GAS TURBINE MODELING FOR LOAD-FREQUENCY CONTROL

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Instalaţiile de turbine cu gaz au un răspuns rapid la variaţii de putere, ideal, pentru îmbunătăţirea reglajului primar frecvenţă-putere al sistemelor energetice şi de aceea sunt intens folosite la menţinerea stabilităţii sistemelor energetice. Variaţiile mari de putere cerute acestor turbine în funcţionarea normală impun necesitatea modelării şi simulării comportării acestora în regim dinamic. Această lucrare îşi aduce contribuţia printr-o analiză sistemică a controlului frecvenţă-putere pentru o turbină cu gaz industrială multi-ax, în vederea îmbunătăţirii sistemului de reglare prin considerarea neliniarităţilor sistemului.

The traditional role of the gas turbine as fast response unit, ideal for improving primary control response of the power system, has been to a certain extent lost, due to relatively high constraints in ramping up and down the power output during the normal operation. This trend must be fully reflected in the modeling and simulation of the gas turbines in power system analysis programs. The paper is a contribution to the systematic analysis of power-frequency control concepts for multi shaft high power gas turbines and the enhancement of their modeling in conventional power system analysis software.

Keywords: gas turbines, modeling, frequency and load control, power plants

1. Introduction

Power system stability requires accurate models of power system components. The availability of natural gas, together with the relatively short time for planning to commercial operation has imposed a wide use of gas turbines in the deregulated power market environment.

The gas turbine engine is a complex assembly of different components such as compressors, turbines, combustion chambers, etc., designed on the basis of thermodynamic laws [1]. Gas turbines usually consist of an axial compressor, a

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combustion chamber and a turbine operating under Brayton cycle [2]. These three elements form the thermal block are complemented by the air intake system, the exhaust system, auxiliaries and controls (Figure 1).
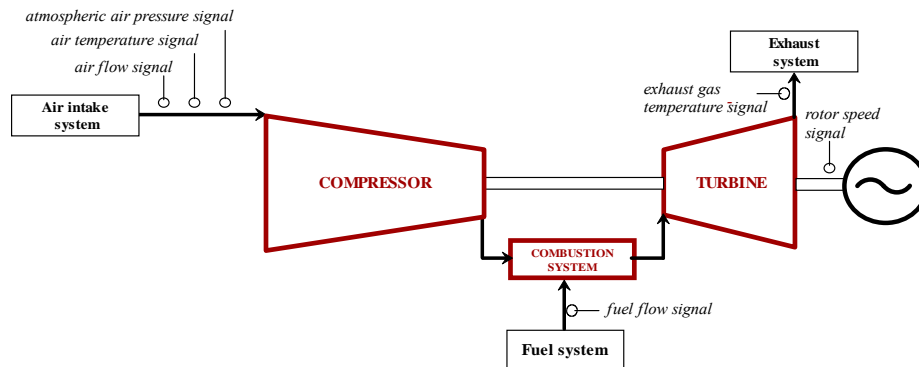

Fig.1. Single shaft gas turbine configuration

The air flow is drawn into the axial compressor and compressed through multiple stages of stator and rotor blades. The compressed air in the axial compressor is then mixed with fuel in the combustion chamber, where the combustion process takes place. The resulting hot gas is expanded through a multi stage turbine to drive the generator and the compressor.

The *fuel flow* determines the *power output of a gas turbine*. The *fuel and air flow together* determine the *firing temperature*, which is the gas temperature at the exit of the combustion chamber. The fuel flow and air flow are adjusted based on measurement of the exhaust temperature and the compressor pressure ratio in order to keep the firing temperature below a design limit. The compressor pressure ratio is determined from measurements of the inlet and discharge air pressure of the compressor (for the entire axial compressor this ratio is typical 15 to 20). The air flow can be adjusted by changing the angular position of the variable inlet guide vanes (VIGVs).

These vanes are essentially the first few stages of the stator blades inside the axial compressor assembly. When the gas turbine is loaded close to base load, the VIGVs are wide open. The air flow is a function of VIGV angle, ambient temperature at compressor inlet, atmospheric pressure and the shaft speed.

