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Mathematical Model of a 106 MW Single Shaft Heavy-Duty Gas Turbine ⋆

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Abstract: In recent years, several thermal power plants were built in Brazil and the percentage of participation of this kind of power generation increased in the local energy market. Since the 1980's, several studies developed mathematical models for gas turbines to be applied in power system analysis. These are simplified representations of static and dynamic behavior of machines. However, published works in dynamic gas turbine models represent a narrow set of machines, and most of the applications in power system analysis employ them, despite the fact that they are not accurate representations of some specific machines. This work presents the modeling procedure and validation for a 106 MW heavy-duty gas turbine working in combined cycle in a Brazilian thermal power plant. The gray-box approach, based on an existing tuned model based on real sampled data, is used, and the modeling involves a static approach in steady state, and dynamic modeling with system identification from sampled data. Sampled data were corrected to standard environmental conditions. The model was developed and validated in MATLAB®-Simulink®.

Keywords: Power system modeling; thermal power generation; thermoelectricity; gas turbine; turbogenerator.

1. INTRODUCTION

In 2005, 85.1% of the Brazilian total power generation was from hydroelectric power stations, whereas only 3.1% was from natural gas-fueled thermal power stations. In 2016, such percentages were 65.2% and 13%, respectively. A 38%-increase in the thermal power generation was due to the natural gas-fueled generation (Tolmasquim et al., 2016). The National Electric System Operator (ONS) reported a growth of 448% in thermoelectric power generation in the period 2002 to 2012 (ONS, 2013).

Combined Cycle Power Plants (CCPPs) have advantages over non-combined cycle power plants such as higher efficiency, lower emissions, shorter installation and operation times, lower initial costs, and fuel flexibility. CCPP operations include frequent startup/shutdown, which must be optimized through model-based analyses (Ferreira, 2015; Tică et al., 2012).

Models for CCPPs are commonly based on the Modelica language, or other suitable simulation platforms, so as to provide for optimization studies (Tică et al., 2012).

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1.1 Modeling of Gas Turbines

The Gas Turbine (GT) is an important component of a CCPP, and its appropriate modeling is mandatory (Shalan et al., 2010). A commonly employed modeling technique is the gray-box identification supported by nonlinear approaches such as Wiener modeling, NARX structures, artificial neural network-based modeling, multivariable model predictive control or hybrid fuzzy models. Some works employed behavioral modeling in contrast (Pires et al., 2018; Meyer et al., 2015; Mohammadi and Montazeri-Gh, 2015; Asgari et al., 2014). Also, some researchers employed their own nonlinear model simulation frameworks, or developed simplified physics-based models (Gülen and Kim, 2014). For example, W. I. Rowen provided a simplified dynamic model for a simple cycle, single shaft power generation GT, aiming at carrying out power system stability studies (Rowen, 1983).

Regarding power generation, heavy-duty GTs operate in simple cycle with an efficiency of about 36%, whereas they may reach an efficiency of about 58% in combined cycle operation. In such applications, the GTs must respect the operating limitations of the Heat Recovery Steam Generator (HRSG) (Kehlhofer et al., 2009).

1.2 Models for Combined Cycle Power Plants

Some mathematical models of GTs are composed of equations of thermal, mass, and energy balance for dynamic simulations in MATLAB®-Simulink® (Asgari et al., 2014).

The GT of a typical CCPP is equipped with a variable Inlet Guide Vane (IGV) that adjusts the airflow to maintain a high exhaust gas temperature. Load optimization is the primary function of the modulating IGV control (Rowen, 1992). The control loop for exhaust gas temperature is taken into account in the model. Rowen (1992) presented this model as the block diagram reproduced in Figure 1.

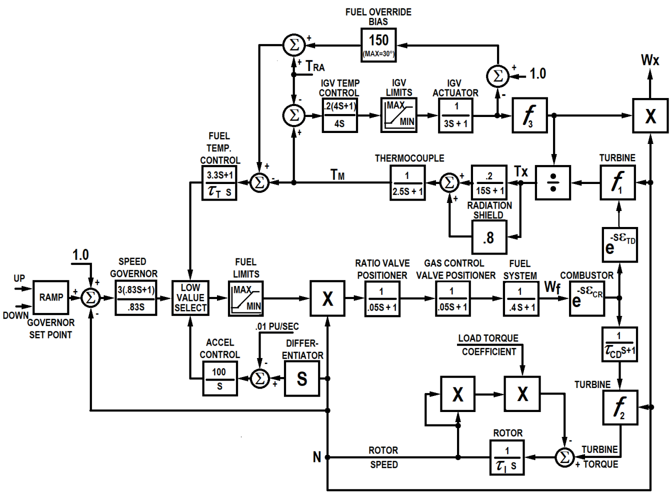

Figure 1. Simplified Representation of Single-Shaft Mechanical Drive Gas Turbine (Rowen, 1992)

Closing the IGV decreases the airflow, increases fuel-to-air ratio in the combustion chamber and causes the exhaust temperature to increase approximately in inverse proportion to the airflow change (Massucco et al., 2011).

