Field Testing and Model Validation of Motor-Generators

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Abstract**—** In this paper, the field tests conducted by the IITREE-LAT to verify the performance of motor-generators are presented. These machines are used as distributed energy resources (DER) in oil fields and different cities across Argentina.

On the basis of these tests, the models regarding generator, power-speed control system and voltage control system are presented.

Index Terms**—** Tests. Synchronous Generator. Motor-generator. Voltage regulator. Governor.

I. INTRODUCTION

A restructured distribution network which uses a large number of distributed energy resources can improve the level of system reliability and allow the division of the network according to the required service quality (critical and non-critical loads).

The DER, including distributed generation and distributed storage are energy sources that are located near local loads and can provide a significant benefit if correctly operated. The distributed generation units are small energy sources, consisting of photovoltaic cells, wind turbines, fuel cells, microturbines, and motor-generators. These last ones use gas or fossil fuel as primary energy.

The motor-generators are equipped with a power-speed control system to regulate the engine speed and an automatic voltage regulator that controls the internal voltage of the synchronous generator, as shown schematically in Fig. 1.

The integration of many small-scale generators in the interconnected power system impacts on their operation, control and protection. Given the proliferation of these small generators, there is uncertainty about the effect thereof on the overall system performance.

Nowadays, power plants equipped with motor-generators represent a major portion in the total generation and are installed approximately 1000 MW for a total of 23000 MW of generation.

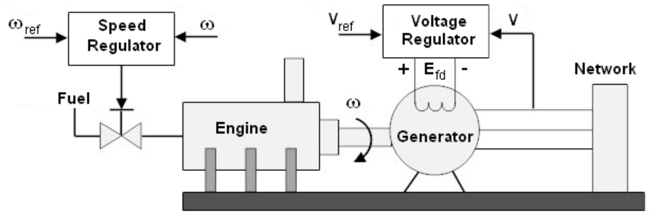

Fig. 1: Motor-generator's schematic diagram and associated control systems.

It is therefore convenient to provide simulation models for these motor-generators, including determination of its dynamic characteristics such as the inertia constant and the determination of excitation and power-speed control systems.

This paper presents, as an example, the field tests conducted on two typical power plants equipped with motor-generators. On the basis of these tests, the models regarding generator, power-speed control system (governor) and voltage system control (Automatic Voltage Regulator, AVR) are presented. The simulation results are compared with field records.

II. POWER PLANTS DESCRIPTION

Power Plant 1 is composed of 14 motor-generators, 2000 kVA /1600 kW each one and is located in the city of La Rioja, La Rioja. Power plant 2 is composed of 16 motor-generators, 1750 kVA/1400 kW each one and is located in the vicinity of the city of Colonia Catriel, Neuquén.

Basic data of two power plants are presented in TABLE I.

TABLE I: BASIC CHARACTERISTICS OF THE POWER PLANTS.

Power Plant 1	Power Plant 2
Engine Brand: Caterpillar Type: 3516 Fuel: diesel Frequency: 50 Hz	**Engine** Brand: Jenbacher Type: JGS 420 GS Fuel: gas Frequency: 50 Hz
Synchronous generator Brand: Caterpillar Type: 826 Excitation: Brushless with rotating excitater and permanent magnet pilot exciter Apparent Power: 2000 kVA Active Power: 1600 kW Power Factor: 0.8 Voltage line/phase: 400/230 V Poles: 4 Efficiency at rated load: 96.9 %	**Synchronous generator** Brand: Jenbacher Type: PE734F2 Excitation: Brushless with rotating excitater and permanent magnet pilot exciter Apparent Power: 1750 kVA Active Power: 1400 kW Power Factor: 0.8 Voltage line/phase: 400/230 V Poles: 4 Efficiency at rated load: 97.5 %
Automatic Voltage Regulator Brand: Caterpillar Type: CAT digital voltage regulator Power Factor Controller: No	**Automatic Voltage Regulator** Brand: STAMFORD Type: MX 321 Power Factor Controller: STAMFORD PFC-3
Power-Speed Regulator Brand: Caterpillar	**Power-Speed Regulator** Brand: STAMFORD
Transformer Brand: Vasile Power: 2000 kVA Connection group: Yd11 DC Voltage: 5.22 % Switch: -2x2,5 % y +2x2,5 %	**Transformer** Brand: Tadeo Czerweny S.A. Power: 1800 kVA Connection group: Yd11 DC Voltage: 5 % Switch: -4x2,5 % y +2x2,5 %
Synchronous machine Protections Over-voltage: 450 V (112,5 %) / 2 s Under-voltage: 320 V (80 %) / 2 s Over-frequency: 53 Hz / 20 s Under-frequency: 47 Hz / 20 s	**Synchronous machine Protections** Over-voltage: 450 V (112,5 %) / 2 s Under-voltage: 320 V (80 %) / 2 s Over-frequency: 53 Hz / 20 s Under-frequency: 47 Hz / 20 s

