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Applied Energy 80 (2005) 1–10
APPLIED ENERGY
www.elsevier.com/locate/apenergy

Matlab/Simulink-based simulation for digital-control system of marine three-shaft gas-turbine

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Accepted 8 March 2004
Available online 6 May 2004

Abstract

A gas-turbine plant model is required in order to design and develop its control system. In this paper, a simulation model of a marine three-shaft gas-turbine's digital-control system is presented. Acceleration processes are simulated via a Matlab/Simulink program. The effects of some of the main variables on the system's performance are analyzed and the optimum values of parameters obtained. A simulation experiment upon a real gas-turbine plant is performed using the digital-control model. The results show that the simulation model is reliable.

Keywords: Gas-turbine; Digital-control; Simulation; Simulink

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1. Introduction

In recent years, many investigations have been performed concerning the performance simulation of industrial gas-turbines in order to reduce both calculation times required for dynamic simulation and costs of computer systems [1–5]. With the development of modern digital-control techniques, one can enhance the perfor-

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doi:10.1016/j.apenergy.2004.03.006

Nomenclature

g	mass-flow rate
k	ratio
n	shaft-speed
nh	high-pressure spool real shaft-speed
nhc	high-pressure spool target shaft-speed
nhm	high-pressure spool setting shaft-speed
nhs	high-pressure spool initial shaft-speed
nl	low-pressure spool shaft-speed
N_e	power (kW)
p	pressure (MPa)
s	Laplace operator
T	temperature (K); time constant
W_f	fuel-flow rate

Subscripts

c	compressor
h	high-pressure
in	inlet
l	low-pressure
min	minimum
out	outlet
t	turbine
1,2,3,4	order number

Abbreviations

CC	combustion chamber
HC	high-pressure compressor
HS	high-pressure spool
HT	high-pressure turbine
LC	low-pressure compressor
LS	low-pressure spool
LT	low-pressure turbine
MT	middle-pressure turbine
PID	proportional-integral-derivative controller
V	volume

mances of turbine engines by using optimal control. The simple, hydro-mechanical control systems have been replaced by digital-control systems.

The design of a control system requires accurate models of the ‘‘plant’’ to be controlled. In the past, lumped models were often sufficient for the design and development of control systems. With the development of modern control equipment and design methods, more accurate, fully dynamic, detailed models are required. With the present dynamic-modeling technology, volume–inertia methods have been developed for the realistic simulations of gas-turbine components and systems. They are suitable for use in advanced control-system development.

Matlab/Simulink [6,7] has become the most widely used software package for modeling and simulating dynamic systems. The digital-control model adopted for the simulation of a marine three-shaft gas-turbine is described in this paper, and some examples of Matlab/Simulink formulations adopted for implementing the model are provided. The effects of some of the main variables on the systems performance are analyzed and the optimum values of the parameters obtained. A simulation experiment of a real gas-turbine plant is performed by using the digital-control model. The results show that the simulation model is reliable.

2. Matlab/Simulink environment

With the advances of control theory and computer techniques, the computer-aided control system design (CACSD) has been developed. MATLAB is one of the representatives of high-performance language for the CACSD. Simulink is a software package for modeling, simulating, and analyzing dynamic systems. It supports linear and non-linear systems, modeled in continuous time, sampled time, or a hybrid of the two. Simulation is an interactive process, so one can change parameters "on the fly" and immediately see what happens. One has instant access to all of the analysis tools in MATLAB®, so one can analyze and visualize the results. With Simulink, one can move beyond idealized linear models to explore more realistic non-linear models. For modeling, Simulink provides a graphic user interface (GUI) for building models as block diagrams, using click-and-drag mouse operations.

3. Control system modeling

For the control studies, a detailed, dynamic model is desired. The control system of a gas-turbine is made up of the control object and the controller.

3.1. Control-object module

The non-linear gas-turbine model adopted for calculations was developed in [4,5,8–12]. The overall representation of a specific gas-turbine is carried out by identifying the necessary modules and connecting them appropriately by means of thermodynamic and mechanical links.

