Modeling of Thermal Generating Units for Automatic Generation Control Purposes

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***Abstract*—A simple discrete time model of a thermal unit has been formally developed for designing automatic generation control (AGC) controllers. This model has been developed using data obtained from specific tests and historical records. This model consists of a nonlinear block followed by a linear one. The nonlinear block consists of a dead band and a load change rate limiter, while the linear block consists of a second-order linear model and an offset. Although most of these elements have already been included in unit models for AGC presented in the literature, a certain mix up exists about which of them are necessary. This is clarified in this paper. It has been found that the unit response is mainly determined by the rate limiter, while the other model components are used for a better fitting to the real response. An identification procedure is proposed to estimate the values of the model's parameters.**

***Index Terms*—Automatic generation control (AGC), dead band, identification procedure, load change rate limiter, thermal unit model.**

I. INTRODUCTION

LOAD-FREQUENCY CONTROL (LFC) is organized in three levels. Primary control is performed by the speed governors of the generating units, which vary load when frequency changes. With primary control, a variation in system frequency greater than the dead band of the speed governor will result in a change in unit power generation ([1]–[3]). Transients of primary control are in the time-scale of seconds.

Secondary control restores frequency to its nominal value and, in systems with several control areas, also maintains the power interchange between areas. In order to do so, it adjusts the load setpoint of the generators ([3]–[6]). Transients of secondary control are in the order of minutes. Secondary control is also called automatic generation control (AGC).

Tertiary control is an economic dispatch. It is used to drive the system as economically as possible and restore security levels if necessary. Tertiary control is usually performed every 5 min ([1], [7]).

The discrete time model presented in this paper has been developed to be used for secondary control purposes, so it has to deal with time constants greater than several seconds. Several continuous time models have been proposed in different previous works, but either they are very complex for AGC studies ([1], [2], [8], [9]) or the time constants used in the model are too fast compared with AGC execution time ([5], [10], [11]). A certain mix up is found in these works about the necessary elements to correctly model a generating unit for AGC purposes, which is clarified in this paper. Although similar models have been used by some generating companies for AGC tuning purposes (such as Leeds & Northrop), a formal analysis had not been presented before.

Although continuous time models for the whole system not taking sampling into account can also be used for simulation if time constants are high enough compared to AGC sample time, a discrete time model is proposed here because AGC is discrete time implemented. AGC samples system variables with typical sample times (T_{AGC}) between 2 or 4 s. Then, AGC computes unit setpoints and sends them to the units. This setpoint will be used until the next execution of AGC, T_{AGC} seconds later.

Simple models can be obtained from a much more complex one applying some sensible simplification or using real data to extrapolate it. This paper focuses on this last approach. A simple model of thermal units has been developed and validated using real data of several units of Endesa (the largest Spanish electric utility). A simple model is preferred because: (a) its effects and limitations on the system are easier to understand, which helps in system analysis and control design, (b) it is easier and faster to simulate, and (c) to encourage the design of robust control systems [12]. Although today's computers can handle simulations of great size models, simulation time has to be always kept in mind when developing a model. This is especially important if the system to be simulated comprises many units (up to 73 in [13]), if the simulation time is long (24 h in [14]) or if a statistical analysis involving several simulations is going to be carried out [15]. Using a simple model that includes all the relevant elements in unit response to AGC control makes possible to focus upper level controllers design on the most important issues of generating unit response. Thus, AGC control can be made more efficient and robust. The model presented in this paper gives a good representation of the behavior of the different units within the time scale of AGC response. Coal and fuel/gas units have been studied. This paper fully details this simple model and the procedure to obtain the values of the model's parameters.

