# Real-Time Simulation of a Gas Turbine Driven Power Plant for Control System Design

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**Abstract:** Development of control systems for power plants must demonstrate satisfactory real-time performance in both, the development and the target platforms, before going into actual operation. This paper presents the simulation of a gas turbine driven electric generator and its control system to assess their performance in a real-time PC-based development platform. All programming was built with the Matlab/Simulink technical computing environment. The combustion turbogenerator 14th order model reproduces the whole dynamics in all operating stages, at start-up, from turngear-speed up to synchronization-speed, synchronization, and generation, from minimum-load up to peak-load conditions. The control system comprises the automation sequences and the feedback control loops, including speed, voltage, active power and reactive power controls. Real-time simulation experiments are presented for each operating stage. Results reveal appropriate real-time performance of the combustion turbogenerator and the control system models.

*Keywords:* Combustion turbogenerator, Gas turbine model, Synchronous generator model, Real-time simulation, Speed control, Power control.

## 1. INTRODUCTION

Power generation by means of combustion turbine driven generators plays a major role worldwide. Most power plants to be built in the next 20 years will be combined cycles based on topping combustion turbine-driven generators due to their advantages over other technologies. Key advantages include relatively low commissioning, operation and maintenance costs per unit of power, fast startup and response to load change, capability to use diverse fuel (diesel, oil and biomass), as well as versatility to integrate high performance combined cycles with fuel cells and cogeneration systems to produce electricity and steam (Horlock 2001).

A typical combustion turbine driven generator or combustion turbogenerator (CTG) consists of several major components that operate continuously and simultaneously to produce electric power (Fig. 1). The starting device can be an electric motor to initially move the CTG. The compressor takes in atmospheric air, compresses it and delivers it to the combustion chamber. In the chamber, pressurized air is mixed with fuel and burned to produce the hot flue gas that is delivered to the turbine moving blades through expansion nozzles. The exhausted flue gas is released to the atmosphere and the rotational mechanical energy is transmitted to the electric generator, which converts it into electric energy that is delivered to the power grid.

The typical CTG control system has two major components: the turbine governor and the electric generator AVR (automatic voltage regulator). The turbine governor controls speed during startup and active power after synchronization. The generator AVR controls voltage before synchronization and reactive power during generation.

CTGs operate at relatively higher speeds, pressures and temperatures, with wider variation ranges and faster changes of points of operation, than other plants. Moreover, operation of CTGs has a very high level of automation, which includes the stages of startup, synchronization, loading in different modes and stop. All these characteristics set very tight requirements for the control system. Operation, efficiency and physical integrity of a CTG depend to a great extent on the correct operation of the control system. To guarantee this, the control system real-time performance must be fully evaluated during control system development in both, the development platform and the target platform. Evaluation is carried out under controlled laboratory conditions through simulation experiments using the mathematical models of turbine and generator. Simulation experiments must include all tests in the FAT (factory acceptance test) protocol. It is strictly necessary for the control system software to show 100% error free performance (Garduno and Sanchez 1995).

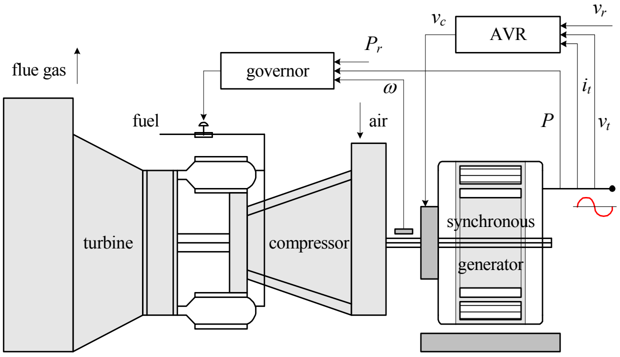


Fig. 1 Combustion turbogenerator.