The dynamic behavior of each module is described by means of equations representing the thermodynamic transformations and kinematic balance. As a control object, Fig. 1 shows a three-shaft gas-turbine layout by assembling the modules on the computer screen via Matlab/Simulink [13]. The volume–inertia method of simulation of a gas-turbine is applied in this model.

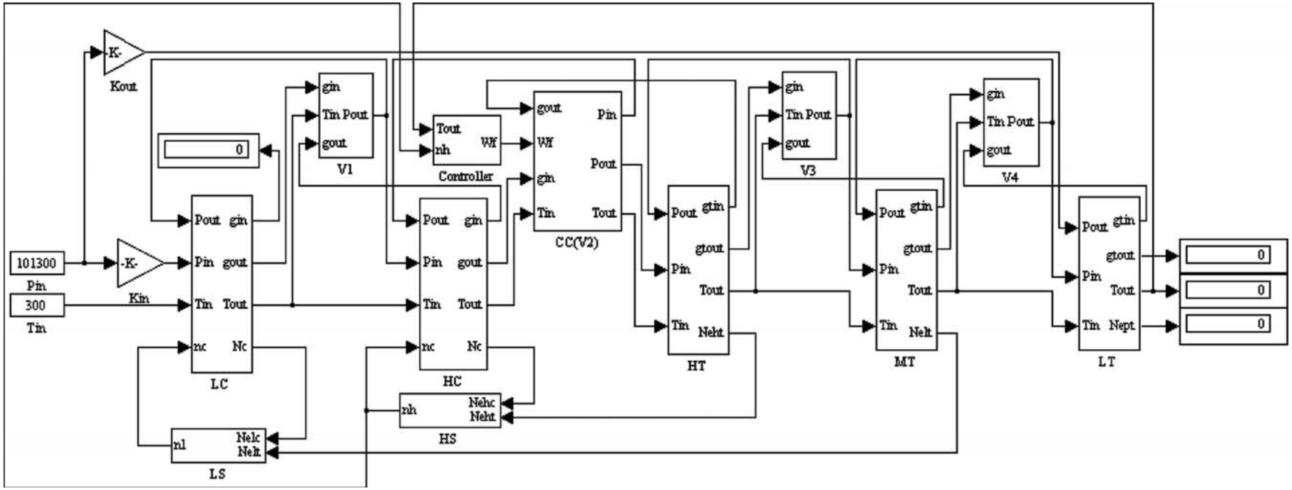

Fig. 1. A three-shaft gas-turbine layout based on Simulink.

3.2. Controller module

For a marine gas-turbine, despite the multi-variable control synthesis, the fuel control is still the main control. In order to illustrate the control process of the gas-turbine, an example of the acceleration process is provided. Fig. 2 shows the fuel-flow rate and high-pressure turbine spool-speed curves: curve *acb* is a steady process, curve *amb* is an acceleration process, and curve *bda* is a deceleration process. Point *a* is the initial state, and point *b* is the final state.

If the control process is performed simply by means of the theoretical fuel-flow rate, an over-adjustment may arise. For the control process to operate smoothly, it is important to induce a shaft-speed error control subsystem in the digital-control strategy. Therefore, a forward-feedback fuel-flow rate control consisting of the direct function control in the forepart and PID control in the rear is adopted. The temperature-control subsystem and the acceleration control subsystem are, as shown in Fig. 3.

3.2.1. Shaft-speed control subsystem

The difference-adjustment mode is applied to the shaft-speed control subsystem. A proportion-control method is employed in the PID controller. It is reasonable to

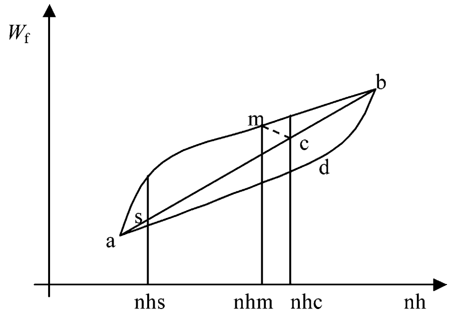

Fig. 2. Fuel-flow rate characteristic.