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III. SYNCHRONOUS MACHINE

To model the generator it was used the model GENSAL [1], which corresponds to a salient poles synchronous machine of the Interactive Program Power System Simulator PSS/E. In TABLE II, the parameters used to model the synchronous machine are described, and P-Q diagrams of both generators are show in Fig. 2 and Fig. 3.

IV. AUTOMATIC VOLTAGE REGULATOR (AVR)

A. Operation principle of the voltage regulator.

Both plants, have rotating excitation system, therefore the need for slip rings and brushes is eliminated. The DC voltage is supplied directly to the generator field winding. Figure 4 shows a simplified block diagram of the power plant 2 excitation system.

As shown in Fig. 4, the armature windings (rotor) of the main exciter and diodes rectifier rotate with the generator field winding (rotor). It also rotates along with them the permanent magnet rotor of the pilot exciter.

The rectified output of the pilot exciter stator winding energizes the stationary field of the main exciter. The AVR modulates the DC voltage applied to the main exciter field winding, which also determines the field winding voltage of the generator. This excitation system is known as “Brushless Excitation System ".

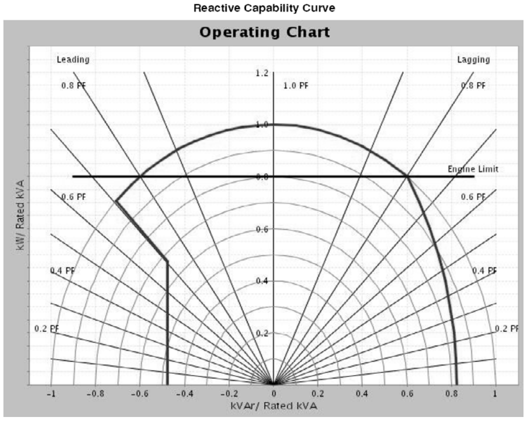


Fig. 2: Plant 1. Generator's P-Q diagram.

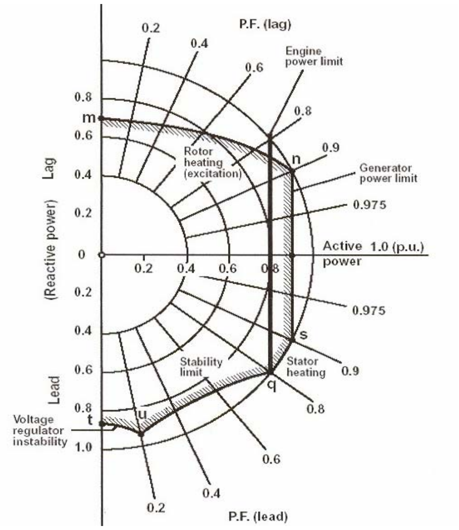
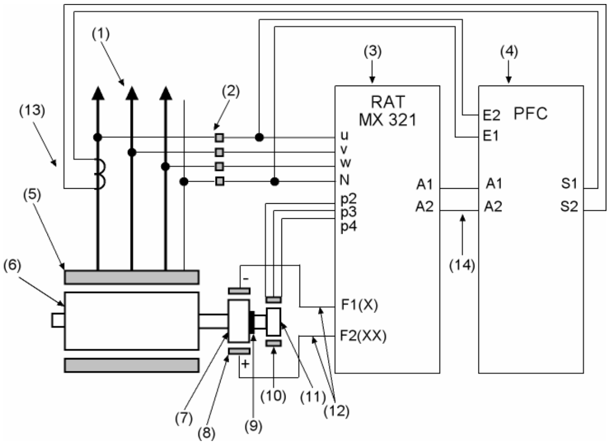


Fig. 1: Plant 2. Generator's P-Q diagram.