This paper presents the programming of a CTG model and its control system, under a simulation environment intended to evaluate real-time performance in both development platform and target platform. Section 2 presents the CTG 14th order model and a PID-based control system configuration. Section 3 presents the simulation environment developed with Matlab-Simulink to carry out all test of a FAT protocol for a CTG and its control system. Section 4 presents the results of some real-time simulation experiments. These experiments include CTG operation in: a) Startup, from turn-gear speed up to synchronization speed, b) Synchronization with speed and voltage regulation, and c) Generation, from minimum load up to peak load throughout the generator capability curve. Section 5 concludes that real-time performance of CTG and control programming is highly satisfactory.

## 2. CTG AND CONTROL SYSTEM MODELS

The CTG model replicates the dynamic behavior of a 32 MW power plant. The CTG model is composed with a 4th order gas turbine model and a 10th order electric generator model, yielding a 14th order CTG model (Hernandez 2008).

### 2.1. Combustion turbine model

The combustion turbine model consists of about 30 algebraic equations and 4 integro-differential equations (Garduno et al 2009). Main equations are provided in what follows.

Angular speed of the compressor-turbine system:

$$\frac{d\omega_{tbna}}{dt} = \frac{I}{\omega_{tbna}}\left(E_{tbna} + E_{marq} - E_{cmpr} - E_{ftbna} - E_{gndr}\right) \tag{1}$$

Energy produced by the turbine:

$$E_{tbna} = G_{getbna}(H_{gccbn} - H_{gstbna}) \tag{2}$$

Energy consumed by the compressor:

$$E_{cmpr} = G_{aecmpr}\ \frac{P_{atm}}{\rho_a}\ k_{cmpr}\left(\left[\frac{P_{gccbn}}{P_{atm}}\right]^{Y_a} - 1\right) \tag{3}$$

Friction energy dissipated in the turbine:

$$E_{ftbna} = K_{ftbna}\ \omega_{tbna} \tag{4}$$

### 2.2. Electric generator model

The electric generator model is composed with about 20 algebraic equations and 10 integro-differential equations. Equations are obtained from rotor and stator circuits (Fig. 2). The rotor circuits comprehend the field winding and two damping windings ($k_d$, $k_q$). Coefficients of these equations are made constant with the Park´s transformation. After that the equations are normalized (Garduno et al 2009).

Stator equations in *dq0* coordinates:

$$e_d = p\psi_d - \psi_q\omega_r - R_a i_d \tag{5}$$

$$e_q = p\psi_q + \psi_d\omega_r - R_a i_q \tag{6}$$

$$e_0 = p\psi_0 - R_a i_0 \tag{7}$$

$$\psi_d = -L_d i_d + L_{afd} i_{fd} + L_{akd} i_{kd} \tag{8}$$

$$\psi_q = -L_q i_q + L_{akq} i_{kq} \tag{9}$$

$$\psi_0 = -L_0 i_0 \tag{10}$$

Rotor equations in *dq0* coordinates:

$$e_{fd} = p\psi_{fd} + R_{fd} i_{fd} \tag{11}$$

$$0 = p\psi_{kd} + R_{kd} i_{kd} \tag{12}$$

$$0 = p\psi_{kq} + R_{kq} i_{kq} \tag{13}$$

$$\psi_{fd} = L_{ffd} i_{fd} + L_{fkd} i_{kd} - \frac{3}{2} L_{afd} i_d \tag{14}$$

$$\psi_{kd} = L_{fkd} i_{fd} + L_{kkd} i_{kd} - \frac{3}{2} L_{akd} i_d \tag{15}$$

$$\psi_{kq} = L_{kkq} i_{kq} - \frac{3}{2} L_{akq} i_q \tag{16}$$

It is considered that the generator is connected to the electric grid with a transmission line, in a single-machine-infinite-bus system. The terminal voltage is:

$$e_{dr} = R_E i_{dr} - X_E i_{qr} + E_{Bdr} \tag{17}$$

$$e_{qr} = R_E i_{qr} - X_E i_{dr} + E_{Bqr} \tag{18}$$

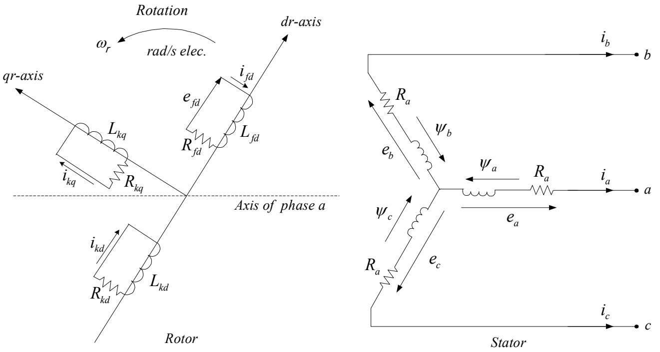


Fig. 2 Rotor and stator circuits of a 3-phase synchronous generator.

