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Synchronous Generator Stability Characterization for Gas Power Plants Using Load Rejection Tests

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Abstract: For power grid operators, knowing the transient response of the synchronous generators (SGs) included in their grids is important in order to simulate and monitor faults and other contingencies. However, the time constant of the automatic voltage regulator (AVR) and speed governors of SGs are not fast enough to show their transient dynamics in the case of a fault in the grid. This paper presents a fieldwork carried out in more than 60 gas power plants, where the response of their controllers was studied. These power plants are running and supplying electricity to the Spanish grid. The study consists of recording some SG responses in different situations, varying the AVR or the speed governor setpoints while the generator is running at no-load conditions, and also performing load rejection tests, achieving a real fault emulation. Once all the data are gathered, a fitting of the SG parameters is performed by computer simulations using GENSAL, GAST and SEXS models replicating the performed field tests. This work allows us to build an accurate network model for the whole power system and check which plants are having trouble in the case of contingencies in the grid.

Keywords: automatic voltage regulator; load rejection; fault; speed governor; synchronous generator; parameter setpoint

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1. Introduction

Electrical power systems are by far one of the greatest achievements of engineering and, at the heart of them, electrical generators are found, which pump the electrical power into the network. Back in the old days, the power system was small and weakly interconnected, but with the industrial development and the increase in household consumptions, it has had to become larger and more interconnected.

The expansion of the power system, such as the addition of new generators or transmission lines, can lead to increased stress on the system. This stress can result in an increased likelihood of incorrect operation, such as power outages or equipment failures, which can negatively impact the reliability of the power system. As a result, the predictability of the system's operation can be reduced, making it more difficult for operators to anticipate and respond to potential issues in a timely manner. Therefore, it is important to carefully plan and manage the expansion of the power system to ensure that it remains reliable and predictable even under increased stress. Additionally, interconnections with neighboring power systems make the network stronger. However, they expose the system to more interferences because of the larger covered area. This type of situation jeopardizes the system, causing it to face many disturbances simultaneously or within a short interval of time [1].

A default power system is meant to sustain N-1 contingencies, i.e., the power system should be able to continue operating without one of the elements that compose it. However, it does not guarantee full security to the power system [2]. The main reason for the systems' blackouts in a power system is due to dynamic instability and voltage instability [3–6]. In this field, many advances in improving the network interconnection stability and efforts in restoring the system after major disturbances have been carried out [7,8]. Nevertheless, there are problems defining and classifying power system stability problems as they can be voltage, frequency or load angle stability problems. This is a task that aims to provide a systematic basis for the discussion on issues like power system security and reliability [9].

One important point that must be remarked is the protection system and its relationship with the system's stability, which can cause a major outage in the power system [10]. Protection relays are involved in about three out of four contingencies in the electric system [11] due to wrong system coordination or improper controllers' adjustments at power plants, which cause the cascade tripping of upstream relays.

In order to solve this issue, power system operators (PSOs) require transient technical parameters from the different power plants in order to better fit their protections, perform contingencies simulations and deeply study the transient behavior of the grids. However, the estimation of these parameters is not a trivial task. For example, in synchronous generators (SGs), the automatic voltage regulator (AVR) voltage variation rates are quite slow in performing the emulated transients required to characterize the machines in compliance with the requirements of the PSO.

In this paper, three real cases of the study and characterization of real gas power plants are exposed from more than 60 examined power plants, all coupled to the Spanish power grid, the product of a project carried out for the Spanish PSO. A load test rejection is proposed to solve the problem and provoke a fast rejection response similar to a real fault in order to study the transient behavior. Then, the transient power plant parameters are fitted through simulations to replicate the real load rejection response.

The model used in this paper to replicate the power plant gas turbine and speed governor is the GAST model, as it is one of the most used for dynamic modeling [12–14]. The AVR model chosen was the simplified excitation system (SEXS) [15,16] and, to represent the SG, the model used was GENSAL [17–19]. The full models that combine GAST, SEXS and GENSAL are already validated models that can be found in the literature [20–24] and they are widely used by PSOs in simulation programs like PSS/E®.

With the research motivations explained, the main contributions of this study are summed up as follows:

- Performing load rejection tests is proposed in order to study the power plant's and synchronous generator's transient response. This test allows us to provoke realistic fast transients emulating real faults where the AVR and the speed governor dynamics are not fast enough.
- With the load rejection tests' data, well-known models are fitted to satisfy the dynamic response in order to provide this information to the corresponding PSO.
- To corroborate the dynamic transient response characterization, load rejection tests have been carried out over more than 60 real power plants of the Spanish power grid. In this manuscript, three of them are shown as examples.

The paper is structured as follows: first, Section 2 describes the theoretical model used for the transient stability parameters acquisition and fitting. Secondly, Section 3 shows the experimental tests carried out in three real gas power plants. Afterwards, Section 4 is focused on the simulation results of parameters fitting. Finally, Section 5 concludes the paper with the main ideas obtained during the research.