TABLE II: SYNCHRONOUS MACHINE PARAMETERS

Parameter	Description	Plant 1	Plant 2	Unit
Sbase	Apparent Power	2.0	1.75	MVA
Cos φN	Nominal Power Factor	0.8	0.8	---
F	Nominal Frequency	50	50	Hz
U	Rated voltage	400	400	V
I	Rated Current	2886.8	2528.8	A
Xd	Unsaturated synchronous reactance of direct axis	3.069	2.76	pu
X´d	Unsaturated transient reactance of direct axis	0.214	0.17	pu
X”d	Unsaturated subtransient reactance of direct axis	0.133	0.12	pu
Xq	Unsaturated synchronous reactance of quadrature axis	1.45	1.78	pu
X´q	Unsaturated transitory reactance of quadrature axis	----	1.78	pu
X”q	Unsaturated subtransient reactance of quadrature axis	0.124	0.25	pu
Xl	Dispersion reactance	0.15	0.44	pu
T´d0	Transient time constant of direct axis	3	3.9	s
T”d0	Subtransient time constant of direct axis	0.008	0.028	s
T´q0	Transient time constant of quadrature axis	----	5.08	s
T”q0	Subtransient time constant of quadrature axis	0.006	0.226	s
S(1.0)	Terminal Voltage saturation coefficient 1.0 pu	0.2298	1.29	---
S(1.2)	Terminal Voltage saturation coefficient 1.2 pu	1.0104	1.98	---
H	Inertia constant of the rotating masses:	0.5	0.44	s



1: Generator output voltage.
2: Generator Terminal Voltage
3: Voltage regulator MX321.
4: Power Factor Controller PFC-3.
5: Generator stator.
6: Generator rotor.
7: Main exciter rotor.
8: Main exciter stator.
9: Rotating thyristor rectifier bridge.
10: Pilot exciter stator (permanent magnet generator, PMG).
11: Pilot exciter rotor (permanent magnet generator, PMG).
12: AVR Output.
13: Measuring current from the generator to the PFC.
14: PFC Output.

Fig. 4: Brushless excitation system.

The AVR measures the three-phase voltage of the generator through an isolation transformer connected directly to the generator stator windings. The measured voltage is compared with a reference voltage. The reference voltage can be adjusted internally or externally.

The Power Factor Controller (PFC) compares reactive current with a fraction of the measured active current. This fraction can be adjusted by a control potentiometer. If the reactive current is over the reference value, the PFC works by reducing the internal voltage reference of the AVR (via terminals A1 and A2) thus reduces the reactive power generated (and therefore the power factor) to the desired level. If the reactive current is below reference the opposite action is performed, i.e. the AVR internal reference increases in order to increase the power factor. Thus, the PFC performs a closed-loop control of power factor of the generator.

B. Tests performed on voltage regulator.

Following are presented the tests performed on a machine of each plant.

Voltage variation of small amplitude. Unit at full speed no load.

This test seeks to identify the dynamic response of the automatic voltage regulator. This test was performed with the generator disconnected from the network (no load), excited, rotating at rated speed, and rated voltage. The disturbance consisted in the application of pulses in the voltage reference, so that the generator terminal voltage varies between 1% and 10% of its rated value. The duration of these pulses was 20 seconds.

Voltage variation of small amplitude. Unit at load.

This test seeks to verify the performance of the automatic voltage regulator with the unit at load. This test was performed with the generator operating close to rated power.

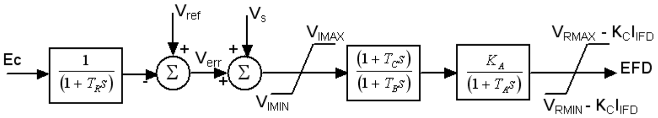


Fig. 5: EXAC4 model of the voltage regulator.

TABLE III: AVR MODEL PARAMETERS.