It has been verified that unit response is mainly characterized by the limiting elements of the generating unit (load change rate limiters and dead bands). Although load changes due to AGC are usually small, they usually consist of step or ramp signals. So, load change rate limits are usually present. Dead bands, which come from speed governors or are used as filters in the load reference input, are also important. The main effect of dead bands is a delay in unit response, which may be of high importance if time criteria is used for the evaluation of the AGC performance ([16]). As an example, with typical values for load

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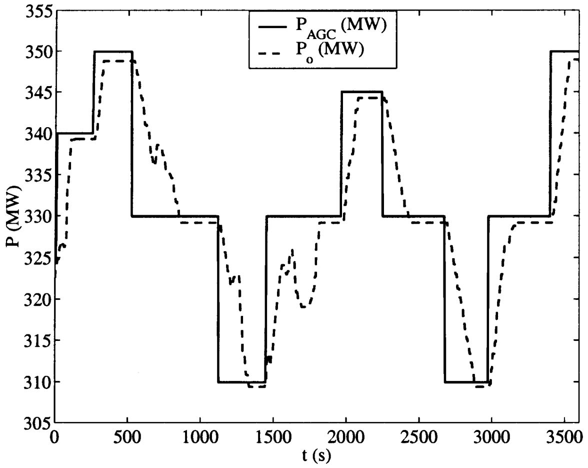

Fig. 1. Setpoint sent from AGC to the unit P_{AGC} and output power P_O from an step response test. Data from unit H1.

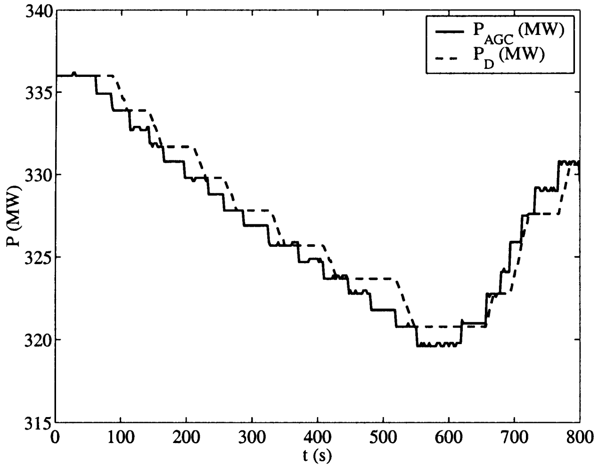

Fig. 2. AGC power P_{AGC} and demanded power P_D from historical behavior. Data from unit H2.

ramp and dead band a delay of 15 s would be found in unit response.

A second-order linear transfer function, which represents plant response, is included in the model. This transfer function may be set to unity when plant response meets load change requirement (given by ramp limit) fast enough. Finally, an offset is sometimes present between the requested power output and the measured one, which is also included in the model.

The paper is organized as follows. Section II analyses the generating unit response. The model obtained for a generating unit is presented in Section III, and a procedure to determine model's parameters values is detailed in Section IV. Results obtained for two generating units are shown in Section V. Section VI contains conclusions of the paper.

II. ANALYSIS OF GENERATING UNIT RESPONSE

A detailed study of data from different unit responses has been done to find an appropriate model for a thermal generating unit. Data from 14 different units (11 coal fired units and 3 fuel-gas fired units) have been studied, using both step response tests and historical data from real operation. A list of generating units studied is presented in the appendix.

For every unit, data for three different signals have been recorded: P_{AGC} is the power requested to the unit from AGC controls, P_D is the power really demanded to the unit, which is obtained after applying certain limitations and/or filters to P_{AGC}, and P_O is the output power generated by the unit.

Here, only some examples of studied data will be presented to show the main characteristics found.

The most relevant dynamic of unit response is due to the load change rate limiter, which is present on every studied unit. As an example, data from a step response test for unit H1 are presented in Fig. 1. Up and down rate limits have usually the same value for a certain unit, but they can be different, as in the unit shown. Values identified for this unit are 10 and 6 MW/min for up and down load change rate limits, respectively.

In addition, a dead band is usually present, either as a noise filter or due to speed governors (both can also be present at the same time). The presence of a dead band is shown in Fig. 2, where historical data from real operation of H2 have been presented. In this example, demanded power P_D does not change until the difference between AGC power P_{AGC} and demanded power P_D is greater than a certain value (2 MW for this unit).

Other filtering methods have been found instead of a dead band. A quantization (only certain values are possible) of demanded power P_D is used in some units with a similar effect. For the sake of simplicity, only a dead band has been included in the model, representing any nonlineal filter of that kind.