2. Theoretical Models

As the automatic voltage regulator (AVR) response is not fast enough to clearly show the transient dynamics of a synchronous generator (SG) during a fault event, a load rejection test is proposed to model the SG behavior. A load rejection test is a controlled and deliberate test where the SG is subjected to a sudden reduction in load. This helps to simulate a fault condition and provides valuable information about the SG's transient response.

Understanding the transient dynamics of SGs during fault events is crucial for power grid operators as it allows them to monitor and simulate faults and other contingencies in the power system. This information can be used to improve the overall stability and reliability of the power system. The proposed model in Figure 1 illustrates the SG's behavior during a load rejection test, where the main circuit breaker (CB) is opened once the SG is running at rated speed and power, and the model can also be obtained at reduced power.

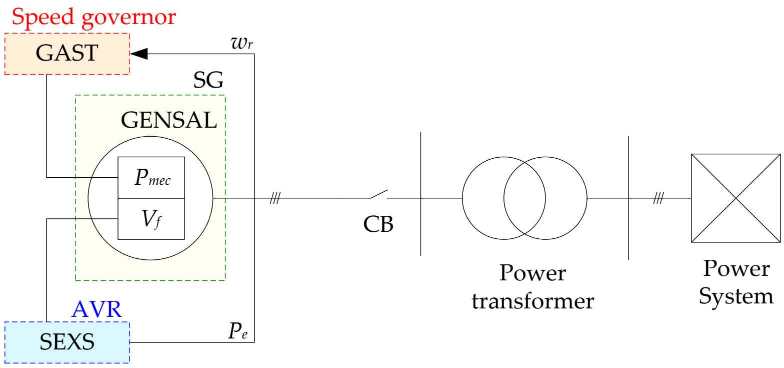


Figure 1. Electrical scheme and simulation model correlation for an SG connected to an infinite power bus.

In Figure 1, the models used in simulations and their correlation are plotted. The theoretical model consists of the SG as GENSAL, which produces as outputs the electrical power (P_e) and the rotor speed (w_r), the speed governor as GAST, whose output is mechanical power (P_{mec}), and the AVR as SEXS, whose output is the field voltage (V_f). Each of the models is described in more detail below.

Saturation factor at 1.2 pu voltage	$S_{(1.2)}$

2.1. SG Model: GENSAL

The SG is shaped using the GENSAL model, which is included in Figure 2. Table 1 shows all the parameters related to Figure 2. Most of these parameters are given by the manufacturer.

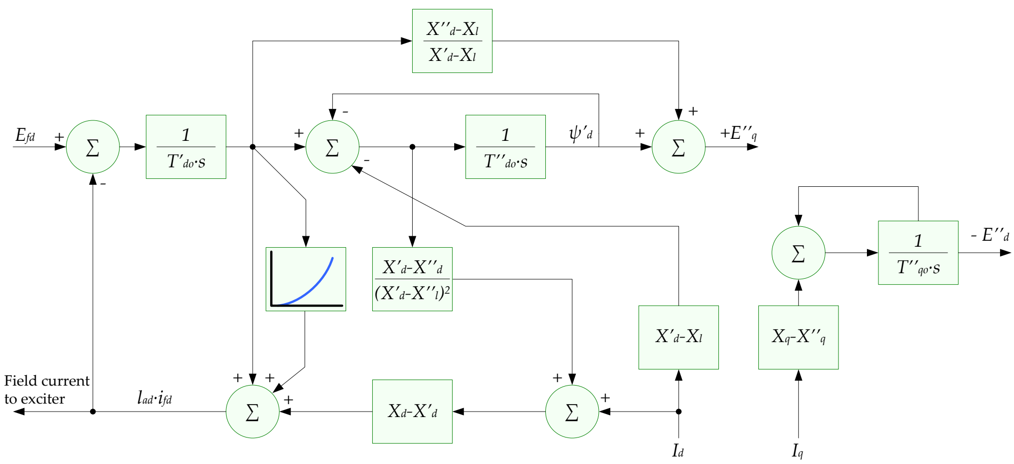


Figure 2. GENSAL model for the SG.

Table 1. GENSAL model parameters.

Description	Parameter	Units
d-axis open circuit transient time constant	T'_{do}	[s]
d-axis open circuit sub-transient time constant	T''_{do}	[s]
q-axis open circuit sub-transient time constant	T''_{qo}	[s]
Machine inertia	H	[s]
Speed damping	D	[s]
d-axis synchronous reactance	X_d	[pu]
q-axis synchronous reactance	X_q	[pu]
d-axis transient reactance	X'_d	[pu]
Sub-transient reactance	X''_d	[pu]
Leakage reactance	X_l	[pu]
Saturation factor at 1.0 pu voltage	$S_{(1.0)}$	

However, three parameters need to be calculated, which include two terms related to the saturation factors and the inertia of the power plant. These factors are encompassed by the turbine and the alternator.