AVR Parameters	Plant 1	Plant 2
TR	0.02 s	0.02 s
TC	1.4 s	2 s
TB	100 s	10 s
KA	300	200
TA	0.1 s	0.1 s
Kc	0	0
VIMIN	-10	-10
VIMAX	10	10
VRMIN	0	0
VRMAX	5	5

TABLE IV: PERFORMANCE RATINGS.

Parameter	Plant 1	Plant 2
Rise time (10 % to 90 %)	0.25 s	0.16
Settling time (Entering a band ±5 %)	1.03 s	0.85 s
Overshoot	18.5 %	14 %

Thedisturbance consisted in the application of pulses in the voltage reference, so that the generator terminal voltage varies between 0.5% and 1% of its rated value. The duration of these pulses was 20 seconds.

C. Voltage regulator model.

The voltage regulator model used for the simulations corresponds to the EXAC4 model [1-2] of the PSS/E program manual. Fig. 5 shows the block diagram of the voltage regulator EXAC4 model. Table III provides the adjusted parameters for the voltage regulators of both power plants and Table IV presents the performance ratings that characterize the voltage regulation at full speed no load of the excitation system.

Fig. 6 and Fig. 8 shows the records of tests conducted on the voltage regulator with the units at no load and the corresponding simulations for power plant 1 and power plant 2, respectively. Fig. 7 and Fig. 9 presents the records of testing performed with units at load of both plants.

These figures show a good agreement between measurements and simulations with the model and specified parameters.

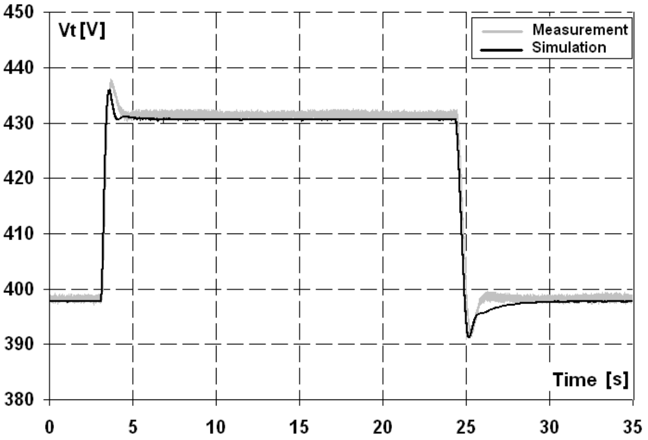


Fig. 6: Measurement and simulation at no load.

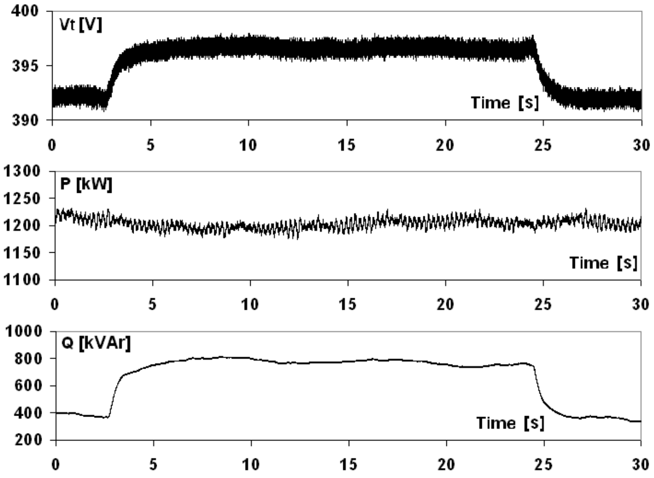


Fig. 7: Measurement with unit at load.

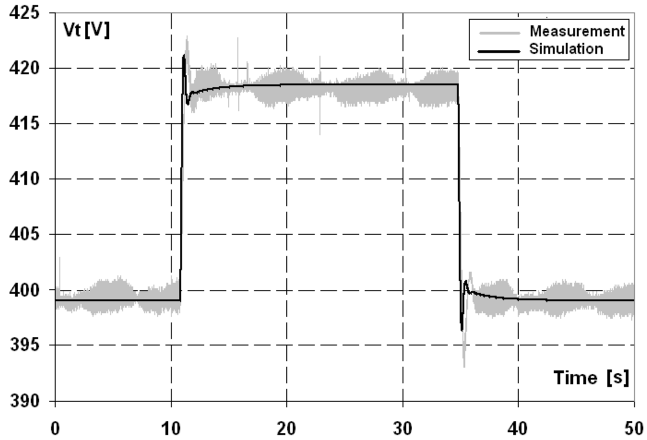


Fig. 8: Measurement and simulation at no load.