### 2.3. Feedback control system model

Essentially, the turbine control system contains two control circuits: the inlet guide vanes position control circuit to regulate air flow and a dual speed and power control circuit to regulate fuel flow. In the former circuit, flue gas temperature, compressor discharge pressure and turbine speed are permanently monitored to set safety limits to the fuel valve demand signal to ensure CTG physical integrity. At startup, the control system activates the closed loop speed control at the time of fuel ignition up to rated speed. At the time of synchronization to the power grid, the closed loop power control is activated. These control loops are usually based on PI or PID control algorithms. The speed control loop and the active power control loop form a parallel-cascaded control scheme, as shown in Fig. 3. The control signals from both control loops add up into a single control signal for the fuel control valve to modulate the gas flow.

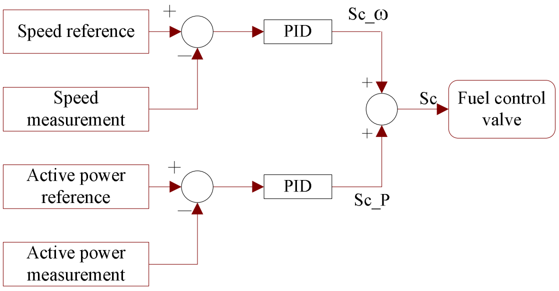


Fig. 3 Speed and active power in a parallel-cascaded scheme.

The generator control system has a voltage control loop and a reactive power control loop, both based in digital PID controllers, which constitute a series-cascade control scheme, as shown in Fig. 4. The control signal of the reactive power is added to the voltage reference signal. The sum is the resultant voltage set-point for the voltage control loop. The control signal of the voltage loop drives the control voltage for the excitation system of the electric generator.

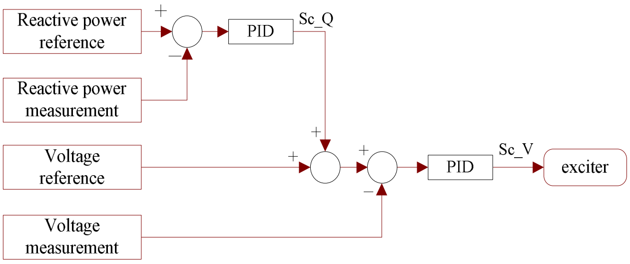


Fig. 4 Voltage and reactive power control loops in a series-cascaded scheme.

### *2.4. Models programs*

The complete CTG model and control system were programmed in the Matlab-Simulink software for modeling and simulation of dynamic systems. Basically, programs are built with block diagrams that are hierarchically ordered in a range of levels. The main block diagram of the CTG model corresponds to level 1 (Fig. 5).

The main blocks of the combustion turbine can be found at level 2 as shown in Fig. 6. These blocks include: actuators, starting motor, gas feeding system, compressor, combustion chamber and power turbine. The main blocks of the generator model are: rotor winding, stator winding, electromagnetic flows, magnetic saturation, electric torque and EtaSin. These blocks are located at level 4 and depicted in Fig. 7. As said before, the turbine control loops form the parallel-cascaded scheme in Fig. 8, while the generator control loops form the series-cascaded scheme in Fig. 9.