On the one hand, the saturation parameters are calculated according to expressions (1) and (2) as:

$$S_{(1.0)} = \frac{A_{10} - B_{10}}{B_{10}} \tag{1}$$

$$S_{(1.2)} = \frac{A_{12} - B_{12}}{B_{12}} \tag{2}$$

The values A_{10}, B_{10}, A_{12} and B_{12} are parameters that are required to be calculated for the modeling of a synchronous generator. These parameters are obtained from the no-load characteristic, which can be found in the generator datasheet. Figure 3 shows an example of a typical saturation test plot that is used to obtain the no-load characteristic.

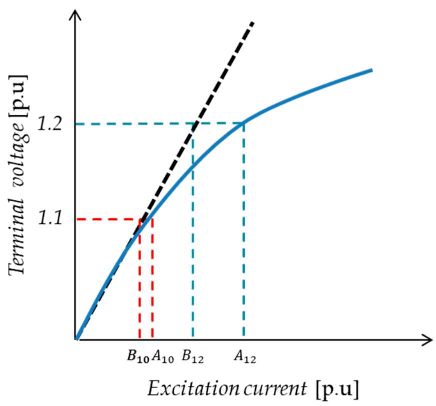


Figure 3. SG no-load characteristic.

On the other hand, during the load rejection test, the inertia of the system can be determined. The kinetic model of the system can be represented by expression (3):

$$\omega_r(t) = \frac{1}{2H}\int T_a(t)dt = \frac{1}{2H}\int [T_{mec}(t) - T_{elec}(t)]dt \tag{3}$$

where $\omega_r(t)$ is the rotor speed, $T_{mec}(t)$ is the shaft torque due to the turbine, $T_{elec}(t)$ is the electrical torque due to the network load and H is the machine inertia.

At the moment of load rejection, the electrical torque becomes null ($T_{elec}(t) = 0$) but the mechanical torque remains. The inertia of the machine determines the frequency variation. Therefore, the values of Δt and Δf used to determine the inertia must be calculated as the difference between the steady state and the first sample obtained after opening the main circuit breaker. By performing this, the influence of the speed governor on the frequency change is not taken into consideration.

Using per-unit values of the machine, the machine inertia, H, can be calculated through (4). Also, a graphical example is plotted in Figure 4.

$$H = \frac{P_{mec}[pu] \cdot \Delta t[s]}{2 \cdot \Delta f[pu]} \quad (4)$$

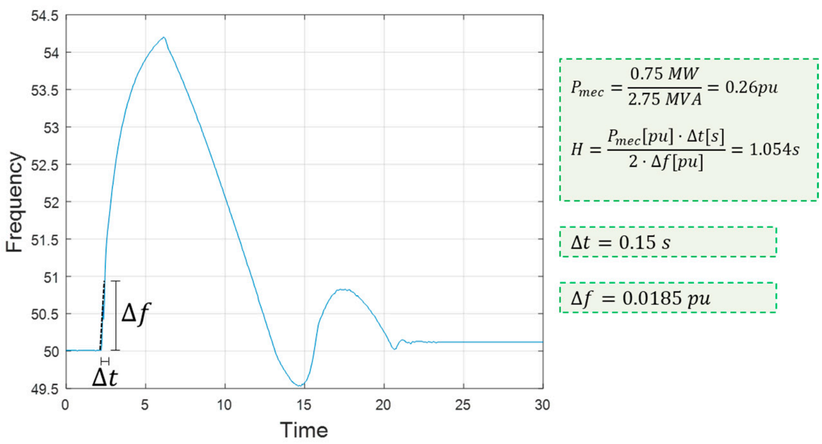


Figure 4. Case example: calculating SG inertia on an actual generator.

The P_{mec} parameter given in (4) is calculated as:

$$P_{mec}[pu] = \frac{P_{test}}{S_b} \quad (5)$$

where P_{test} is the active power delivered to the grid before the load rejection, S_b is the machine rated power, Δt is the time difference between the steady-state measurement and the load rejection measurement and Δf is the frequency difference between the steady-state measurement and the load rejection measurement.

2.2. AVR Model: SEXS

The model chosen to represent the behaviour of the power plants AVR is SEXS. Figure 5 shows the voltage regulation control diagram of the AVR model. In the AVR-SEXS model, the input voltage to the excitation system is denoted by V_S. This voltage is obtained by adding two signals—VPSS, which represents the voltage feedback from the power system stabilizer, and VOEL, which is the difference between the reference voltage setpoint and the generator terminal voltage. Thus, the value of V_S is the summation of these two signals and serves as the input to the excitation system. Additionally, the model uses two other inputs: V_{ref}, which is the reference voltage setpoint, and V_C, which is the compensated terminal voltage, both expressed in per-unit values.

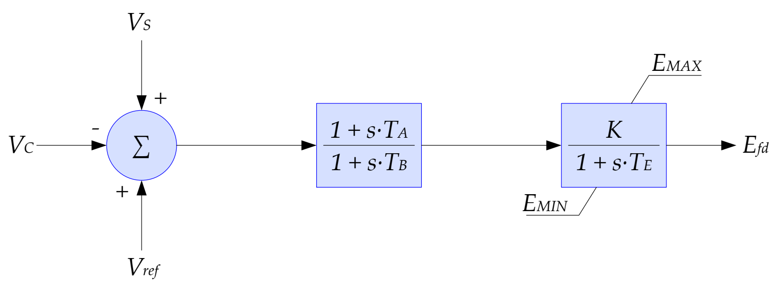


Figure 5. Simplified excitation system (SEXS) model.