A later work shows that model applied for power generation in CCPP applications (Yee et al., 2008), see Figure 2. It has been used in several studies regarding CCPPs, including the present work.

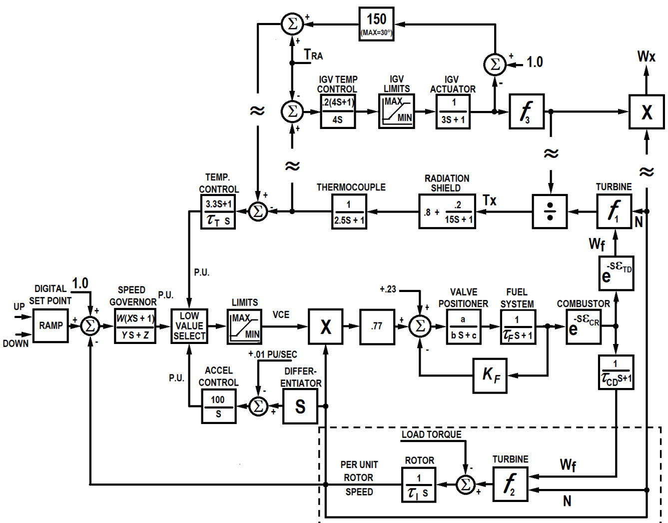

Figure 2. Model for CCPP applications (Yee et al., 2008)

2. POWER PLANT DESCRIPTION

The present study analyzes a CCPP facility of 1.040 MW total capacity, installed near an oil refinery in the state of Rio de Janeiro, Brazil. It is composed of three thermal power generation blocks, each one equipped with two GTs, two HRSGs, and one Steam Turbine (ST).

The model of the GT (Block I) of the CCPP shown in Figure 3 is presented in the following diagram. It is the heavy-duty industrial GT GT11N2, manufactured by Alstom. It has silo-type combustion chamber, 14-stage compressor with pressure ratio of 16:1, 4-stage turbine, air-cooled in the first two stages, and IGV (ALSTOM, 2005).

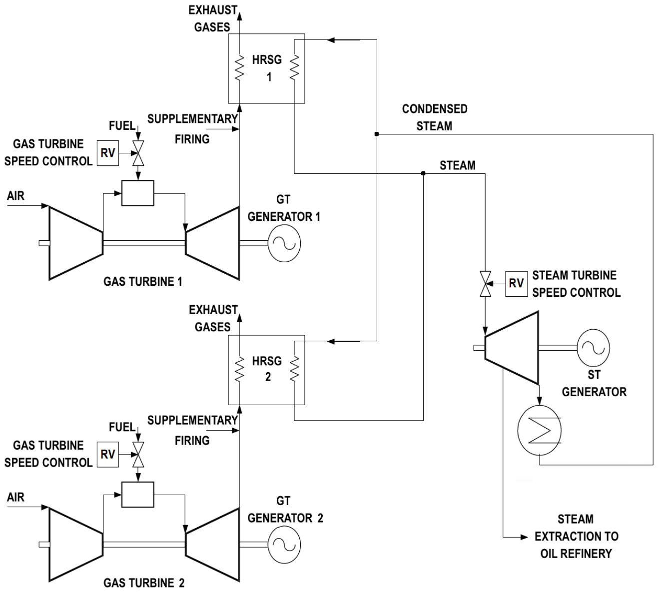

Figure 3. Schematic Diagram of Block I

The studied GT has nominal power of 115 MW (ALSTOM, 2001). The IGV allows the GT to maintain a high exhaust gas temperature, i.e. the Temperature After Turbine (TAT), in a significant range of operation.

3. GAS TURBINE MODEL AND SIMULATION

Previous works already presented models for the thermal power block of the studied CCPP. Some of them show simulation results combined with the results produced by the computer analysis tool called ANATEM. Those simulations supported the stability analysis of the power system near the studied CCPP under several disturbance conditions (Rendón et al., 2015, 2014). A detailed of the stability analysis of the power system in a possible islanding, using electromechanical simulation in ANATEM with the support of a software tool developed by the research team, can be reviewed at (Marcato et al., 2015).