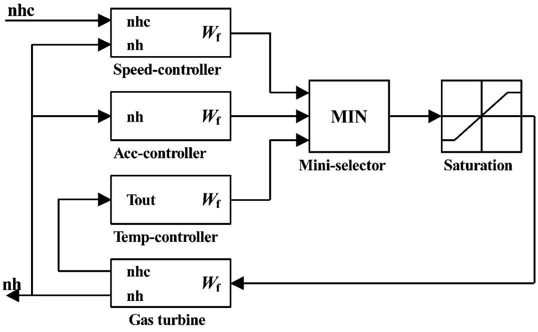

Fig. 3. Digital-control system model.

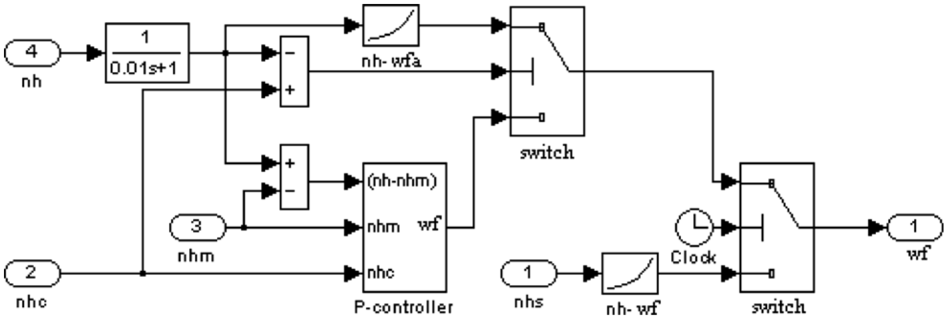

Fig. 4. Shaft-speed control subsystem block.

consider the controller as a single-order proportion–inertia control loop. The transfer function is

$$G(s) = \frac{k_1}{T_1 s + 1}. \tag{1}$$

Fig. 4 shows how the above-described modes have been implemented in Simulink. The inputs are high-pressure turbine spool speeds, including initial speed (nhs), shaft-speed (nh), setting speed (nhm) and target speed (nhc). The block called “P-control” is provided to evaluate w_f from the proportion control-loop. The time constant $T_1 = 0.01$ is set for the inertia loop.

3.2.2. Temperature-control subsystem

When the turbine’s inlet-temperature is high, the turbine’s vanes will distort. In order to restrict the turbine’s inlet-temperature T_4, a temperature-control subsystem is introduced. The power-turbine’s outlet temperature is often used as the control variable because T_4 is difficult to measure. The temperature-control subsystem is obtained by using a “PI” controller. The loop transfer function is written as

$$G(s) = k_2\left(1 + \frac{1}{T_2 s}\right). \tag{2}$$

Taking into account the measurement characteristic of the thermocouple, its transfer function can be expressed by

$$G(s) = \frac{1}{2.5s + 1}. \tag{3}$$

3.2.3. Acceleration-control subsystem

The gas-turbine may overspeed easily when its speed is increased rapidly. The acceleration control subsystem is introduced to avoid this overspeed. Like the temperature-control subsystem, the acceleration control subsystem is performed using a “PI” controller too. Its transfer function is

$$G(s) = k_3\left(1 + \frac{1}{T_3 s}\right). \tag{4}$$

All outputs of the three control-subsystems are the fuel-flow rates. After selection by a minimal selector, the ultimate result is used for controlling the parameters of the marine gas-turbine. Under normal conditions, the shaft-speed control subsystem has the decisive effect. The temperature-control subsystem and the acceleration control subsystem are usually non-effective, except under some special conditions.

4. Results and discussion

In order to complete the overall control-system model, it is necessary to establish the simulation parameters though a simulation experiment.