Table 2 displays the parameters for the AVR model, which are determined through simulation fitting based on tests. These tests include an individual test of the AVR controller that varies the voltage reference without a load, as well as a load rejection test that enables the fitting of the transient response. The transient response allows for the fitting of the time constant T_E, as well as the first block parameters T_A and T_B. The remaining parameters can be fitted using the steady-state varying points observed during no-load conditions.

Table 2. SEXS model parameters.

Description	Parameter	Units
Rate of change in the excitation system numerator	T_A	[s]
Rate of change in the excitation system denominator	T_B	[s]
Exciter gain	K	[pu]
Exciter time constant	T_E	[s]
Maximum AVR output	E_{MIN}	[pu]
Minimum AVR output	E_{MAX}	[pu]

2.3. Speed Governor Model: GAST

The model chosen to represent the behavior of the power plants speed governor is GAST. The model is plotted in Figure 6. Furthermore, Table 3 collects the parameters related to the GAST model.

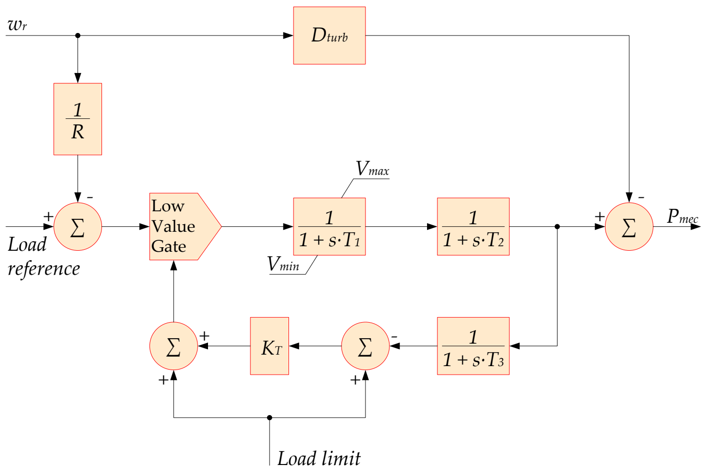


Figure 6. Speed governor model (GAST).

Table 3. GAST model parameters.

Description	Parameter	Units
Permanent droop	R	[pu]
Governor mechanism time constant	T_1	[s]
Turbine power time constant	T_2	[s]
Turbine exhaust temperature time constant	T_3	[s]
Ambient temperature load limit	A_T	[pu]
Temperature limiter gain	K_T	[pu]
Maximum turbine power	V_{max}	[pu]
Minimum turbine power	V_{min}	[pu]
Turbine damping factor	D_{turb}	[pu]

As for the previous AVR model, the speed governor parameters are collected from a gas injection set point changing test and from a load rejection test. The damping factor and tune constants are fitted from the load test rejection; meanwhile, the upper and lower operation limits and permanent droop are fitted from the steady-state set point change tests.

The parameters' fitting from tests and simulations is an iterative process, and there are some standards parameter proposed by [25,26]. However, those are used just to initialize the simulation iteration; first, the individual controllers must be simulated, because the regulators (SEXS and GAST) are decoupled and it is easier to get nearer to the final solution.

After obtaining the parameters through the previous simulations, the load rejection is simulated. The solution is then checked, and if it is unsatisfactory, the no-load set point simulation must be rerun to fine-tune the previous adjustments. Subsequently, the load rejection simulation must be performed again. This iterative process should be repeated until all the simulations converge to a satisfactory adjustment.

Finally, a schematic flowchart that sums up the power plant characterization methodology using load rejection tests is plotted in Figure 7. The iterative process used to fit the parameters of the GAST and SEXS models has been carried out manually in order to adjust the first transient oscillation, which is the most important for stability studies. However, other fitting tools such as evolutionary algorithms could be used to solve the problem [27–29].