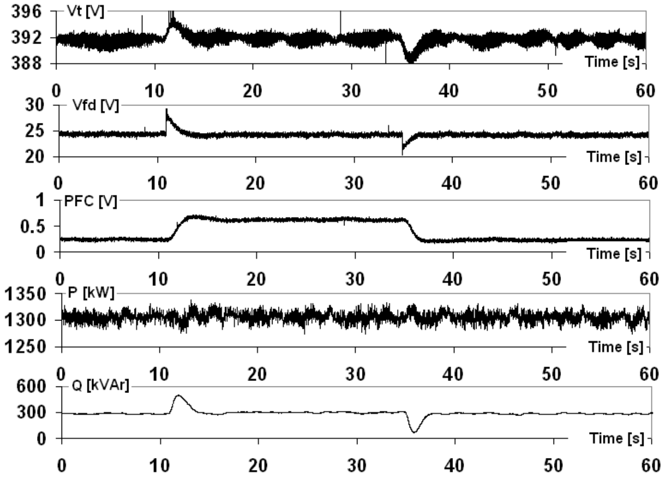


Fig. 9: Measurement with unit at load.

V. POWER-SPEED CONTROL SYSTEM

A. Determination of the inertia constant of motor-generators.

The manufacturer supplies the inertia moment of the synchronous machine, its excitation system and its coupling to the prime mover as a whole. With this value it can be approximated the inertia constant, which ignores the mass of the prime mover (engine).

Since the inertia constant is very small, it is convenient to determine it with a load rejection test. The rotating mass model of the motor-generator represents the relationship between the accelerating torque and rotor angular speed according to the following:

$$\omega_r(t)=\frac{1}{2H}\int T_a(t)dt=\frac{1}{2H}\int\left[T_{mech}(t)-T_{elec}(t)\right]dt \qquad (1)$$

If the previous expression is expressed in per unit, the rotor angular speed can be changed by the electrical frequency. By opening the machine breaker there is a step-type change, in the electrical torque from its initial value to zero. The speed governor respond is not instantaneous and therefore in the first moments, mechanical torque remains constant. Therefore, initially the rotor angular speed grows as a ramp until the governor begins to act.

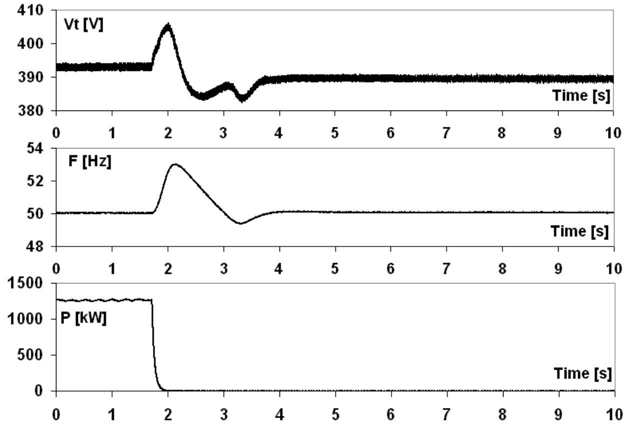


Fig. 10: Plant 1. Load rejection.

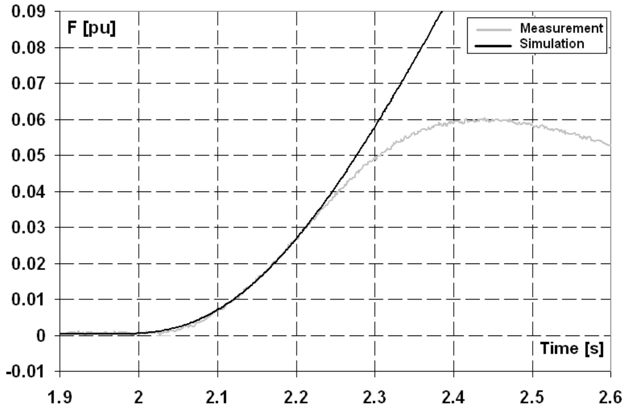


Fig. 11: Plant 1. Load rejection. Measurement and simulation of frequency.