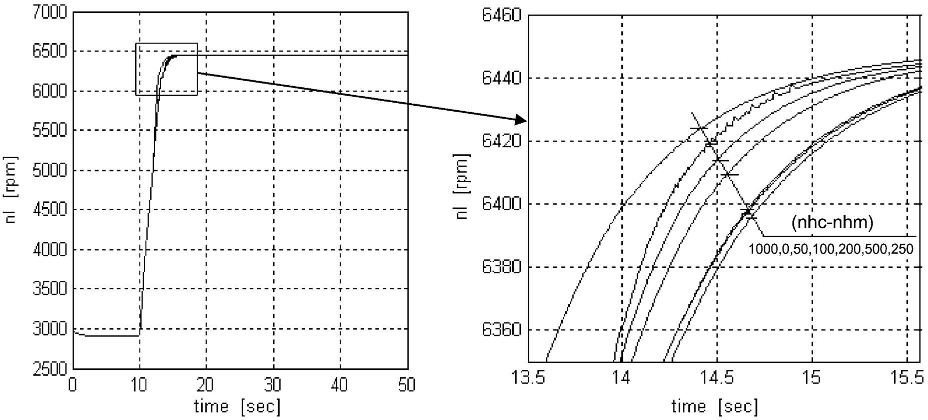

Fig. 5. Low-pressure spool-speed versus time.

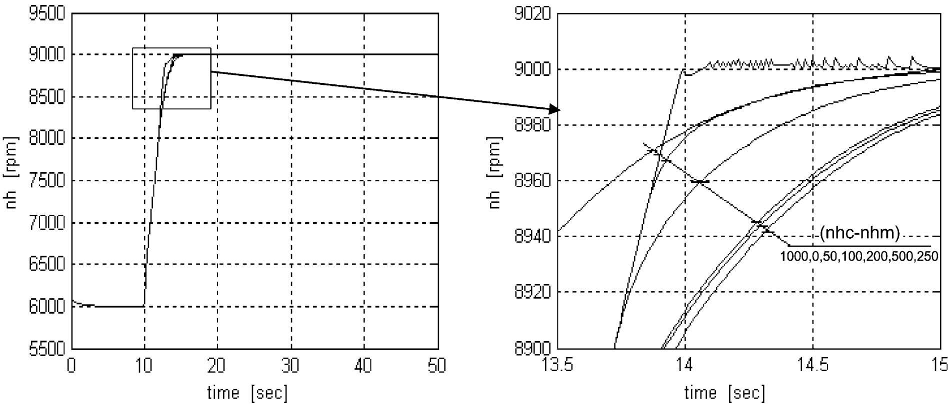

Fig. 6. High-pressure spool-speed versus time.

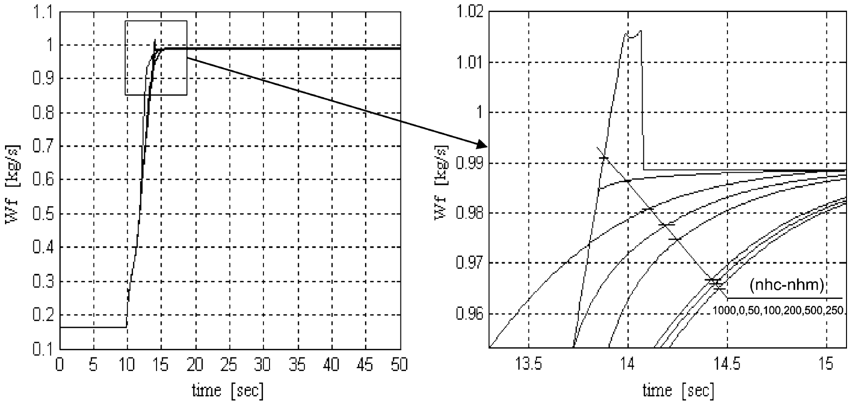

Fig. 7. Fuel-flow rate versus time.