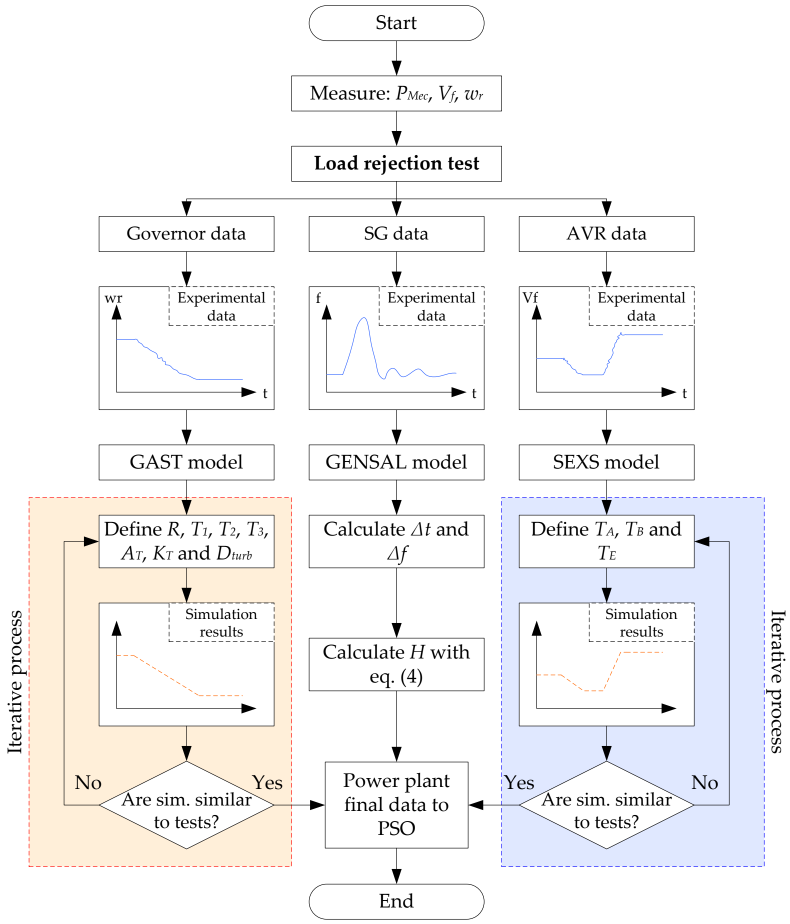


Figure 7. Schematic flowchart of the power plant characterization via load rejection test.

3. Experimental Tests

The audit process is composed of two groups of tests that have to be carried out in order to observe the dynamic response of the gas power plant. The AVR and speed governor controllers have to be firstly tested individually and then together.

3.1. Test Procedure

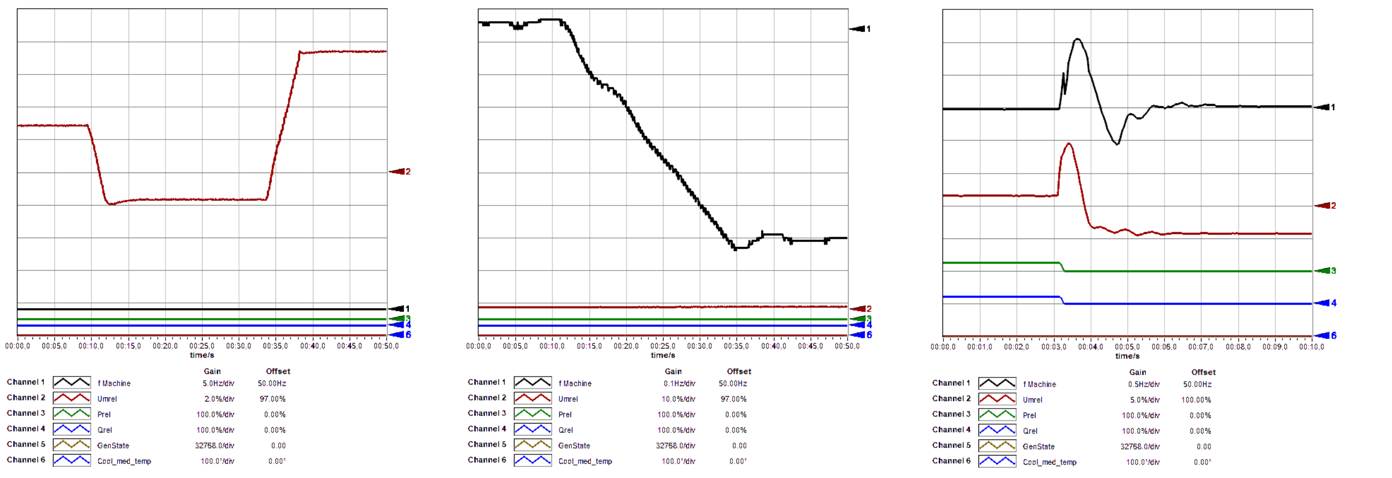
The first step in the audit process was obtaining the project dossier of the power plant, i.e., the summary description of the entire project of the power plant construction and its outputs. It contains all the technical information and a description of each component of the plant.

Next, individual controller tests were performed, which can be classified into two types: AVR set point changes without load and speed governor set point changes without load. To carry out these tests, the power plant's load was gradually reduced until the generator becomes idle, after which the set points of the AVR and speed governor can be changed (either automatically or manually through the control panel) to observe how the controllers respond to voltage and frequency variations. This no-load test provides information about how the controllers behave as separate entities.

A second set of tests was conducted to observe how the AVR and speed governor controllers behave when working together. Load rejection tests were then carried out to evaluate the transient response to power grid faults. For these tests, the load was set to between 10% and 15% of the generator's rated load to prevent overstressing the system, which could potentially damage the plant. Once the load reached steady-state operation, the main circuit breaker was turned off to isolate the generator and create an islanded condition.

