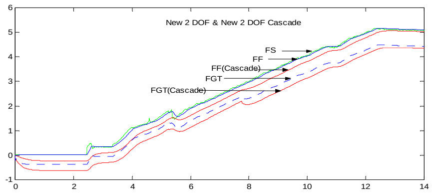


Fig. 12 Temperature feedback loop control by NNF 2-DOF PID controller.