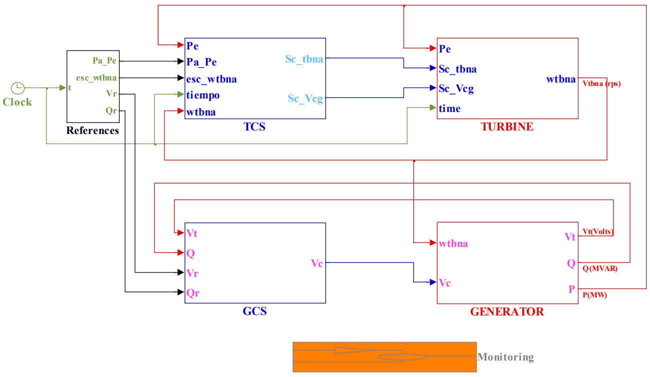


Fig. 5 CTG model and control system in Level 1.

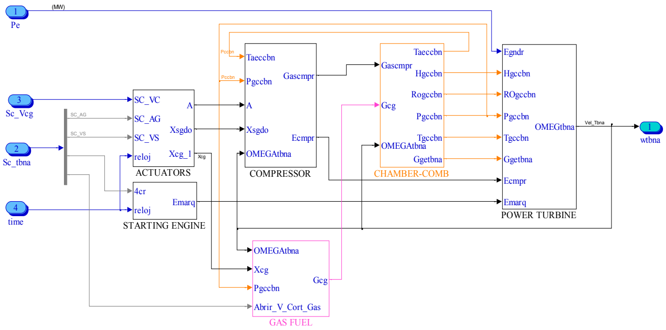


Fig. 6 Gas turbine model in Level 2.

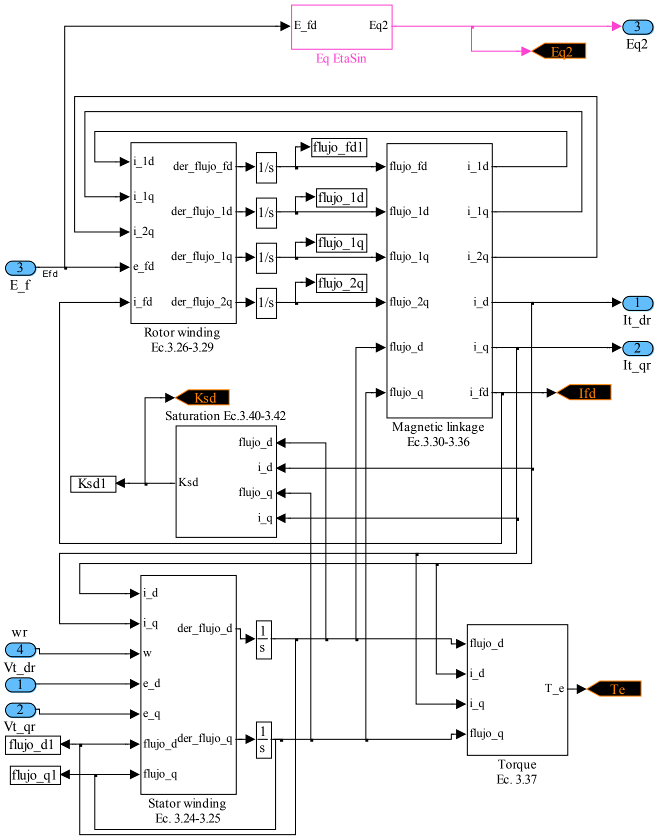


Fig. 7 Synchronous generator model in Level 4.

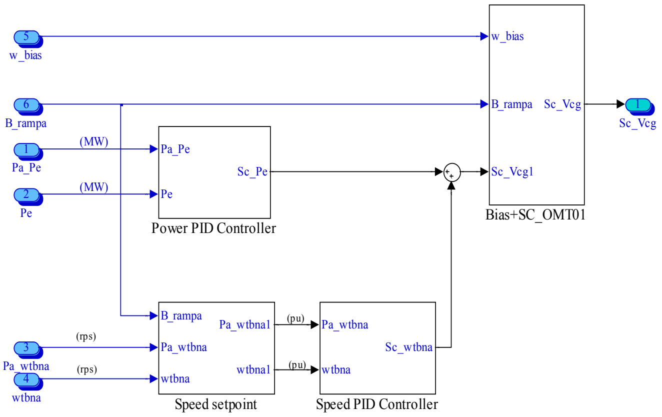


Fig. 8 Turbine control scheme.

