Control of an industrial gas turbine based on fuzzy model

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***Abstract*— Today, gas turbines are one of the major parts of modern industry. They have played very imported in aeronautical industry, power generation, and main mechanical drivers for large pumps and compressors, In this paper a proportional integral (PI) control design of an industrial gas turbine based on fuzzy modeling is constructed, this work addressed the major problem of the gas turbine, the system modeling, a fuzzy modeling is used to build the system model, a PI speed control is proposed, a comparison with the mathematical model proposed by Rowen is discussed, the simulations results show that the proposed fuzzy model is reliable and can be used for gas turbine control and diagnosis.**

***Keywords*— Gas turbine; Fuzzy modeling and identification; rowen's model ; PI control.**

Nomenclature

ACDP axial compressor discharge pressure
ACDT axial compressor discharge temperature
AP ambient pressure
AT ambient temperature
CPR axial compressor pressure ratio
ET exhaust temperature
FCM fuzzy c-means
FLC fuzzy logic controller
FP fuel pressure (between SRV and GCV)
HP high pressure speed
IFT inlet fuel temperature
IGV inlet guide vanes
LP low pressure speed
NGV nozzle guide vanes

I. Introduction

Nowadays gas turbines are widely used in important applications such as power generation, oil and gas industries, processing plants, and aerospace industries. Industrial gas turbines are designed to be more efficient and reliable. To reach high efficiency, they should work close to their instability tolerance. Therefore, small external perturbation, and non-effective control systems can cause instability and even shutdown in the gas turbines. In addition, operating in non-optimal conditions can result in lower efficiency and large functional degradation. For these reasons, the demand for comprehensive nonlinear modeling of gas turbines is increasing to study the system's behavior in different scenarios and enhancing the control methodologies [1]. The mathematical modeling of gas turbines was extremely used for the sake of design, test, and control of system development [2,3]. Using nonlinear modeling techniques such as neural networks or fuzzy systems have great advantages for monitoring and fault diagnostics [8]. In this work a complex and comprehensive model based on the fuzzy clustering method using Gustafson-Kessel (GK) algorithms [4-6] and adaptive neuro fuzzy inference system (ANFIS) [5] is constructed. A PI speed control based on fuzzy modeling is proposed, to examine the effectivity of the proposed model, a comparison with the mathematical model proposed by Rowen [2] is discussed

This paper is organized as the following:

In section two, the gas turbine and system identification are described, the system fuzzy modeling and its validation are developed in section three, in section four Rowen model is described, in section five the synthesis of PI controller is developed. The simulations results of the proposed method are shown in section six, finally general conclusions of this work are presented in last section.

II. PROCESS DESCRIPTION AND SYSTEM IDENTIFICATION

A. Process Description

The Solar Titan 130 gas turbine is made of three main sections [1]: the axial compressor, the combustion chamber, and the turbine. There are a variable inlet guide vane (IGV) in the inlet of the axial compressor and a variable nozzle guide vane (NGV) in the turbine section.

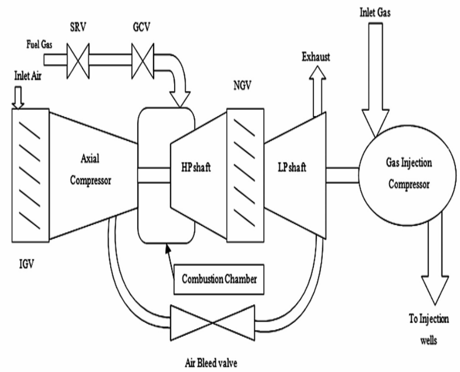

Fig. 1. The schematic of a solar *Titan 130* two shaft gas turbine.

In addition, two valves that are at the inlet fuel line of the combustion chamber are used as the main controlling devices of the gas turbine, one for control of the inlet fuel pressure that is known as the stop ratio valve (SRV) and the most important one that is used for governing the speed of the load shaft the gas control valve (GCV).The gas turbine used in this research is the solar turbines TITAN 130 two-shaft industrial gas turbine specifically designed for mechanical drive applications with a wide operating speed range to meet operating conditions of the most common driven equipment, centrifugal compressors, and pumps. In our application it is used as a gas compressor drive in the MEDJEBARA gas injection station located in Djelfa-Algeria. The last Figure 1, represent the schematic of the gas turbine system. The nomenclature used in this paper is described in ***Table 1***. The detailed information can be founding in the product manuals.

B.1 Nonlinear System Modeling:

In this work the *GK* clustering [14] is used for initial training of a Takagi–Sugeno inference system by extracting a set of rules that models the gas turbine data behavior. The GK requires separate sets of input and output data as input arguments. This model is used as an initial fuzzy inference system (FIS) for training adaptive neuro-fuzzy inference system (ANFIS) [21]. In the following sections these methods are briefly discussed.