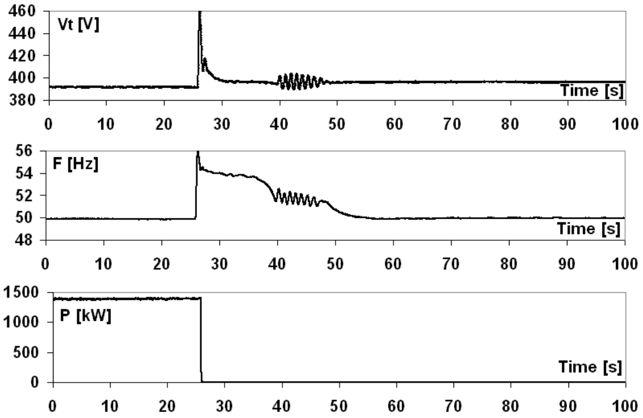


Fig. 12: Plant 2. Load rejection.

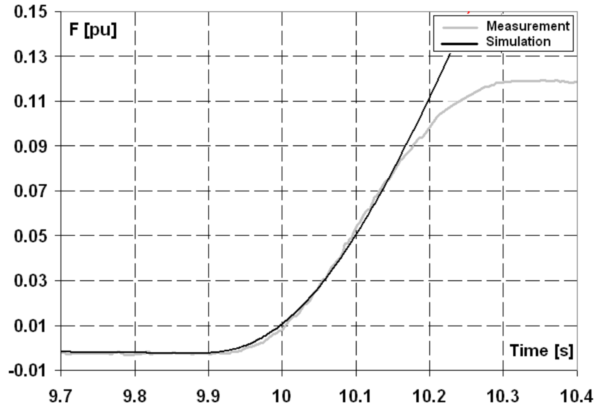


Fig. 13: Plant 2. Load rejection. Measurement and simulation of frequency.

Fig. 10 and Fig. 12 show records of load rejection test on power plant 1 and power plant 2,respectively. Fig. 11 and Fig. 13 show the electrical frequency deviation measured and simulated in the first moments after the load rejection.

The simulated value of the frequency deviation was obtained with the following expression:

$$\Delta f_{sim}\left(t\right)=\frac{1}{2H}\int\left[-\Delta T_{elec}\left(t\right)\right]dt \qquad (2)$$

Due to the dynamics associated with the measurement, frequency variations are not ramps. This effect was taken into account in the simulations. By adjusting the inertia constant in the simulation to match with the measurement, the following values for the inertia constants are obtained: Plant 1: H = 0.5 s Plant 2: H = 0.44 s.

B. Power-speed regulator model.

The block diagram of the Governor DEGOV1 model (Woodward Diesel Governor) from PSS/E is presented Fig. 14, while TABLE V shows the settings of this model for the operation at load.

The governor of the two power plants can operate in two modes: The first one is called preselected load, in which the power delivered by the unit remains unchanged due to variations in system frequency.

The second mode is called droop, and in this case the electrical power delivered by the unit varies with frequency variations of the system. If the system frequency increases, the electric power generated decreases and vice versa. Therefore operate in "droop" implies to contribute to the primary frequency regulation.

The droop or statism represents the percentage of change of the speed or frequency with regard to the percentage of change in power output. For example, a statism of 5% means that a 5% change in frequency causes a 100% change in power output. The adjusted value of the motor generators statism of the plant 1 is 3% and in the plant 2 is 5%.

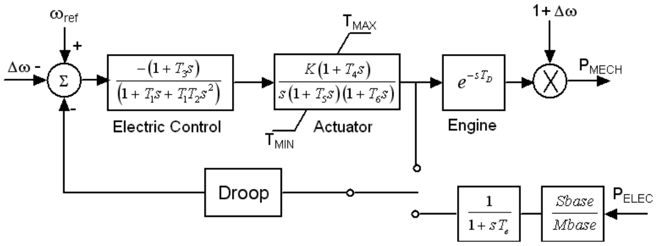


Fig. 14: DEGOV1 model of the governor

TABLE V: DEGOV1 MODEL PARAMETERS.