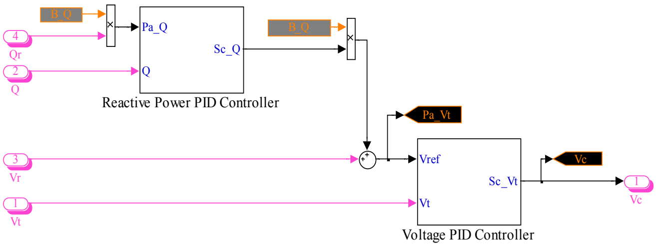


Fig. 9 Generator control scheme.

## 3. SIMULATION ENVIROMENT

The simulation environment is the set of programs whose interaction produces the simulation experiments required to test the control systems for the combustion turbogenerator. These programs can be executed in both a PC platform, to perform non-real-time and real-time simulation experiments, and a PXI target platform to perform real-time simulation experiments. The simulation environment (Fig. 10), in both platforms, consists of three major software components: a set of Matlab files (m files), a graphical user interface (GUI) and the CTG models in Simulink (mdl file).

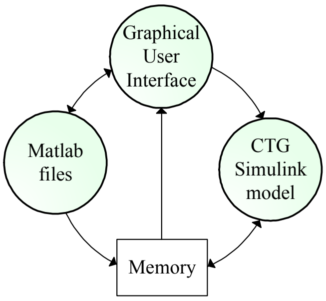
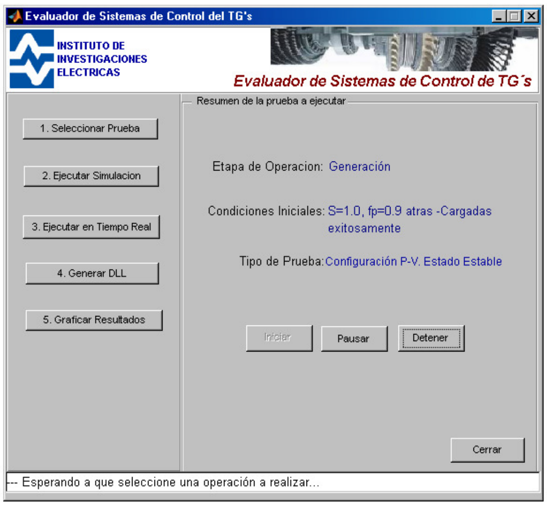


Fig. 10 Simulation environment.

The Matlab files are source code that define and load into the working memory the numerical values of parameters and initial conditions of the CTG model, and also set the parameters for simulation. The GUI provides the means to select and to define the characteristics of the simulation experiments. Lastly, the CTG model in Simulink is a set of block diagrams that constitute the programming of the CTG and control system mathematical models (Alcaide 2009).

### 3.1. Graphical User Interface

The GUI consists of a Matlab file and a set of figures to be displayed through the operation dialog. The GUI performs five major actions: 1) Provides the means to select any of the 150 tests available, 2) Calls the Matlab files to load data into memory as required by the selected test, 3) Calls the CTG Simulink model for execution of the simulation experiment in either non-real-time or real-time, 4) Generate code for real-time as a dll for target platform, and 5) Display graphs of data saved in memory at the end of simulations. In general, the model gets the required data from memory and performs the simulation experiment.


Evaluador de Sistemas de Control del TG's

INSTITUTO DE INVESTIGACIONES ELECTRICAS

Evaluador de Sistemas de Control de TG´s

Resumen de la prueba a ejecutar

Etapa de Operacion: Generación

Condiciones Iniciales: S=1.0, fp=0.9 atras -Cargadas exitosamente

Tipo de Prueba: Configuración P-V. Estado Estable

-- Esperando a que seleccione una operación a realizar...

Fig. 11 Graphical user interface of simulation environment.

### 3.2. Set of tests

The simulation environment allows realization of simulation experiments to evaluate the performance of the control system (Fig. 12). During startup only the startup test is available, which is a fixed schedule of events. At synchronization there are 5 tests available related to the ability of the control system to regulate the generator speed and the generator terminal voltage. During generation, there are 144 tests available at 12 points of operation within the generator capability curve and at 4 points of operation outside the generator capability curve (overload conditions).