Model variables vary with the environmental conditions, such that design values must be defined in order to correct values of environmental variables (Volponi, 1999). In this work, sampled data were corrected to the standard ambient conditions: 22 °C and 101 kPa (ALSTOM, 2001).

The model variables are in '1.0 Per Unit' (pu) values, the decimal equivalent of the design value. It consists of dividing a given quantity by its base value in the same unit and order (Anderson, 1995). Since the model represents the dynamic energy conversion between components, variables such as W_f and W_x were calculated in energy flow units [J/s]. Table 1 presents the base values for the present work.

Table 1. Base Design Values at 22 °C and 101 kPa

Depiction	Design Value	Unit
GT Fuel Flow W_f Base [a]	342.4	MJ/s
GT Power Generation Base [b]	106.1	MW
GT Speed N Base	3600.0	rpm
GT Exhaust Gas Flow W_f Base [c]	366.0	MJ/s
GT *Torque* Base [d]	281.4	N·m

[a] Converted from mass flow with Low Heat Value (LHV).
[b] Nominal power by catalog is 115 MW (ALSTOM, 2005).
[c] Calculated with DESTUR (Avellar, 2010).
[d] Calculated from power generation and speed.

The model includes the control laws for two operating conditions, either i) isolated or ii) in parallel with the power grid, and may be observed in Figure 2. It is based on the gray-box method, i.e. derived from physical relations (first principles) whose coefficients are adjusted so that the model responses are able to fit real sampled data. It was necessary to obtain data in several operating conditions, with load variations from no load to full load. Most of the blocks were validated with sampled data in steady state conditions.

Samples and technical documentation by Alstom helped to calculate the TAT limit (T_r) of 540 °C, Turbine Inlet Temperature (TIT) part load limit of 1065 °C, TIT base load limit of 1085 °C, and IGV limits from −41 °C to 5 °C (ALSTOM, 2001). The available sampling time was 1 s. Table 2 provides details about the sensors of the CCPP.

Table 2. Sensor Information (ALSTOM, 2005)

Depiction	Sensor	Units	Deviation	Symbol
SPEED	gen. meter	rpm	±1%	N
TAT	thermocouple	°C	±1%	TAT
IGV COMM.	digital	°C		IGV_c
IGV POS.	potentiometer	°C		IGV
AMB. PRESS.	capacitive	mbar	±1%	p_a
AMB. TEMP.	PT100	°C	±2%	T_a
FUEL FLOW	turbine meter	kg/s	±1%	W_f
FUEL LHV	gas analyzer	kJ/s	±1%	
TIT	calculated	°C	±2%	TIT
GEN. POWER	wattmeter	MW	±1%	

The exhaust gas flow W_x was calculated with the aid of DESTUR, a software developed in FORTRAN and dedicated for GT analysis (Avellar, 2010). The *torque* was determined in steady state conditions relying upon data from the electric generator power and N, and an estimation of GT electric generator efficiency from zero to full load (ALSTOM, 2005).

4. GAS TURBINE MODELING PROCEDURE

The employed procedure consisted in the following steps:

(1) To correct GT data to standard environmental conditions (Volponi, 1999), and calculate the variables which are not measured in the CCPP system, as mentioned in Section 3;
(2) To convert GT data of Set Point (SP), fuel flow (W_f), *torque*, speed (N), and W_x to pu representation using the base values in Table 1;
(3) To adjust the parameters in the blocks for TAT control by IGV for limits: −41 °C to 5 °C for IGV and 0.46 to 1 for L_{igv};
(4) To define the 'REFERENCE TEMPERATURE' equation using the standard temperature condition (22 °C);
(5) With the standard temperature T_a, IGV limits (−41 °C to 5 °C), and steady state data for IGV, power generated, W_f, W_x, and N using least squares method to calculate the parameters of equation f_{1-GT};
(6) From corrected data, to calculate the no load fuel demand (W_{fmin});
(7) To adjust parameters in the equation f_{2-GT} using data from W_f, N, and *torque* in steady state conditions;
(8) To calculate the inertia rotor time constant τ_I, as well as values for '*droop*' and K_D, based on the information from the ONS;
(9) To use steady state data for L_{igv} and W_x, as well as the least squares method, to calculate the equation f_{3-GT};
(10) To determine values for the 'IGV TEMPERATURE CONTROL' block based on dynamic values for L_{igvc} command and L_{igv} position;
(11) To correct the parameters in the blocks 'IGV ACTUATOR' and 'THERMOCOUPLE' based on dynamic data from load variations;
(12) To correct the parameters in the blocks 'VALVE POSITIONER', 'FUEL SYSTEM', 'COMBUSTOR', 'TURBINE DISCHARGE', 'COMPRESSOR DISCHARGE', and acceleration control loop based on the analysis results of the load rejection test;
(13) To validate the first approach model with several sets of data.