B.2 Fuzzy c-Means Clustering:

In this work the clustering with the optimal output predefuzzification approach is used to train Takagi–Sugeno fuzzy systems. Clustering for specifying rule premises fuzzy clustering is the partitioning of a collection of data into fuzzy subsets or “clusters” based on similarities between the data and can be implemented using an algorithm called fuzzy c-means

B.3 Adaptive Neurofuzzy Inference System :

In order to optimize the parameters which are related to fuzzy inference systems, training algorithms known from the area of neural networks can be employed. These techniques exploit the fact that at the computational degree a fuzzy model can be seen as a layered structure (network), similar to artificial neural networks. Hence, this approach is usually referred to as an adaptive neuron fuzzy inference system [11,14,21]. Figure 2 gives an example of a singleton fuzzy model with two rules epresented as a network. The rules are

$$\text{IF } x_1 \text{ is } A_{11} \text{ and } x_2 \text{ is } A_{21} \text{ Then } y = b_1$$
$$\text{IF } x_1 \text{ is } A_{12} \text{ and } x_2 \text{ is } A_{22} \text{ Then } y = b_2$$

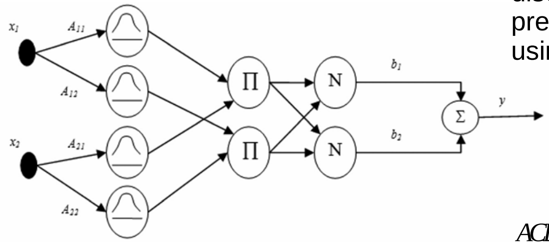

Fig. 2. A typical ANFIS model with two inputs and one output

The nodes in the first layer compute the membership degree of the inputs in the antecedent fuzzy sets. The product nodes *P* in the second layer represent the antecedent conjunction operator. The normalization node *N* and the summation node *P* realize the mean operator.

A Gaussian function is used as nonlinear membership function

$$\mu_{A_{ij}}(x_j; c_{ij}; \sigma_{ij}) = e^{-\left(\frac{x_j - c_{ij}}{2\sigma_{ij}}\right)^2} \quad (1)$$

The c_{ij} and σ_{ij} can be adjusted by gradient-descent learning algorithms, such as back propagation. This allows for fine tuning of the fuzzy model to the available data in order to optimize its prediction accuracy [1,21].

III. GAS TURBINE SYSTEM MODELING

Generally it is not suitable to train a fuzzy system with a whole range of operational data, it means that for each mode such as startup, shutdown, and normal operation a different model should be used. In this work we did not used such a classification, instead the gas turbine is divided into many subsections, including axial compressor, high pressure (*HP*) shaft, low pressure (*LP*) shaft, fuel system, and exhaust system.

A. Axial compressor

The two main variables are discharge temperature (*ACDT*) and pressure (*ACDP*) that can be modeled using

$$ACDT(k) = F_1(ACDT(k-1), HP_{speed\%}(k-1), IGV_{final}(k-1), AT(k-1)) \quad (2)$$

$$ACDP(k) = F_2(ACDP(k-1), HP_{speed\%}(k-1), IGV_{final}(k-1), NGV_{final}(k-1), AT(k-1), AP(k-1)) \quad (3)$$

HP Shaft

Normal operation (turbine is running and $HP_{speed\%}$ >65)

$$HP_{speed\%}(k)=F_3(HP_{speed\%}(k-1),FP(k-1),NGV_{final}(k-1),IGV_{final}(k-1)) \quad .(4)$$

B. LP shaft

$$LP_{speed\%}(k)=F_4(LP_{speed\%}(k-1),ACDP(k-1),FP(k-1),NGV_{final}(k-1),IGV_{final}(k-1)) \quad (5)$$

C. Exhaust systeme

$$ET(k)=F_5(ET(k-1),ACDP(k-1),ACDT(k-1),IGV_{final}(k-1)) \quad (6)$$

Where $F_n, n=1,2...,5.$ are fuzzy inference systems that were trained using real data of the industrial gas turbine. The Figures 3, 4 shows the shaft speed fitness of the HP and LP speed in the examined gas turbine and the Figure 5 shown the proposed fuzzy model validation. The *AT* and *AP* denote ambient temperature and pressure, respectively, *FP* is fuel pressure, and *ET* is exhaust temperature. To see the accuracy of this nonlinear model, it was tested and validated using several hours of turbine data to evaluate the fitness of the model, the following criteria is used:

$$\text{fitness}_{\%}=100\times\left(1-\frac{\sqrt{\sum_{i=1}^{N}\left(y^i_{\text{model}}-y^i_{real}\right)^2}}{\sqrt{\sum_{i=1}^{N}\left(y^i_{real}-mean(y_{real})\right)^2}}\right) \quad (7)$$