The most important effect of a dead band in unit response is to produce a delay between AGC power P_{AGC} and output power. This delay is not negligible relative to AGC time constants. For example, with a dead band of 2 MW, and a rate of 5 MW/min in P_{AGC}, the output of the dead band would remain constant for 24 s. This may have destabilizing effects [10] and may affect the generator tracking test if applied. In deregulated markets, failing the tracking test may have economic penalization (e.g., Spanish electricity market).

Unit response dynamic after the non linear elements described before (dead band and rate limits) can be modeled as a second order transfer function. This conclusion has been obtained from the analysis of real data from several units recorded during operation and tests. The response of many of the units has the shape of a second order transfer function with unity gain and a certain overshoot (about 20%). Comparison between real data and simulated data using this kind of transfer functions has given satisfactory results. The difference between one unit and another is the speed of the second order response. Some units have such a fast response, compared to typical AGC time constants, that the linear transfer function can be set to unity (without any dynamic). Others present a very clear and slow second order response. As an example of the latter, in Fig. 3 an historical record of unit E1 has been represented. There is a delay and a certain inertia in output power. This delay can not be only due to a dead band, because its value would have to be unrealistically high (data presented in Fig. 3 correspond to the worst case found), of about 10 to 15 MW. Thus, a linear transfer function is what better represents unit behavior between demanded power P_D and output power P_O. From the AGC point of view, the main effect of a slow response

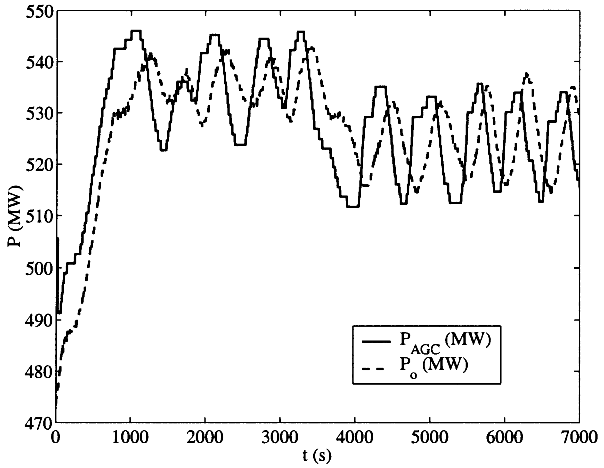

Fig. 3. AGC power $P_{\rm AGC}$ and output power P_O from an historical record. Data from unit E1.

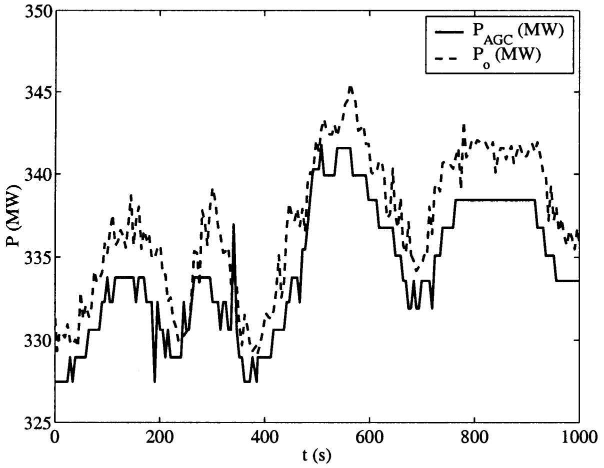

Fig. 4. AGC power $P_{\rm AGC}$ and output power P_O from an historical record. Data from unit G3.

of a unit is a certain delay in the response to control actions. This delay has to be taken into account in the design of AGC controllers.

It has been found that a constant offset exists in some units between its AGC power $P_{\rm AGC}$, which is the setpoint sent to the unit, and its output power P_O, which is the measured power. This difference is specially clear when the unit setpoint $(P_{\rm AGC})$ is kept constant resulting in a constant measured power (P_O) which is some megawatts different from unit setpoint. In Fig. 4, historical data from unit G3 have been represented, where the presence of an offset is clear (about 2.5 MW). This offset is supposed to be due to a measurement error.

Some other dynamics have been found in this study, but they have not been included in the model. An example of this can be seen in Fig. 1, between $t = 1600$ s and $t = 1800$ s. While output power is growing, it suddenly decreases for some time and then grows again, without any change in requested power. This is due to a loss of boiler pressure, which is recovered after some time. This behavior is a disturbance in the control loop, is difficult to predict and does not occur frequently. Thus, this effect has not been included in the model.