The validated model is shown in Figure 4.

The 'DIGITAL SET POINT' is the power demand sent to the GT. It is defined by the '*droop*' in the 'SPEED GOVERNOR' block. In the present work, a '*droop*' condition of 5% was defined based on the ONS' information. The value $K_D = 1/droop = W = 1/0.05 = 20$ is used in the 'SPEED GOVERNOR' block.

Table 3 shows the calculated parameters for the validated model in Figure 4.

Table 3. Parameters of the Validated Model

Depiction	Value	Unit	Depiction	Value	Unit
$a; b; c$	$1; 0.1; 1$		T_a	22.00	°C
$W; X$	$K_D; 0$		τ_T	250.00	s
$Y; Z$	$0.05; 1$		Max VCE [1]	1.50	pu
'*droop*'	0.05		Min VCE [1]	−0.10	pu
K_D	20.00		T_r	540.00	°C
τ_f	0.80	s	τ_I	17.65	s
K_f	0.00		Max L_{igvc}	1.00	pu
ϵ_{CR}	0.01	s	Min L_{igvc}	0.46	pu
ϵ_{TD}	0.04	s	Max IGV	5.00	°C
τ_{CD}	0.40	s	Min IGV	−41.00	°C

[1] VCE is the Fuel Command (Figure 4)

The expression of f_{1-GT} is given by

$$T_x = \frac{num}{W_x\,(1 + 0.005\,(22 - T_a))} \tag{1}$$

where

$$\begin{aligned} num =\ & 0.29\,(5 - \text{IGV}) + 0.745\,(1 - W_f) \\ & - 453\,(N^2 - 2.6162\,N + 1.6341) \end{aligned} \tag{2}$$