Parameter	Plant 1	Plant 2
T1	0.03 s	0.03 s
T2	0.01 s	0.01 s
T3	1.60 s	1.60 s
K	3.31	3.31
T4	0.14 s	0.14 s
T5	0.28 s	0.28 s
T6	0.6 s	0.6 s
Droop	0.03	0.05
TD	0.03 s	0.03 s
Tmax	1.1	1.1
Tmin	0.0	0.0

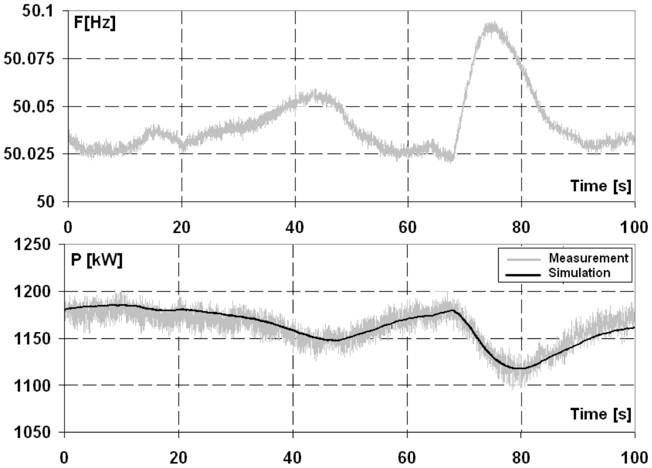


Fig. 15: Plant 1. Measured frequency and measured and simulated power.

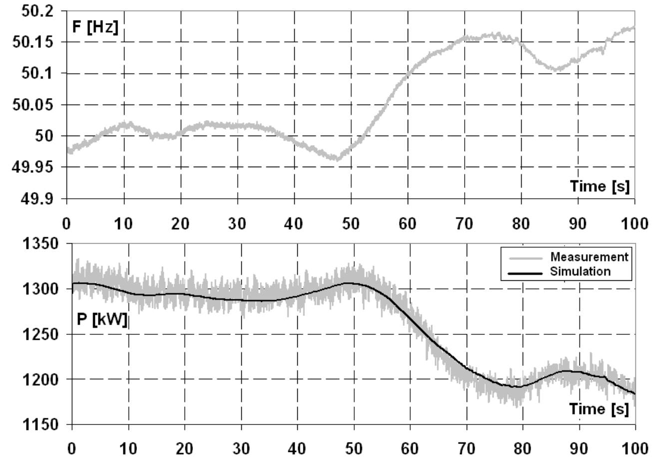


Fig. 16: Plant 2. Measured frequency and measured and simulated power.

For both plants, the tests consisted of recording the power due to changes in system frequency. In the corresponding simulation, the measured frequency record is entered in the model.

The tests records and simulations for the respective motor-generators power plants, both in the droop mode are presented in Fig. 15 and Fig. 16.

VI. CONCLUSIONS

From the tests performed and subsequent simulations it is showed that the motor-generators of both plants have similar performance parameters for excitation control systems and power-speed control, even so if they are from different manufacturers and use different fuel types.

The proposed models for the generator, the power-speed control system (governor) and the voltage control system (voltage regulator) of the motor-generators have a very good agreement with the results of field tests and have been included in the CAMMESA (Compañia Administradora del Mercado Mayorista Eléctrico Sociedad Anónima) database for use in studies of the Argentinean power system.

VII. REFERENCES

[1] PSS/E User Manual. Program Application Guide: Volume II. Power Technologies, Inc.

[2] IEEE Std. 421.5-1992. IEEE Recommended Practice for Excitation System Models for Power System Stability Studies.

VIII. BIOGRAPHIES

Jorge Luis Agüero: was born in Mar del Plata, Argentina, on January 31, 1953. Engineer degree from Engineering School of La Plata National University, Buenos Aires, Argentina, in 1976. Electrical and Electronic Engineering Department Professor at La Plata University since 1983. Elected Vice-Dean at Engineering Faculty for 1997-1998, re-elected for 1998-2001.

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