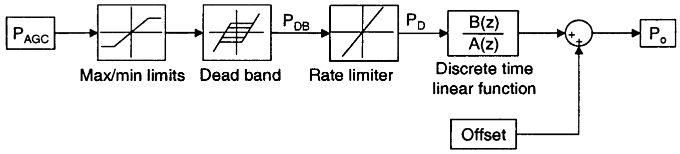

Fig. 5. Model for a generating thermal unit.

III. MODEL PRESENTATION

Based on the analysis previously presented, the model shown in Fig. 5 is proposed to represent the behavior of a thermal unit for AGC studies.

Every model block is explained in Sections III-A–D.

Although trends in the remote control of generating units (such as in Spain) are to send the total requested power for the next cycle $(P_{\rm AGC})$, Unit Control Error (UCE) is also used. Basically, UCE is the requested power increment for the next cycle. Therefore, UCE can be easily formulated in terms of $P_{\rm AGC}$ as shown in (1), and model in Fig. 5 may straightforwardly be transformed to have UCE as input.

$$UCE = P_{\rm AGC} - P_O. \tag{1}$$

Several physical and operator-fixed limits are present in any generating unit. Although some of them are usually included in detailed models, they are usually disregarded in simple ones ([5], [10], [11]). Operator-fixed limits applied to the power setpoint have been included in Fig. 5 because they might influence on AGC properties. These limits do not need to be identified because they are supposed to be known.

A. Rate Limiter

The most important effect in unit dynamic is a load change rate limiter in service in every generating unit. If the input slope is lower than rate limiter's value, the output is equal to the input. If it is higher, the output is a ramp of slope equal to the rate limiter's value.

An example of rate limiter's behavior is presented in Fig. 6. Up and down load change rate limits have been set to 1 MW/min. Signal names are those used in Fig. 5

B. Dead Band

A dead band is applied to AGC power $P_{\rm AGC}$. If the absolute difference between AGC power $P_{\rm AGC}$ and demanded power P_D is lower than the dead band's value, dead band's output for next control cycle keeps constant. If it is higher, dead band's output for next control cycle is equal to AGC power $P_{\rm AGC}$.

An example of dead band's behavior is presented in Fig. 6. A dead band value of 2 MW has been used. For the sake of simplicity, up and down rate limits have been set to 1 MW/min though these values are considerably lower than actual ones. Signal names are those used in Fig. 5

C. Discrete Time Linear Transfer Function

AGC operates in a discrete way. However, the actual plant response is continuous. A zero order hold is typically present at the input of the plant to keep constant the setpoint calculated

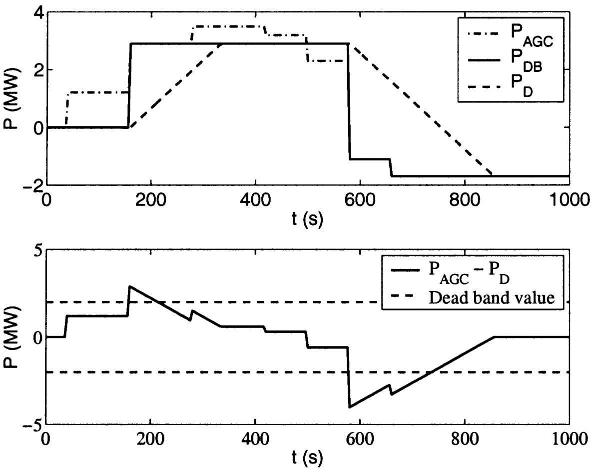

Fig. 6. Behavior of dead band and rate limiter. Signal names are those used in Fig. 5 Dead band's value is 2 MW and up and down rate limits have been set to 1 MW/min.