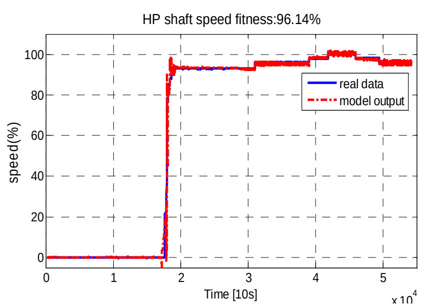

Fig. 3. HP shaft speed fuzzy model validition

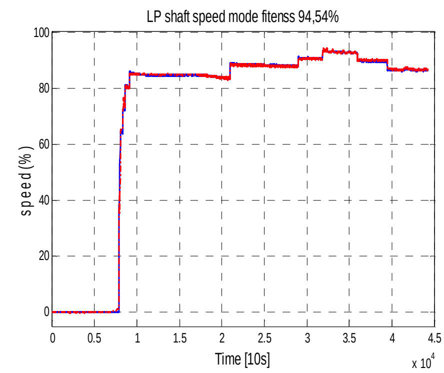

Fig. 4. LP shaft speed fuzzy model validition

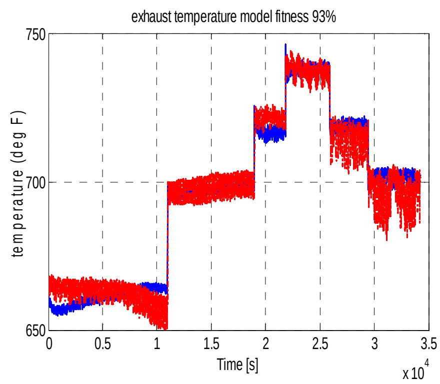

Fig. 5. Exhaust temperature fuzzy model validation

IV. ROWEN'S MODEL

In 1983, W. I. Rowen provided a model of a gas turbine that can be used for dynamic performance studies of a power system [2]. Rowen's model, shown in Figure 6, consists of a set of algebraic equations describing the steady-state characteristics of the gas turbine thermodynamics, simple time delays, and a few related controls including the temperature control, governor, and acceleration control. The model has been utilized to investigate the impacts of governor on system operation Figure 4.

A. Rowen's Model Assumptions:

As illustrated in [2], Rowen's model is based on the following assumptions:

- It is a heavy duty gas turbine, simple cycle, generator drive only
- Allowable speed range is between 95 and 107 percent of rated speed
- Open Inlet Guide Vanes (IGV) only, i.e. no Heat Recovery
- ISO conditions apply i.e. *AT* = 15*C°*,*AP*=1013.25 *pa*

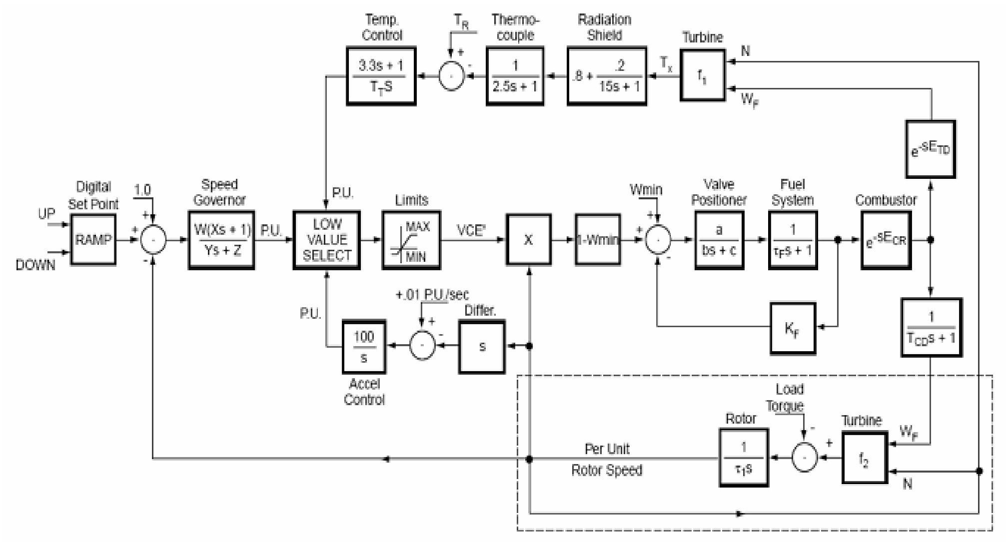

Fig. 6. Rowen's Model

V. PI CONTROL DESIGN

A PI Controller (proportional-integral controller) is a special case of the PID controller where the derivative of the error is not used, shown in Figure 7. It is a generic control loop feedback mechanism widely used in industrial control systems. It generally calculates an "error" value which is the difference between a measured process variable and a desired set point and is denoted as Δ. The PI controller attempts to minimize the error by adjusting the process control inputs. The PI Controller contains proportional term (P) and integral term (I). Here P depends on the present error and I depend on the accumulation of past errors.