Summarizing the gas turbine outputs / inputs dependencies, a black-box system representation is given in figure 2.
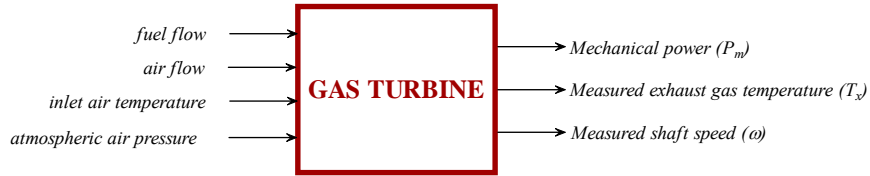
Fig. 2. System representation of gas turbine

2. Gas turbine control

The typical model of gas turbines in stability studies [3] consists of three control loops: load-frequency control, temperature control, acceleration control
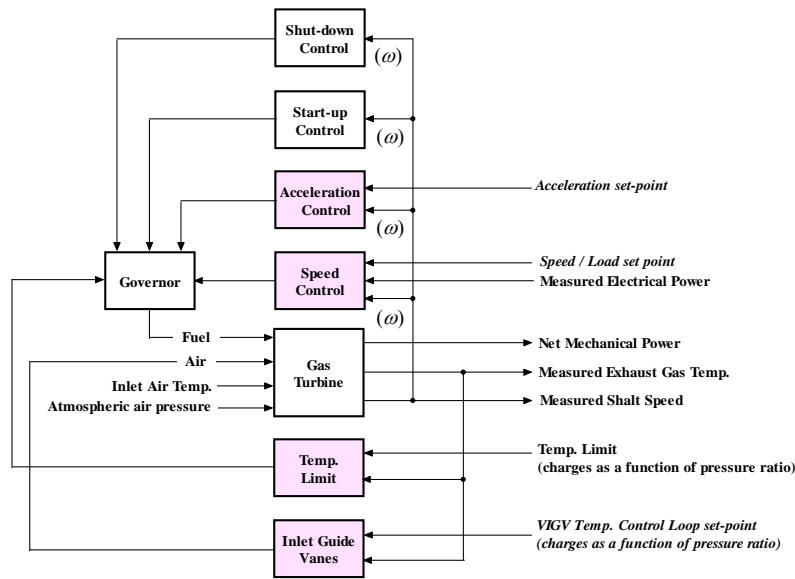Figure 3 shows a representation of gas turbine control diagram [4].

Fig. 3.Gas turbine control diagram

The start-up and shutdown controls blocks contained more control loops and logic sequences that allow ramping the unit up during start-up and downing during shutdown. The start-up controls ensure proper purging of the gas paths, establishing the flame, controlling acceleration and proper warming up of the hot paths before loading the turbine. These controls are not pertinent to power systems analysis. Typical the acceleration control loop is active during start-up and shut-down period as its set-point is variable through these processes.

The startup control sets fuel commands for firing, warm-up, and acceleration limit for starting and accelerating the gas turbine to operating speed. The fuel stroke reference determined by the startup control is passed to the fuel system.

The acceleration control controls the acceleration rate of the gas turbine during the acceleration to operating speed. The acceleration control output is restricted by the minimum fuel limit to maintain flame.

The *speed control* controls the speed of the gas turbine at operating speed when the turbine is not synchronized to the power system or is selected by the operator to perform frequency control in a multi-machine interconnected system. The speed control is restricted by the minimum fuel limit.

The *load control* is used in normal parallel operation to observe a base or a peak load limit based on temperature control. Load is controlled by changing the speed/load set point.
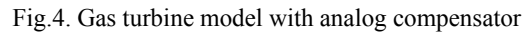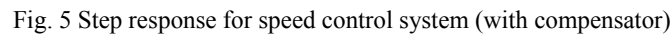
The exhaust temperature control regulates fuel in order to provide a controlled temperature increase or decrease and an upper limit for normal operation. The average value of the thermocouples sorted highest to lowest is the exhaust temperature feedback.

The inlet guide vane (IGV) control modulates the IGV angle on a schedule of corrected speed, which is a function of the compressor inlet temperature and the gas turbine speed when the gas turbine is started up. The IGV control also modulates the IGV angle to maintain high exhaust temperature during part load. The load brings the IGV angle to open due to increasing exhaust temperature. The IGV control program depends on the operation type selected of simple cycle operation and combined cycle operation.