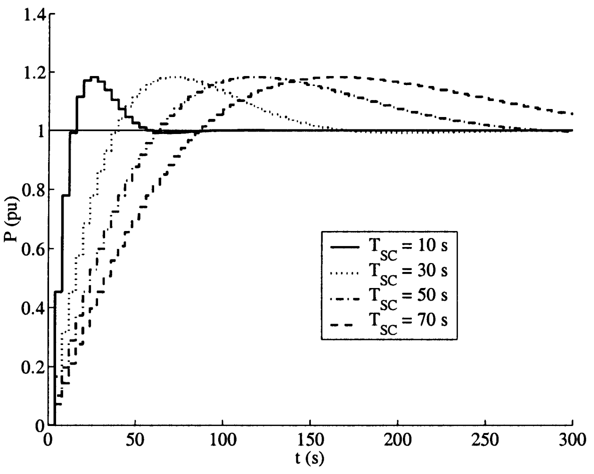

Fig. 7. Different discrete time linear function responses depending on the value of T_{SC}.

by AGC during the AGC execution period (T_{AGC}). AGC samples output power every T_{AGC} seconds. The second-order linear transfer function proposed for the unit is given in (2).

$$F(s) = \frac{1 + 1.3 \cdot T_{sc} \cdot s}{\frac{1}{\left(\frac{1}{T_{sc}}\right)^2} \cdot s^2 + \frac{2 \cdot 0.7}{\frac{1}{T_{sc}}} \cdot s + 1} \tag{2}$$

where T_{SC} is a parameter.

As justified in Section II, this transfer function has been chosen to have unity gain and an overshoot of about 20%. T_{SC} is used to vary response speed, since this is the main difference found between unit responses after the non linear elements described before. Equivalent discrete transfer function is just obtained applying the standard method for systems with zero order hold and regular sampling time [17]. As an example, the equivalent discrete transfer function for $T_{SC} = 10$ s and $T_{\text{AGC}} = 4$ s is shown in (3).

$$F(z) = \frac{0.4538 \cdot z - 0.3329}{z^2 - 1.45 \cdot z + 0.5712}. \tag{3}$$

Step responses for several equivalent discrete transfer functions, each one obtained for a different value of parameter T_{SC}, are presented in Fig. 7.

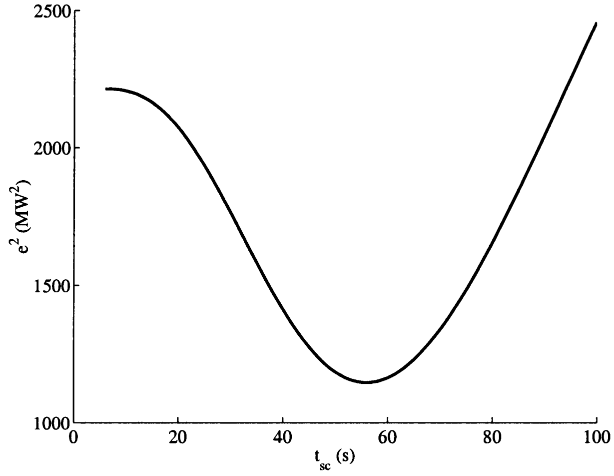

Fig. 8. Square error (e^2) between simulated and real output for several values of T_{SC}. Values obtained for unit C1.

D. *Offset*

A constant offset is added to the output of the transfer function to obtain the output power of the model.

IV. MODEL IDENTIFICATION

This section proposes a method to identify the values of the model's parameters from measurements. For unit identification a step response test and data from historical behavior of the unit are needed. Identification of the parameters has to be done in the order shown in Sections IV-A–E, because previously calculated values are needed for the identification of the next ones. Parameters' values of the nonlinear part of the model are firstly estimated, i.e., rate limits and dead band. Then, offset and linear transfer function are estimated. If any of the model parameters is known in advance, the identification process shown below should only be applied for the unknown model parameters. For example, dead band and rate limiter are sometimes known from the unit control system. However, even in that case it might be useful to obtain those values from an identification process to check if theoretical values are the actual ones.

A. *Rate Limiter Identification*

Data from a step response test are used for load change rate limiter identification. Both up and down limits are identified simultaneously from a test with up and down steps. The method used finds the values that minimize the square error between real output power and simulated output power for the same input [18]. Identification could be done separately for up and down limits using separated up and down step response tests. Several different steps are preferred to just one. Note that mixing up and down steps allows keeping mean power output nearer to base load along the experiment. Using big enough step values in the tests, the dead band is avoided and the ramp rate limits can be identified separately from dead band.