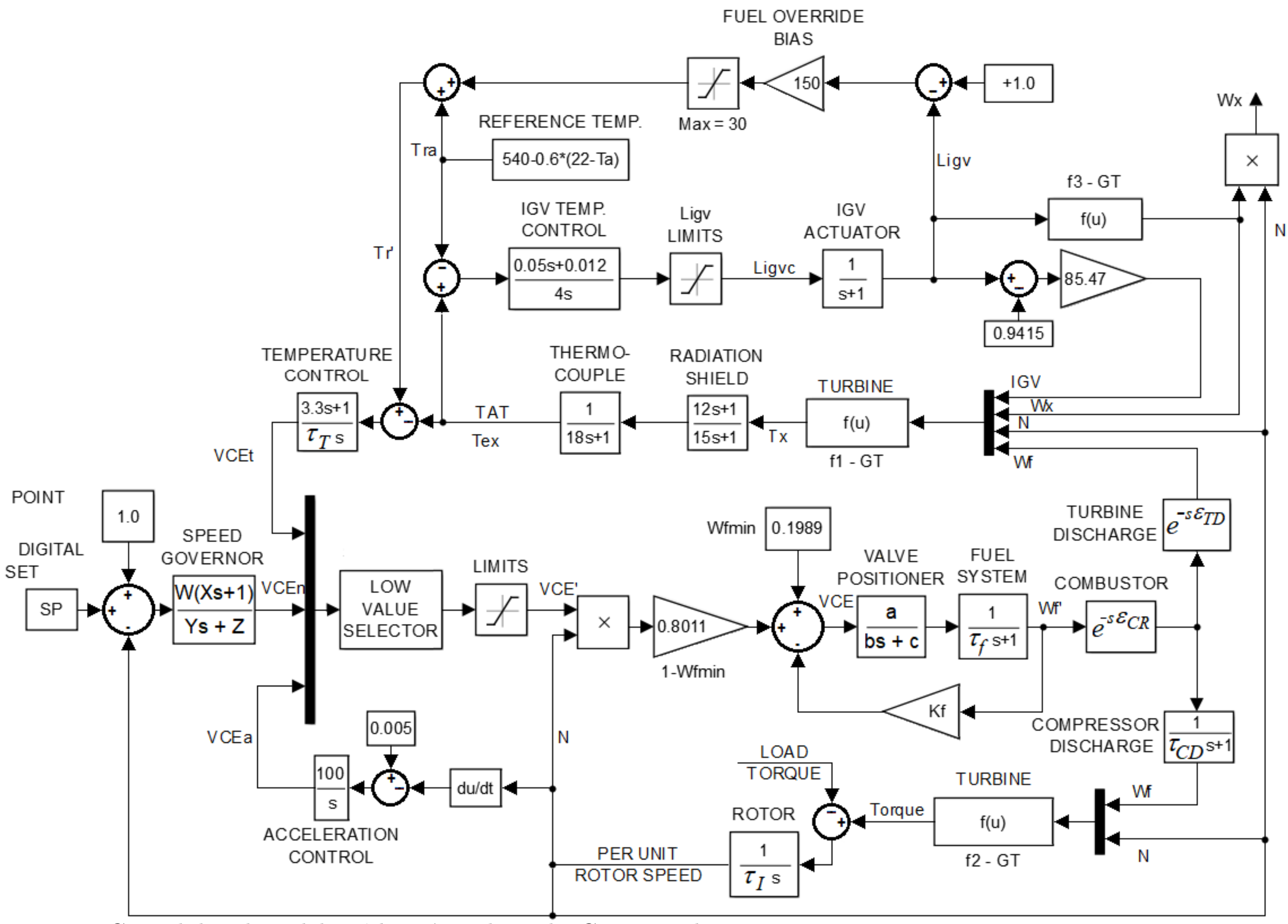

Figure 4. GT validated model in '*droop*' mode with IGV control

Since all data was recorded with N around 1 pu, parameters in (1) and (2) remained the same as in Rowen (1992).

The expression of f_{2-GT} is given by

$$torque = 1.2483\,(W_f - 0.1989) + 0.5\,(1 - N) \qquad (3)$$

which is similar to that in Yee et al. (2008), and has the same structure as in Rowen (1983). The role and influence of N in the equation remained unaltered.

The expression of f_{3-GT} is given by

$$W_x = \left(\frac{295.15}{T_a + 273.15}\right) L_{igv}^{0.572} \qquad (4)$$

where the exponential coefficient was calculated through the application of the least squares method to the steady state data from several conditions of operation. The parameters were adjusted to $T_a = 22\,°\mathrm{C}$.

5. GAS TURBINE VALIDATION RESULTS

5.1 Load Rejection Tests

The load rejection test was carried out in order to calculate the dynamic parts of some model blocks. During the test, the GT suffered a sudden loss of charge in the electric generator output. The supervisory system detected the event and switched the control mode from '*droop*' to 'isochronous', to cope with the axis speed regulation.

By using the graphical results from two load rejection tests, the time constants of blocks 'FUEL SYSTEM', 'COMPRESSOR DISCHARGE', 'IGV TEMPERATURE CONTROL', and 'IGV ACTUATOR', as well as the reference in acceleration control loop, were all adjusted.

The 'isochronous' Proportional-Integral (PI) control law in the 'SPEED GOVERNOR' block was adjusted such as

$$\mathrm{VCE_n}(s) = \left(\frac{3.5s + 1.4}{s}\right) \Delta N \qquad (5)$$

5.2 GT Validation Cases

The control system regulates two variables concurrently: i) *torque* (output power) and TAT. The first one follows the power demand SP, whereas the other is kept most of the time at its maximum (540 °C) through the IGV adjustment. Both of them are controlled independently, in such a way that the required power is generated and the TAT is maintained at its maximum, except for lower loads. The GT efficiency is not affected by the operation of the IGV.

Three data sets (cases) were selected regarding power variations from no load to full load. Data were available at the sampling time of 1 s. Figures 5–7 present such data sets. Solid lines correspond to real data, whereas dotted lines correspond to data from simulations. There is no real data to validate W_x.