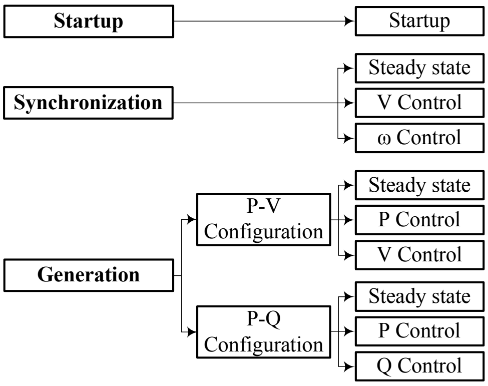


Fig. 12 Tree of available simulation experiments.

### *3.3. Generation and execution of real-time code*

Production of real-time code is illustrated in Fig. 13. The executable code is built with the Real-time Workshop software, which uses the CTG block diagram in Simulink and the Matlab code to convert them in C language. Then, C code is compiled to generate the executable code of the CTG, which is called Real-Time Application.

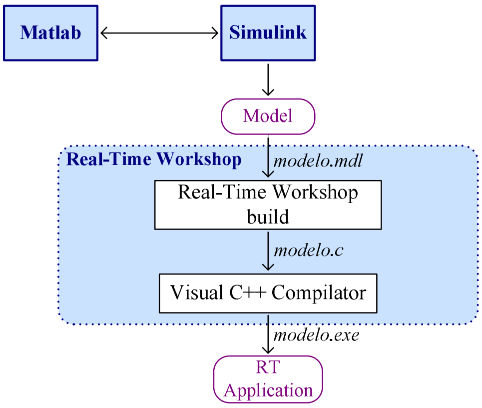


Fig. 13 Generation of CTG model real-time application.

Code execution in real-time is governed by the Real-Time Windows Target through a Kernel that manages the PC resources (Fig. 14). The Kernel intercepts the interrupts of the PC clock to update calculations in the real-time applications and to send them for displaying to the Simulink diagram, which must operate in external mode. Table 1 provides major real-time simulation characteristics.

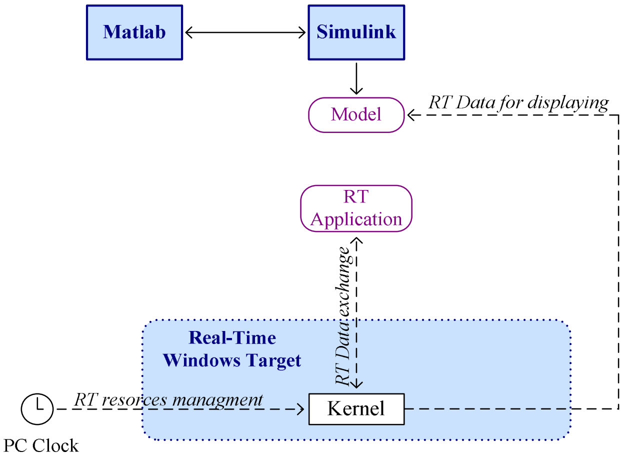


Fig. 14 Execution of CTG model in real-time.

**Table 1. Real-time simulation characteristics**

| Characteristic | Parameter |
|---|---|
| Start time, stop time | $t_0$ , $t_1$ |
| Solver type | Fixed-step |
| Solver | Ode3 (Bogacki-Shampine) |
| Fixed-step size | h=0.001 |
| Simulation mode | External |
| System target file | Real-time windows target |

## 4. REAL-TIME SIMULATION PERFORMANCE

This section presents some results of real-time simulation experiments. The experiments include normal CTG operation maneuvers such as those realized in everyday operation, including: a) CTG startup, from turn-gear speed up to synchronization speed, b) Speed and voltage regulation as for synchronizing the CTG to the electric grid, and c) Generation, from minimum load up to peak load throughout the generator capability curve (Fig. 15).