Values found for these parameters lay between 4 and 10 MW/min for studied units (between 300 and 550 MW). A typical value of 3% of unit power per minute is proposed in [3] and [19]. However, in this study no relationship has been found between rate limits' values and nominal power or fuel type of the unit.

B. Dead Band Identification

Recorded data from historical behavior is used to identify dead band's value. Using these data, a model with the rate limiter values previously identified and a dead band is simulated for several dead band values. Square error between real demanded power P_D values and simulated output values for the same input is calculated for each dead band's value. Dead band's value which minimizes square error is selected.

Values found for this parameter lay between 1 and 2 MW for studied units (between 300 and 550 MW). In 4 out of 14 units studied the presence of a dead band has not been detected.

C. Offset Identification

Offset identification can be done by calculating the difference between AGC power P_{AGC} and output power P_O for data recorded from historical behavior. The difference is calculated for each sampled value. The averaged value of this difference over the recorded time gives an estimation of the offset value. However, analyzing the complete signal obtained for the difference is the best way to find the offset value.

Values found for this parameter lay between 1 and 2.5 MW for studied units (between 300 and 550 MW). The presence of an offset has been detected in 6 out of 14 units studied. Offset can be either positive or negative.

D. Discrete Time Linear Transfer Function Identification

Discrete time linear function identification is performed in the same way as dead band identification. Rate limiter, dead band and offset identified values are set in unit model. This model is simulated for several values of T_{SC} using recorded data from historical behavior as input. The value of T_{SC} that minimizes the square error between real and simulated power output for the same input is then selected. An example of square errors obtained for different values of T_{SC}, during identification process, is presented in Fig. 8. In this example, a value of T_{SC} between 50 and 60 s can be chosen.

Values found for this parameter lay between 10 s and 40 s for studied units (between 300 and 550 MW), although a value of 100 s has been identified for one of them. For 5 out of 14 units studied, plant dynamic is fast enough to meet demand power in time lower than several seconds. In these cases, linear function is set to unity.

Once each parameter value has been identified using previously presented procedures, a simulation of the model obtained must be done. Due to noise in recorded data and/or due to a strange behavior during a certain period of recorded data (Fig. 1, $t = 1600 \div 1800$ s), parameter value which minimizes square error could be not the best one. Expertise plays a fundamental role in the final tuning of parameter values when needed.

E. Typical Values

Typical values obtained for the parameters of the simplified model for the thermal generating units analyzed in the former paragraphs have been summarized in Table I.

TABLE I
TYPICAL VALUES OBTAINED FOR THERMAL GENERATING UNITS

Rate limit	4 - 10 MW/min
Dead Band	1 - 2 MW
Offset	1 - 2.5 MW
T_{SC}	10 - 40 s

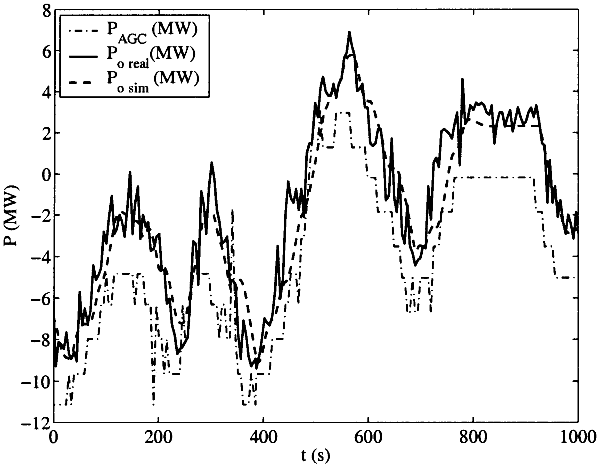

Fig. 9. AGC power P_{AGC}, real output power $P_{o\,\mathrm{real}}$ and simulated output power $P_{o\,\mathrm{sim}}$ for unit G3. Only variations of AGC power over the base load power are presented.

V. VALIDATION RESULTS

Model parameters values have been found for 14 thermal units: 11 coal units and 3 fuel/gas units (these units can use fuel or gas depending on market price). A list containing power and fuel type of studied units is presented in appendix. For every unit, the model presented in Section III, identified using the procedures of Section IV, has been proved to represent successfully unit behavior for time constants significant to AGC. Results for a coal unit and a fuel unit are next presented.