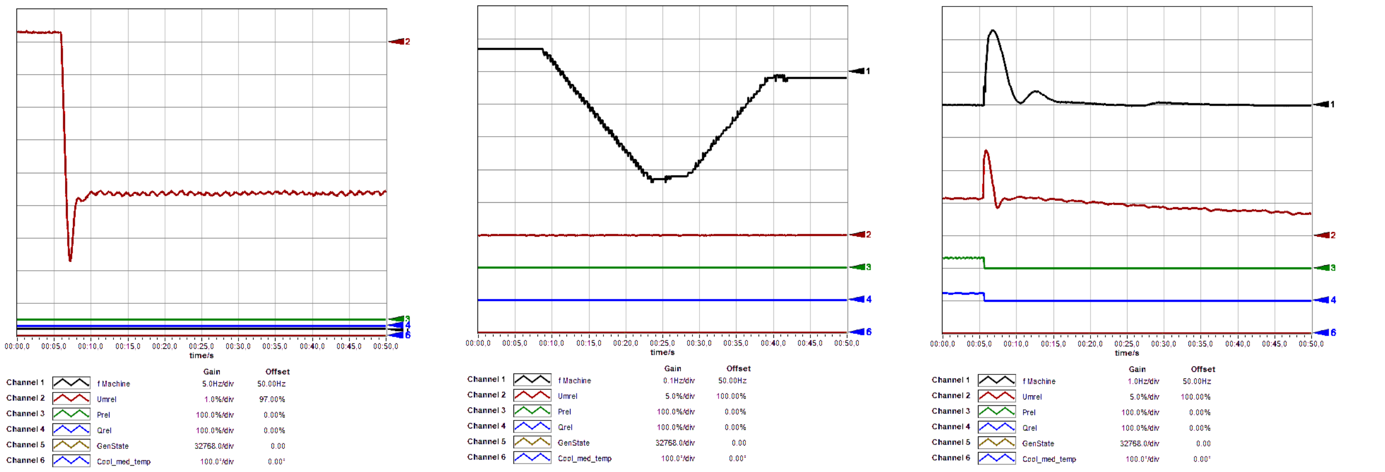
3.2. Measuring Devices and Configuration

A series of records of the tests were carried out on more than 60 gas power plants of the Spanish power grid. The steady-state and transient measurements were registered using a 4-channel oscilloscope where the machine's frequency (CH1 = f), the AVR output voltage (CH2 = E_{FD}) and the output active and reactive power (CH3 = P_S, CH4 = Q_S) were measured. The last two variables were used to fit 10–15% of the rated power condition and to monitor the load rejection. The registers were carried out during 60 s, but different time spread responses were found attending to the different power plants inertias and to the AVR and speed governor settings. The maximum, minimum and time settings for each channel can be also observed in the oscilloscope registers shown in Figures 8–10.



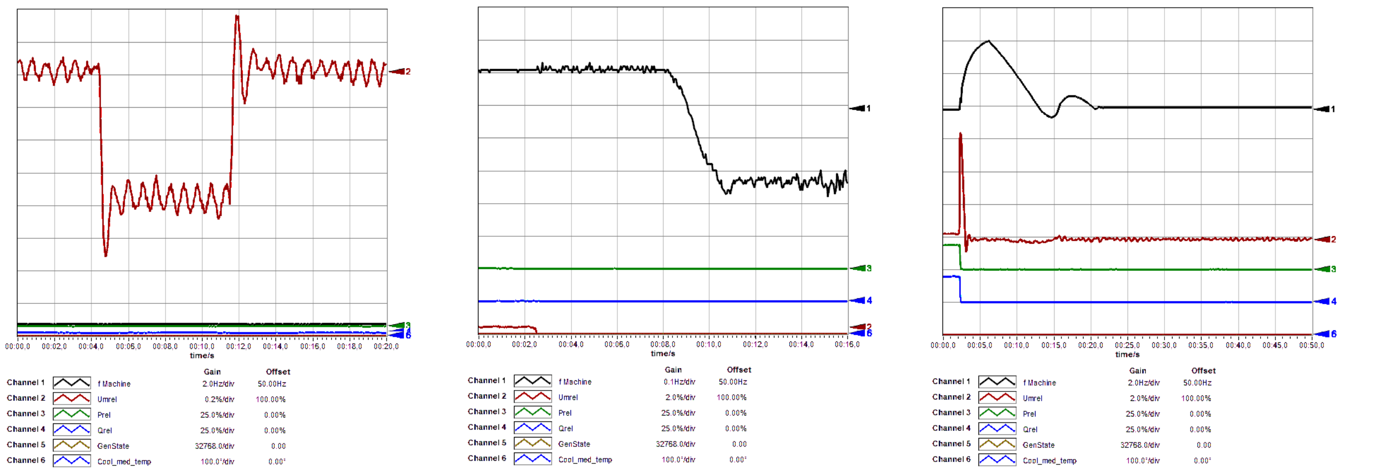
(**a**) (**b**) (**c**)

Figure 8. Plant 1 tests: (**a**) no-load voltage set point changes; (**b**) no-load frequency set point changes; (**c**) load rejection test at P_S = 1.7 MW and Q_S = 1.4 MVAr.