The simulation environment provides up to 16 different points of operation where tests at generation stage can be carried out. Simulations at minimum load can be started in points P1 to P4, at medium load in points P5 to P8, at base load in points P9 to P12 and at peak load in points P13 to P16. Such points also define operation at different power factors: 0.8 lagging, 0.9 lagging, 1.0 and 0.95 leading.

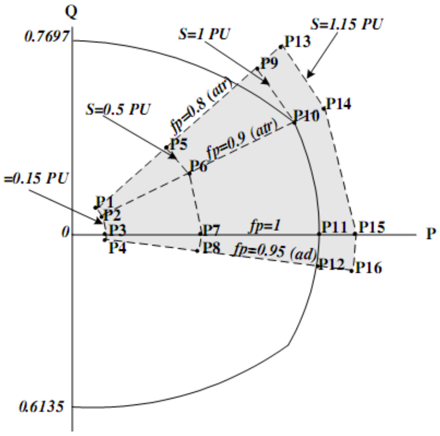


Fig. 15 Capability curve of CTG.

Figure 16 shows CTG startup. Curves are the turbine speed in rps (red), the speed reference in rps to set the acceleration pattern to be followed in real-time by the CTG (blue), the demand signal to the gas fuel control valve (green).

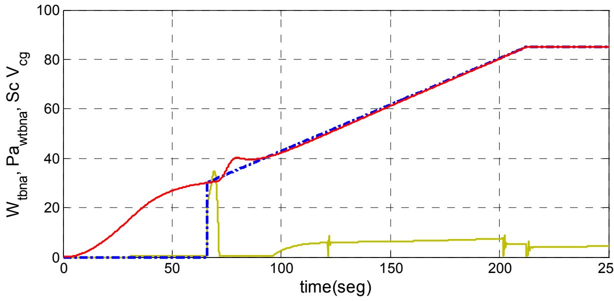


Fig. 16 Speed control during start up.

At the synchronization stage, Figure 17 shows voltage build up at the generator output terminals from 0 pu up to nominal voltage (1.0 pu). The voltage response is reasonable in time and amplitude. Figure 18 shows the speed response to an increasing 0.15 rps step in the speed reference. This step corresponds to a variation of 1 Hz in the frequency of the generator terminal voltage, which is a rather large deviation in an actual power system. Response matches those of actual power plants.

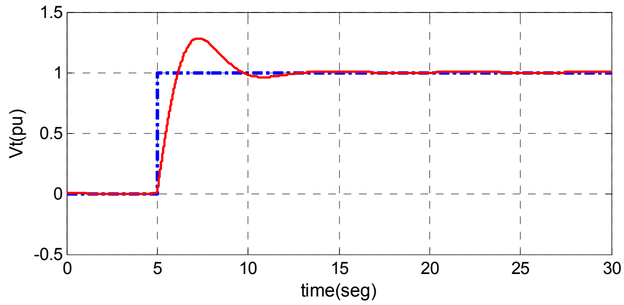


Fig. 17 Voltage control at synchronization speed.

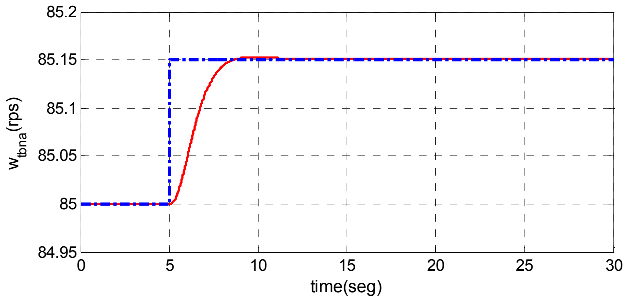


Fig. 18 Speed control before synchronization.

Figures 19, 20 and 21 give an idea about the performance of CTG at the generation stage. Figure 19 shows the response of active power to a 2% step change in the active power reference when the CTG is at medium load and 0.9 lagging power factor.