Simulations in this section are carried out with initial output power value equal to zero. Initial value is subtracted from real output values so that results can be compared. This means that just power related to AGC is presented (base load is omitted), and is the reason why small and negative values are obtained for power signals. Only 1000 s are shown from the complete simulation time.

Different data are used for parameter identification and validation.

A. Coal Fired Unit: Group G3

Identification process for this unit has lead to the following parameter's values: 8 MW/min for both up and down rate limits, 1 MW for dead band, 2.5 MW for offset, and a value of 10 for T_{SC} of the linear function.

This identified model has been simulated using real recorded data as input values for AGC power P_{AGC}. AGC power P_{AGC}, real output power $P_{o\,\mathrm{real}}$ and simulated output power $P_{o\,\mathrm{sim}}$ are presented in Fig. 9. As can be seen in Fig. 9, the coincidence between $P_{o\,\mathrm{real}}$ and $P_{o\,\mathrm{sim}}$ is good enough for the time scale of AGC.

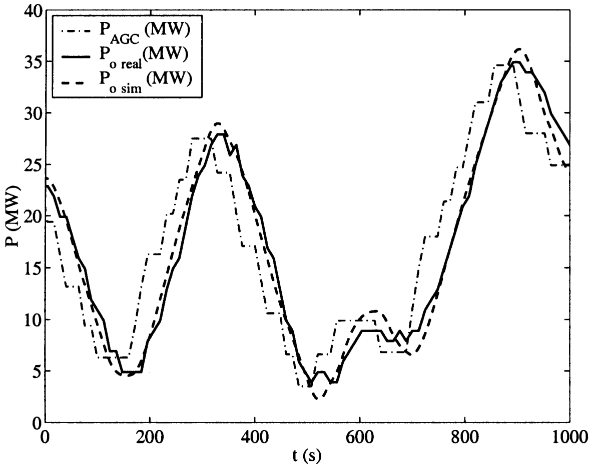

Fig. 10. AGC power $P_{\rm AGC}$, real output power $P_{o\,\rm real}$ and simulated output power $P_{o\,\rm sim}$ for unit A1. Only variations of AGC power over the base load power are presented.

TABLE II
POWER AND FUEL TYPE OF GENERATING UNITS STUDIED

Identifier	Fuel	Power (MW)
A1	Fuel/gas	325
B1	Coal	550
C1	Coal	350
C2	Coal	350
D1	Fuel/gas	520
E1	Coal	550
F1	Fuel/gas	312
G1	Coal	350
G2	Coal	350
G3	Coal	350
G4	Coal	350
H1	Coal	350
H2	Coal	350
H3	Coal	350

B. Fuel/gas Fired Unit: Group A1

Identification process for this unit has lead to the following parameter's values: 9 MW/min for both up and down rate limits; it has not been detected a dead band, so a value of zero is assigned to this parameter; it has not been detected a significant offset between AGC power and output power, so this parameter is set to zero; a value of 30 has been estimated for T_{SC}.

AGC power $P_{\rm AGC}$, real output power $P_{o\,\rm real}$ and simulated output power $P_{o\,\rm sim}$ are presented in Fig. 10. As can be seen in Fig. 10, the coincidence between $P_{o\,\rm real}$ and $P_{o\,\rm sim}$ is good enough for the time scale of AGC.

VI. CONCLUSION

A simple model which can be used to represent a thermal generating unit for AGC purposes has been developed. This model has been obtained after analyzing the real response of 14 thermal units. The model consists of a rate limiter, a dead band, a second-order discrete linear transfer function and an offset. Although most of these elements have already been included in unit models for AGC presented in the literature, a certain mix up of the necessary elements exists, which has been clarified in this paper. The most relevant dynamic of unit response is due to the load rate limiter.

A procedure to estimate the values of model's parameters has also been presented. This procedure uses real data obtained both from a step response test and an historical behavior of the unit.

Results obtained for a coal fired unit and a fuel/gas fired unit has also been presented.

APPENDIX

In Table II power and fuel type of every unit studied are presented.

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