(**a**) (**b**) (**c**)

Figure 9. Plant 2 tests: (**a**) no-load voltage set point changes; (**b**) no-load frequency set point changes; (**c**) load rejection test at P_S = 5 MW and Q_S = 5 MVAr.



(**a**) (**b**) (**c**)

Figure 10. Plant 3 tests: (**a**) no-load voltage set point changes; (**b**) no-load frequency set point changes; (**c**) load rejection test at P_S = 15 MW and Q_S = 10 MVAr.

3.3. Cases of Study

From the tested power plants, three of them are shown and analyzed in this section. Some information about the generators is collected in Table 4.

Table 4. Gas power plants information.

Power Plant	SG Manufacturer	SG Model	Rated Power [MVA]	Rated Voltage [kV]
1	ABB	HSG	6.5	6.3
2	ABB	GBA 1250	22.5	11
3	HMA	DG215ZL-04	47.7	11

Results for the no-load AVR variations, speed governor behavior and load rejection tests are plotted in Figures 7, 9 and 10 for plants 1, 2 and 3 respectively. It can be observed that, attending to the power plant, as the parameters and SGs are different, the responses vary considerably from one another.

4. Fitting Simulations

After obtaining the registers, simulations are necessary to obtain the GAST, SEXS and GENSAL model parameters. These models were fitted manually using Simulink®, with a global simulation scenario that linked all the models together, as shown in Figure 1.

From the no-load voltage variation tests, some of the parameters of the AVR are fitted, and, analogously, from the no-load frequency variation tests, some speed governor parameters are fitted in a first iteration (the real responses can be observed from diagrams (a) and (b) of Figures 8–10). Afterwards, the rest of the parameters are fitted from the load rejection test.

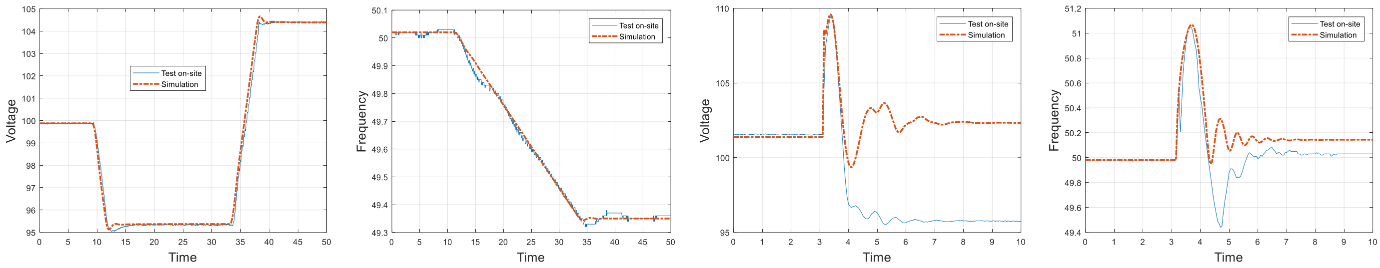
In terms of simulation setup, the simulation time is set to the same time as the real responses obtained above. Once reaching the steady-state simulation, the variations in voltage and frequency references are performed with the same amplitude as in the real cases. As the tests were carried out with no load and with test rejection, an ideal grid was supposed in terminals of the main CB, so, once it is opened, the grid has no influence in the simulation. It is only required to set the initial conditions previously to the SG disconnection.

After several iterations, we obtained the parameters shown in Table 5, which produced the transient behaviors shown in Figures 11–13 for Plants 1, 2 and 3, respectively. As can be observed, the AVR and speed governor single fitting was performed with good accuracy. However, the load rejection test transients were only well fitted for the first oscillation. The transfer functions of real governors and AVRs are more complex than the computer models such as the governor model (GAST) and the automatic voltage regulator model (SEXS). Rather, the simplified models capture the essential behavior of synchronous generators in the case of transient operation. They neglect some of the finer details of the regulators, such as the change in setpoint, in order to have the generator ready to be synchronized again to the power system.

In order to achieve more accurate solutions, heuristic fitting algorithms should be implemented in the iterative processes of GAST and SEXS models, such as genetic [27,28] or evolutionary algorithms [29]. They would be good candidates for this application, as the computation time is not a critical variable in the characterization process and they avoid the effect of local minimum solutions.

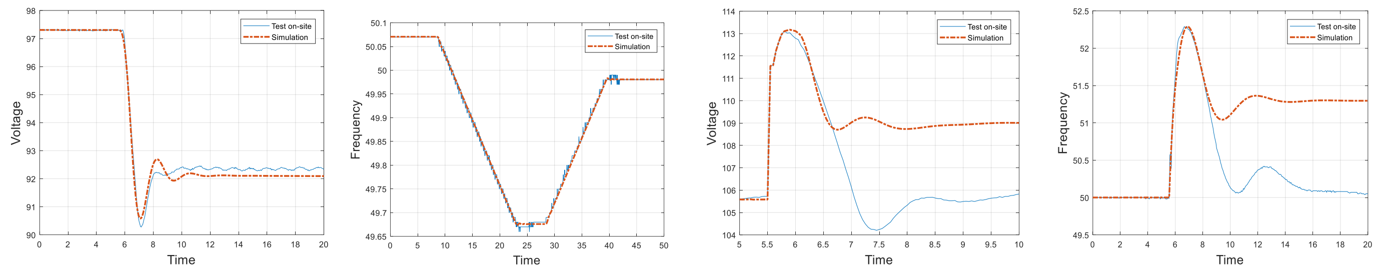
Table 5. Gas power plants simulation parameters.