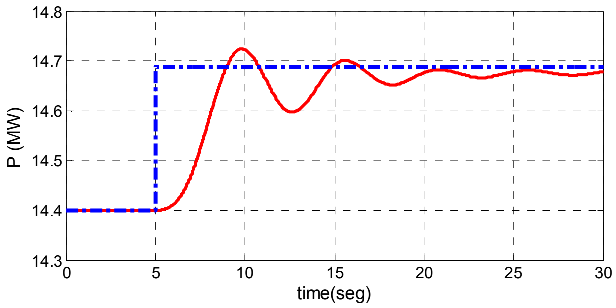


Fig. 19 Active power control at generation stage.

Figure 20 presents the response of the reactive power after a 30 KVAR load loss when the CTG is overloaded at 0.9 lagging power factor. The response produced by the AVR is fast and stable.

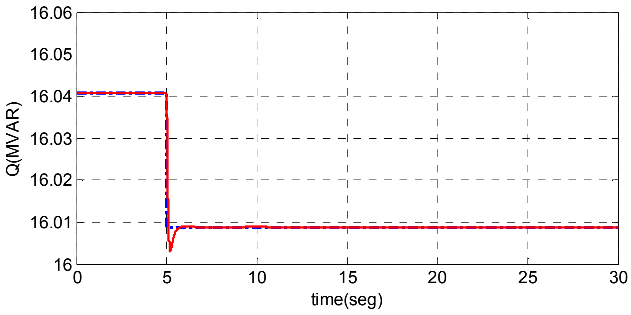


Fig. 20 Reactive power at generation stage.

Figure 21 presents the output terminal voltage after a 0.01% increment in voltage reference at nominal load and 0.9 lagging power factor.

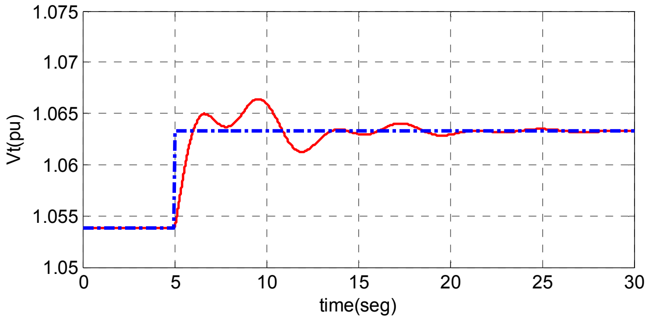


Fig. 21 Voltage control at generation stage.

## 5 CONCLUSIONS

This paper presented the real-time simulation of a gas turbine driven power plant and its control system. Results of simulation experiments at each one of the CTG operating stages demonstrated satisfactory real-time performance.

The proposed simulation environment can be used to carry out some stages for the development of actual CTG control systems. These include control software debugging in non-real-time and real-time, as well as factory acceptance tests, with the advantage of being able to monitor a large quantity of signals from the CTG and the control system, to improve analysis. Therefore, the proposed simulation environment can be used to analyze and to design more sophisticated control systems to improve operation of CTG, such as those already reported in Garduno et al. (2009). Future work includes obtaining the ability to send and receive physical signals.

## REFERENCES

Alcaide, I.X. (2009). *Real-time implementation of a Combustion Turbogenerator model for a control systems test-bench.* B.S.E.E. Thesis. Morelos State Autonomous University, Mexico.

Hernandez, I.V. (2008). *Integrated model of a Turbo-generator: Analysis, simulation and control.* M.S.E.E. Thesis. National Centre for Research and Technology Development, Mexico.

Horlock, J.H. (2001). *Advanced Gas Turbine Cycles.* Krieger Publishing.

Garduno R. and Sanchez M. (1995). Control system modernization: Turbogas unit case study. *Proc. IFAC Symposium on Control of Power Plants and Power Systems, Vol. 2, pp. 245-250.*

Garduno R., Delgadillo M.A., Hernandez I., Alcaide I.X. and Guevara R. (2009). Modelling and simulation of a combustion turbogenerator for control analysis and design. *Proc. IFAC Symposium on Control of Power Plants and Power Systems.*

Garduno R., Rodriguez A. and Castelo L. (2009). 2 DOF fuzzy schemes for combustion turbogenerator wide-range speed control. *Proc. 15th International Conference on Intelligent System Application to Power Systems.*