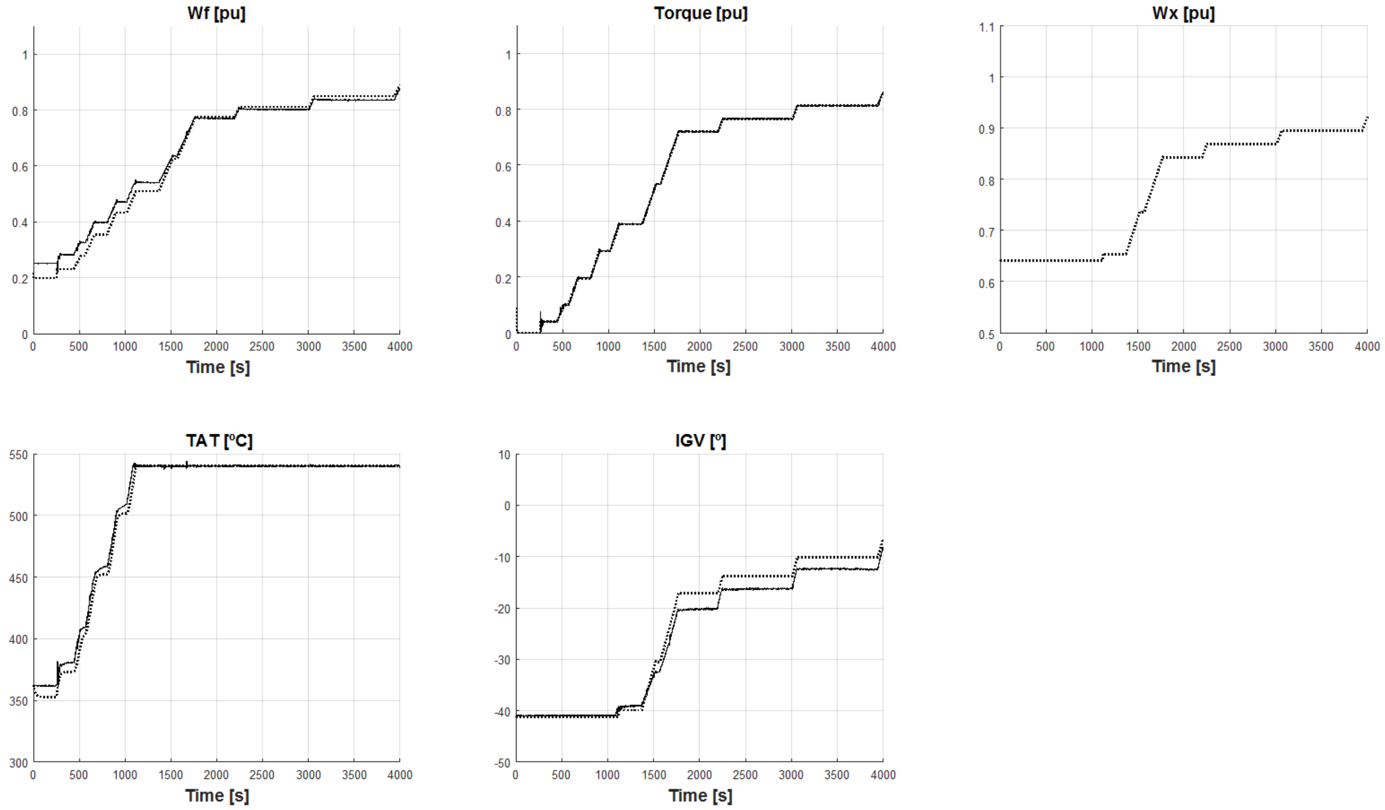

Figure 5. Validation Results — Case 1

Case 1: Measurements were carried out on March 21st, 2013 during a 4000 s-long experiment in which the generated power was raised from 0 to 89.85 MW in several steps. Figure 5 shows that the *torque* matched satisfactorily, therefore it is well validated. As regards W_f and TAT, they did not match satisfactorily near to the no load condition, but they matched in the opposite condition, i.e. full load, therefore they present a relatively poor validation. IGV presents a poor validation in intermediary loads. This fact could be foreseen by estimating the nonlinear behavior of IGV with respect to the output power. At last, W_x followed the behavior of IGV.

The TAT graph helps to understand how the control through IGV works. From the instant 1100 s on, increasing the load, as well as the *torque* beyond 0.4 pu, does not affect the temperature, which is kept at 540 °C.

It is observed that TAT and IGV present additional behaviour related with the control strategy, that the employed model could not represent.

Case 2: Measurements were carried out between 04:16:40 and 05:23:19 on April 30th, 2014 during another 4000 s-long experiment. In this case, the output power started at 104.97 MW and was lowered down to zero. Computer simulations were also performed along with it. Figure 6 presents comparisons of results obtained from both of them. As in the previous case, W_f presents a poor validation near the no load condition, whereas TAT presents a poor validation between 500 and 800 s. As regards the IGV, it presents a poor validation in intermediary loads again.

Case 3: More measurements were carried out between 04:06:40 and 06:53:19 on July 22nd, 2013 during yet another 10000 s-long experiment. Computer simulations were also performed along with it. Figure 7 presents comparisons of results obtained from both of them. It is possible to that the behaviors of variables W_f, *torque*, TAT, and IGV just confirm the previously presented results.