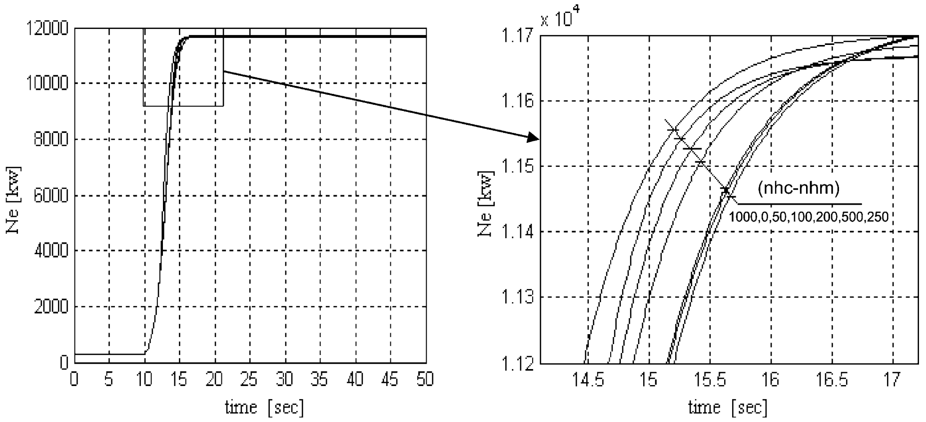

Fig. 8. Turbine's power output versus time.

Since the shaft-speed control subsystem is the main control loop, it is discussed in detail. The simulation experiment is performed by means of an adjustment of the proportion parameter, namely, the difference of nhc and nhm. When the high-pressure spool-speed is accelerated from 6000 to 9000 rpm, the results of the parameter change experiment are shown in Figs. 5–8. In these figures, the different curves show the results of $(nhc - nhm) = 0$, 50, 100, 200, 250, 500 and 1000 rpm, respectively. It can be seen that the performance of the output response is appropriate when the difference is $nhc - nhm = 100$ rpm. Fig. 7 shows that heavy falls of the fuel-flow rate are caused when $nhc - nhm = 0$.

In order to assess the validity of the digital-control system model, the results obtained by the simulation experiment are compared with those measured by gas-turbine manufacturers.

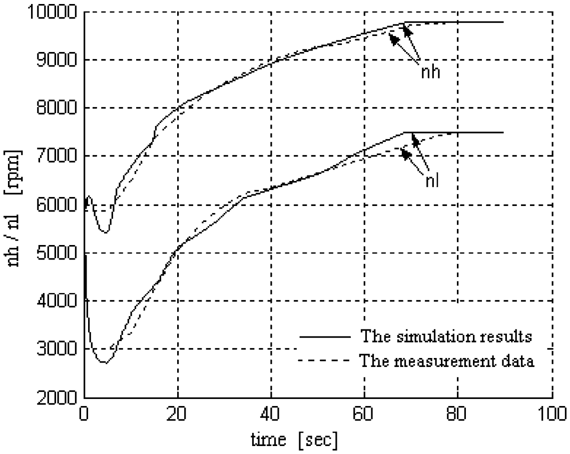

Fig. 9. Low-pressure and high-pressure spool-speeds versus time.

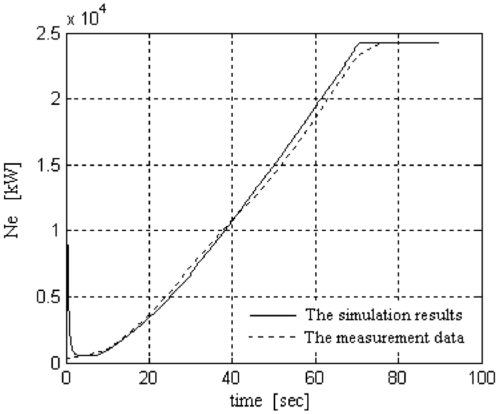

Fig. 10. Turbine's power output versus time.

The measurements for the acceleration operation from idle to the rating state are shown by dashed lines in Figs. 9 and 10. The simulation experiment results of the same operation process are shown by full lines in Figs. 9 and 10. They show that the results of the simulation are reliable.

5. Conclusion

The development of the computer has made it possible to set up a modular non-linear gas-turbine digital-control system based on the Matlab/Simulink. In this paper, a simulation model of a marine three-shaft gas-turbine digital-control system is presented. The simulation experiment of this model is performed using the digital-control model. The simulation parameters are obtained by means of a simulation experiment. The comparison of measurement data with simulation results shows that the digital-control system model is reliable.

Acknowledgements

This paper is supported by the Foundation for the Authors of Excellent Doctoral Dissertations of PR China (Project No. 200136).

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