The overall controller output is given by :

$$K_P\Delta + K_I \int \Delta dt \tag{8}$$

The control scheme is shown in Figure 7.

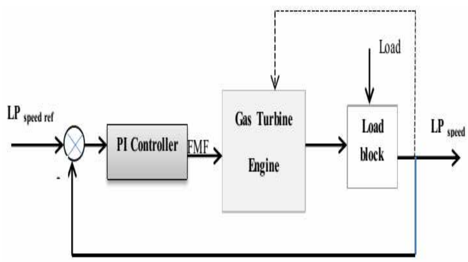

Fig. 7. Schematic of the gas turbine control

The figure 8 and 9 represent the turbine response without load, in the figures 10 and 11 represent the turbine response with load. The figures show that the constructed fuzzy model represents the system behavior and the affectivity of the PI controller.

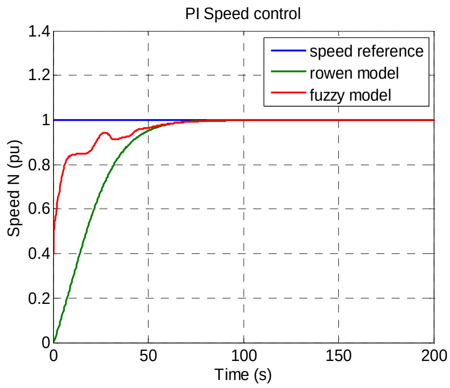

Fig. 8. PI Speed control

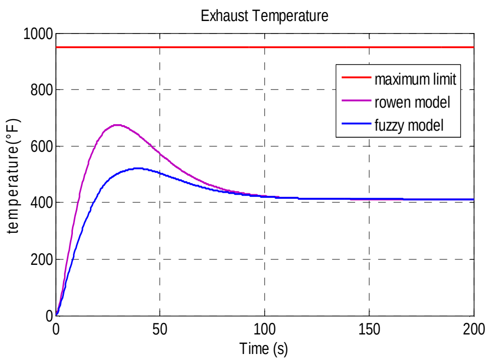

Fig. 9. PI control for Exhaust temperature limitation

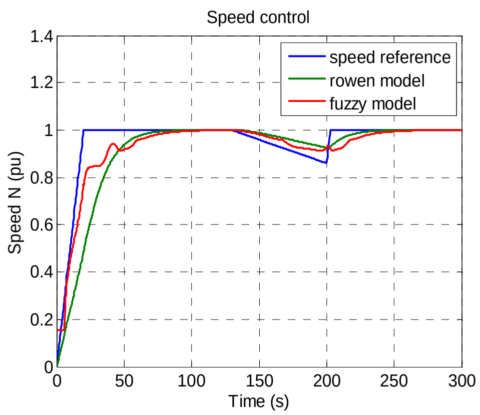

Fig. 10. PI speed control with a load

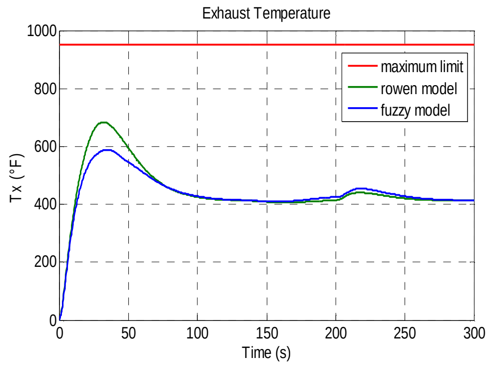

Fig. 11. PI control for Exhaust temperature limitation

VI. Conclusion

This work has addressed one of the major problems when looking for a reliable mathematical representation; the proposed fuzzy model provides a good improvement in performance during its operation for the synthesis of the controller in the examined gas turbine. The use of a fuzzy clustering algorithm has the important advantage to allow the automatic generation of membership functions of fuzzy regions from studied data. This work, confirm that the development of digital approach is obviously more flexible to implement, based on the proposed method of fuzzy clustering algorithms using Gustafson-Kessel algorithm. The obtained results from data classification with the associated models construction offers advantageous performance in modeling of the examined gas turbine system. The comparison with Rowen's model and the proposed PI controller show that this approach can provide reliable models for controlling the gas turbine and system Fault diagnosis.

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