Parameter	Plant 1	Plant 2	Plant 3	Units
T_A	5	2	4	[s]
T_B	12	6	8	[s]
K	100	120	80	[pu]
T_E	0.08	0.03	0.05	[s]
E_{MIN}	−4.53	−4.20	−4.33	[pu]
E_{MAX}	5.64	5.10	5.30	[pu]
R	0.05	0.56	0.58	[pu]
T_1	0.40	0.22	1.40	[s]
T_2	0.15	0.14	0.70	[s]
T_3	3.0	3.2	2.7	[s]
A_T	0.9	0.9	0.9	[pu]
K_T	2	2	2	[pu]
V_{max}	0.8	0.8	0.9	[pu]
V_{min}	0	0	0	[pu]
D_{turb}	0.32	0.50	0.50	[pu]



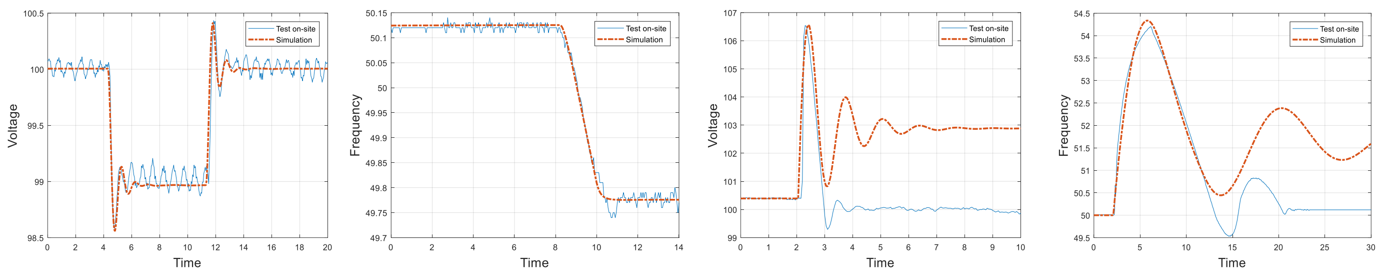
(**a**) (**b**) (**c**) (**d**)

Figure 11. Plant 1 simulation fittings: (**a**) no-load voltage set point changes; (**b**) no-load frequency set point changes; (**c**) load rejection test, voltage transient; (**d**) load rejection test, frequency transient.



(**a**) (**b**) (**c**) (**d**)

Figure 12. Plant 2 simulation fittings: (**a**) no-load voltage set point changes; (**b**) no-load frequency set point changes; (**c**) load rejection test, voltage transient; (**d**) load rejection test, frequency transient.



(**a**) (**b**) (**c**) (**d**)

Figure 13. Plant 3 simulation fittings: (**a**) no-load voltage set point changes; (**b**) no-load frequency set point changes; (**c**) load rejection test, voltage transient; (**d**) load rejection test, frequency transient.

5. Conclusions

This paper studies the characterization of power plants parameters from AVR and speed governor single tests under no-load conditions and a posterior load rejection test at reduced power in order to provide the synchronous generator (SG) parameters to the power system operator (PSO) with which simulates contingencies.

Once given the registers of voltage and frequency variations from the on-site tests, the parameters' characterization is carried out in two stages:

(1) In the first step, the model is simulated under no-load conditions in order to change the controllers' set point (steady-state parameters) of the AVR and speed governor in an idle move.

(2) In the second step, the load rejection simulations make it possible to find the transient controllers' parameters by fitting the parameters in an iterative process, in this case manually performed, in order to reach simulation curves similar to those measured in the experimental tests.

This paper presents some cases of a fieldwork carried out in more than 60 audited gas power plants, where the response of their controllers was studied. Some of them had problems with wrong controllers adjustments creating an instable system, while others did not have proper coordination in the generator protections, resulting in inappropriate disconnections from the network. For these reasons, these types of audits have high relevance for the power system reliability.

In the audits shown in this paper, it must be noted that, at the fitting process, they did not fit well at steady-state after-transient parts of the simulation. The accuracy of a model depends on the level of detail required for the specific application. While the GENSAL model is a simplified model, it captures the essential behavior of synchronous generators and allows the PSO to perform contingencies simulations with admissible computational times. However, for more detailed analysis, more advanced models such as the Park's model or the detailed electromagnetic transient model (EMT) could be used. The choice of model depends on the specific requirements of the analysis. On the other hand, advance fitting tools such as evolutionary algorithms should be used in further studies to perform the iterative parameters' fitting process.

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