6. CONCLUSIONS

Present works states some critical aspects related with modeling a heavy duty GT from sampled data. The studied machine presented a behaviour on its IGV control dynamics that could not be properly represented by the model structure, as observed in Figures 5, 6, and 7. This demonstrates that the structures usually employed in power system analysis do not adequately represent machines with specific behaviors. Future developments will modify the actual model structure, aiming to obtain a more reliable representation.

Developing dynamic models for GT in CCPP from sampled data is not an easy task, because obtaining useful validation data is hard to accomplish. It must be guaranteed dynamic load variation and proper data sampling. Besides that, it must be looked for reliable accuracy of the measurements.

The model focuses on the dynamic behavior of the GT equipped with IGV, as a component of a CCPP. The simplified representation favored the understanding of the dynamic behavior of variables and related control loops. Since the values of most of the model parameters

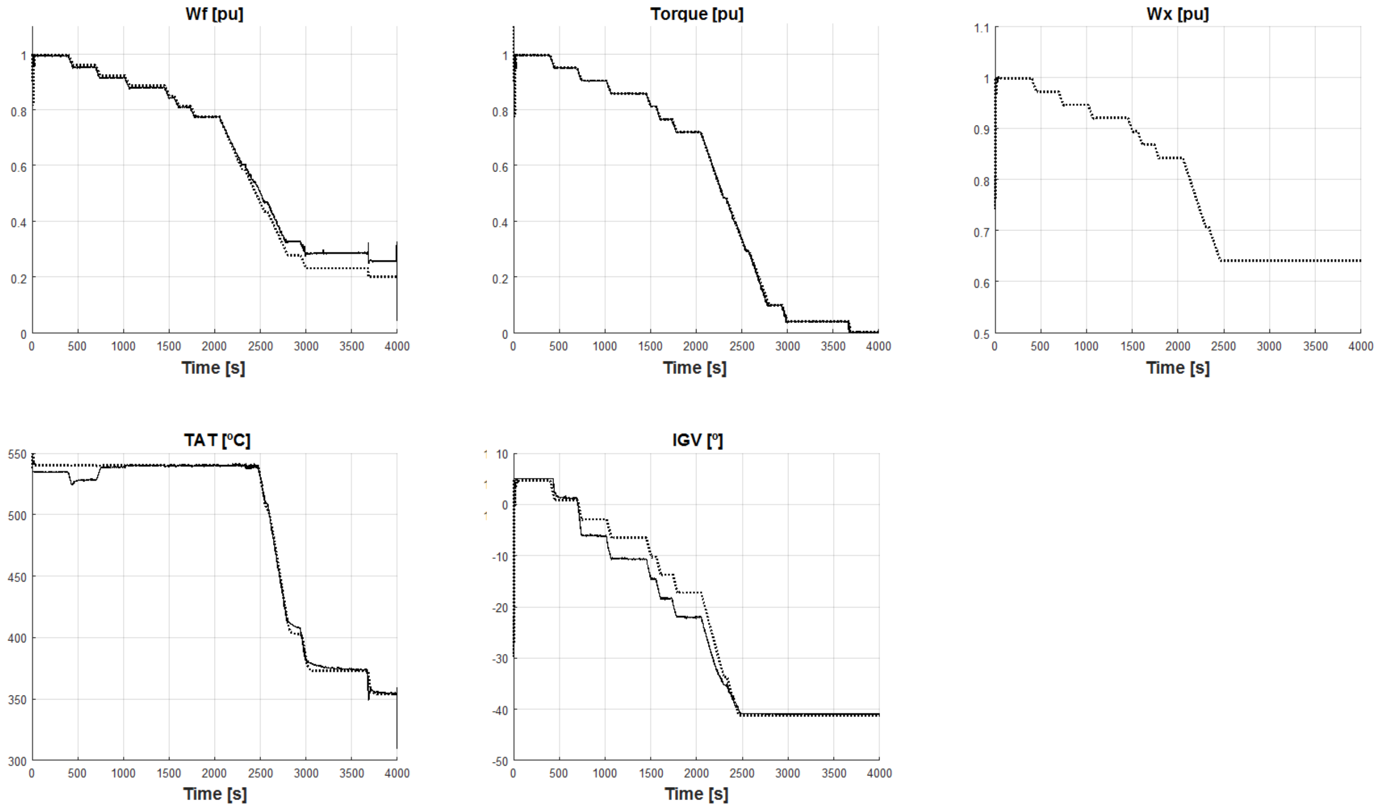

Figure 6. Validation Results — Case 2

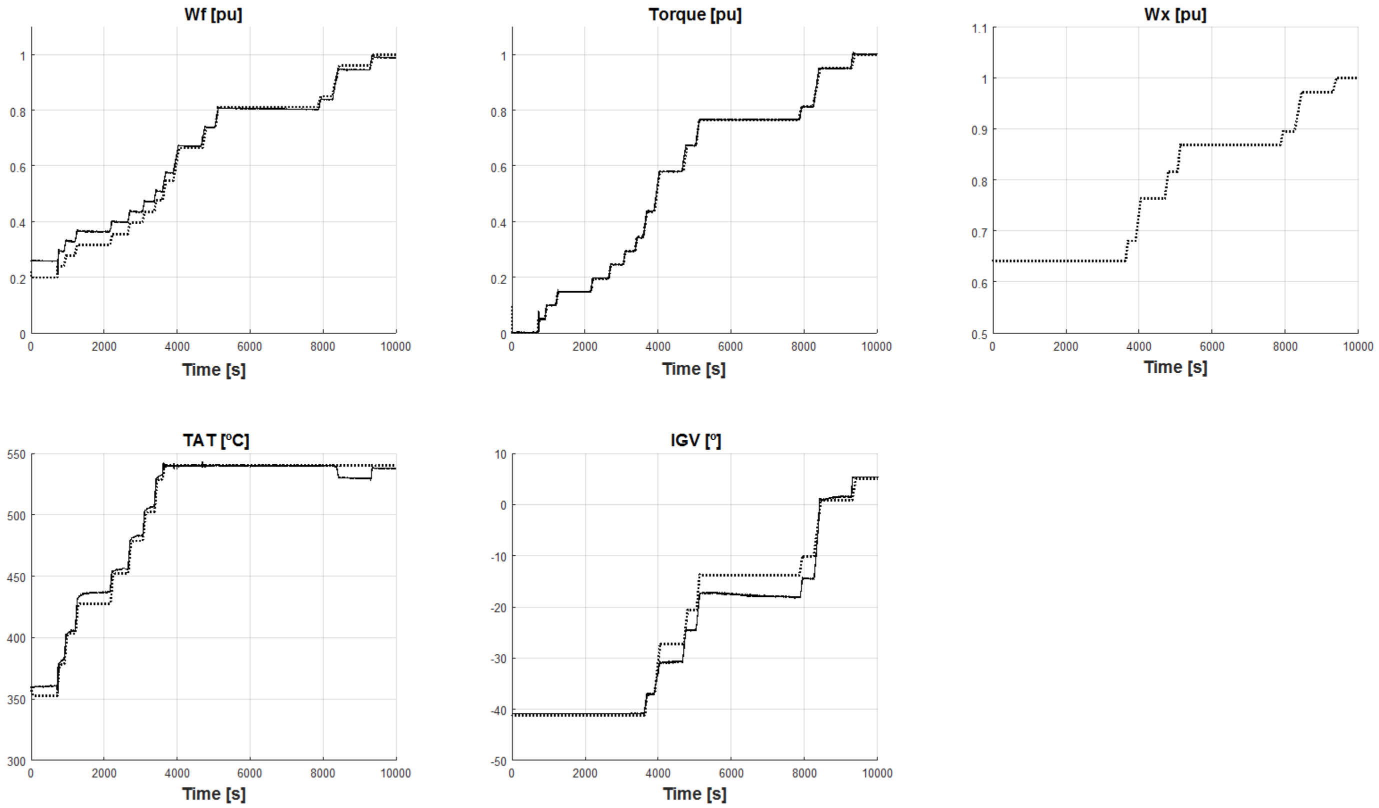

Figure 7. Validation Results — Case 3

were obtained from the literature, some adjustments were needed to guarantee consistency with the modeled plant.

Defining the base values of model variables for pu calculation was mandatory, as well as to convert the values of the variables to standard ambient conditions. It was necessary to adjust the reference temperature to the chosen standard ambient temperature (22 °C), as well some coefficients in equations involving temperatures, since some of them were presented in °F.

The presented simulation results offer a clear view of the operation of the three control loops, as well as that of the minimum value selector in events of power demand variations. Most of the time, the speed controller rules the fuel demand (VCE), except in i) full power conditions, where the exhaust temperature controller limits the generated power, or ii) in abrupt load variations, where acceleration and temperature control loops may command VCE transiently. IGV control loop keeps the TAT at its maximum disturbing neither the power generation nor the efficiency of the GT. Acceleration and temperature control laws have each an integrating pole in their controllers. Most of the time, the speed control prevails (minimum value selector), and control signals VCE_a and VCE_t tend to grow indefinitely, making it necessary to limit them.

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