At generator breaker open, the *shutdown control* ramps the current fuel stroke reference to the minimum fuel limit and ramps to fuel shutoff at a defined condition for the purpose to reduce the thermal fatigue duty imposed on the hot gas path parts.

3. Modeling of gas

The speed/load-frequency control is the main control loop during normal operating conditions and the most important for stability study [5]. The temperature and acceleration control are active in the case of partial operating conditions. Therefore this paper will focus on the gas turbine model with speed/load-frequency control. An example for an analog governor/compensator for simple-cycle gas turbine is drawn in Figure 4.

Fig.4. Gas turbine model with analog compensator

The model parameters [6] are depicted in Table 1 for a single-shaft, simple-cycle, heavy-duty gas turbine and an analog electronic compensator defined by:

$$H(s) = \frac{W \cdot X \cdot s + W}{Y \cdot s + Z} \tag{1}$$

In order to design an efficient control system different controllers were tested. For the speed compensator presented in Figure 4 the obtained step response is given in Figure 5. The improvement of this response was obtained by imposing desired performances at 5% the overshoot value and to 20 s the settling time.

Fig. 5 Step response for speed control system (with compensator)

Using the nonlinear control design toolbox from Matlab and considering the started optimization point the speed compensator parameters depicted in Table 1, the step response was improved (Figure 5).

The improved parameters are: W =16.8670; X =0.1573; Y =0.1229; Z=1.

A PID structure of the controller was proposed with the same performance. Using the classical PID structure:

$$H_C(s) = K + \frac{I}{s} + Ds \tag{2}$$

with K=I=D=1, the optimization procedure results were: K = 100.7769, I = 9.4714e-007; D =2.6487. The step responses of the system using the improved compensator and the PID controller are depicted in Figure 6.

Table 1.

Parameters values for gas turbine model and speed compensator

Parameter	Description	Value
W	Gain=1/droop (pu MW/ pu speed)	16.7
X	Compensator lead time constant (s)	0.6
Y	Compensator lag time constant (s)	1.0
Z	Control mode (1=droop, 0=isochronous)	1
MAX	Demand upper limit (pu)	1.5
MIN	Demand lower limit (pu)	-0.1
a	Valve positioner	1
b	Valve positioner	0.05
c	Valve positioner	1
Wmin	Minimum fuel flow	0.23
T_F	Fuel control time (s)	0.4
K_F	Fuel system feedback	0
E_{CR}	Combustion reaction time delay (s)	0.01
T_{CD}	Compressor discharge volume time constant (s)	0.2
f2	f2=1.3*(Wf-0.23)+0.5*(1-N)	
T1	Inertia	15.64

Step resonse of the gas turbine with speed compensator and PID controller
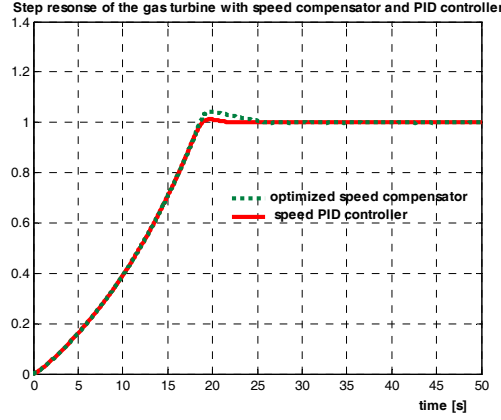

Fig. 6. Step response for speed control system (with compensator and PID controller)

4. Conclusions

Taking into account the latest developments in gas turbine technologies, the paper presents a general methodology applicable for performance analyzing of the gas turbine dynamic models for driven generating units in the power system analysis.

The gas turbine model and the associated control loops are essentially non-linear. Starting from a complex control block diagram and step-response control performances, as typically supplied by a gas turbine manufacturer, the paper reports the results obtained by imposing local response performance to a simplified linear model, readily implementable in conventional power system analysis tools.

The controller synthesis was realized using an optimization algorithm and simulated data from the nonlinear model. Simulations show the performance of the optimized control system compared with the originally implemented control structure. Following this methodology, the subsequent work intends to systematically review the dynamic models for gas turbines in power system analysis software packages and recommend their parameterization for use in system stability studies, especially those simulating major generation outages and the optimization of the under-frequency load shedding.

R E F E R E N C E S

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