Voltage Depending Load Models. Validation by Voltage Step Tests

J. L. Agüero *IEEE Senior Member* (*), M. B. Barbieri *IEEE Senior Member* (*) and M. C. Beroqui (*)

***Abstract*— This paper presents applications of the Exponential Static Load model used to represent voltage depending loads. This model has been used to represent loads of different types: Industrial, Residential and of Petroleum Extraction Fields.**

These loads belong to "Sistema Interconectado Patagónico" (SIP), a small power system of 1200 MW of peak load situated in the South of Argentina.

Models of several load types have been validated by tests.

Tests were made by applying steps to the feeding load voltage.

Load voltage sensitivity coefficients were obtained for the different load types tested.

Load models validated by tests were used for SIP modal analyses.

***Index Terms*-- Load – Load Model - Power system dynamic stability – Simulation - Testing.**

I. Introduction

SEVERAL tests were made at medium voltage feedings of different loads. These tests were made to validate the modeling of different loads used for representation of voltage sensitive loads. Tested and modeled loads belong to SIP, a small power system of 1200 MW of peak load, situated in the south of Argentinean continental territory.

Different load types were tested: Industrial, Residential, of Petroleum Extraction Fields and several combinations of them.

Tests were carried out applying tap changes to the voltage feeding transformers. Test records were used to validate load model simulating load behavior with Simulink-MatLab.

Load models validated by tests were used to carry out small signal analyses to obtain SIP modal behavior as part of studies of power system dynamic stability carried out over the power system.

II. Static Load Model

A general form, named Polynomial Load Model, is normally used to represent Active (P) and Reactive (Q) powers of voltage dependent static loads, **[1]-[4]**.

Equations for this load representation are:

$$P=P_0\left(p_1\left(\frac{U}{U_0}\right)^{n_{P1}}+p_2\left(\frac{U}{U_0}\right)^{n_{P2}}+p_3\left(\frac{U}{U_0}\right)^{n_{P3}}\right) \quad \textbf{(1)}$$

$$Q=Q_0\left(q_1\left(\frac{U}{U_0}\right)^{n_{Q1}}+q_2\left(\frac{U}{U_0}\right)^{n_{Q2}}+q_3\left(\frac{U}{U_0}\right)^{n_{Q3}}\right) \quad \textbf{(2)}$$

Where:

- P_0/Q_0: Nominal Active/Reactive power at nominal voltage U_0.
- p_1/q_1, p_2/q_2 and p_3/q_3: Distribution coefficients for Active/Reactive power, with $(p_1/q_1)+(p_2/q_2)+(p_3/q_3) = 1$
- n_{P1}/n_{Q1}, n_{P2}/n_{Q2} and n_{P3}/n_{Q3}: exponents for Active/Reactive power, where $n_{P1}/n_{P2}/n_{P3}/$ and $n_{Q1}/n_{Q2}/n_{Q3}$ are real numbers.

Usually, exponents for **(1)-(2)** are set to:

- $n_{P1}/n_{Q1} = 0$ to represent constant power loads.
- $n_{P2}/n_{Q2} = 1$ to represent constant current loads.
- $n_{P3}/n_{Q3} = 2$ to represent constant impedance loads.

For small voltage variations, Polynomial Load Model, **(1)-(2)**, could be replaced by Exponential Load Model described by the following equations:

$$P=P_0\left(\frac{U}{U_0}\right)^{n_P} \quad \textbf{(3)}$$

$$Q=Q_0\left(\frac{U}{U_0}\right)^{n_Q} \quad \textbf{(4)}$$

Where:

- P_0/Q_0: Nominal Active/Reactive power at nominal voltage U_0.
- n_P/n_Q: Active/Reactive power exponents, where n_P/n_Q are real numbers.

III. Tests and Simulations

A. Tests

Tests were carried out at several load feedings in the SIP over different load types: Industrial, Residential, of Petroleum Extraction Fields and several combinations of them.

Tests were conducted by applying steps to feeding load voltage. Voltage steps were generated by means of transformer tap changes.

For feeding points with two parallel transformers, one-tap changes for each transformer were applied sequentially.

Records of Active power (P), Reactive power (Q), Frequency Deviation (dF) and Feeding Voltage (U) were taken during tests.

B. Simulations

Test records were used to simulate load behavior with Simulink-MatLab, using the model shown in **Fig. 1**, where gray blocks are test records. The model used for simulations has load representation given by **(3)-(4)**. P/Q were simulated with the blocks "P/Q Model" respectively. Outputs P_s/Q_s are the simulated Active/Reactive power respectively.

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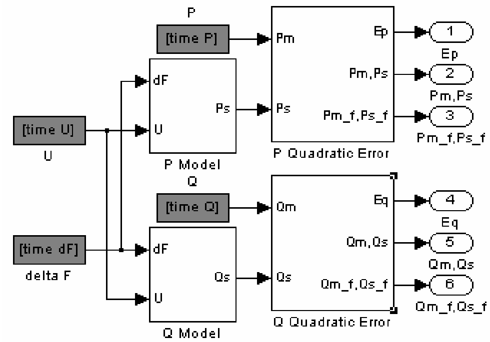

Fig. 1. Load Model for simulation.

Measured and simulated Active and Reactive powers are inputs of the blocks: P and Q Quadratic Error. These blocks calculate Quadratic Errors between measured and simulated quantities. Quadratic Errors, E_p and E_q for P and Q respectively, are given by:

$$E_p = \frac{\int (P_m - P_s)^2\, dt}{\int P_m^2\, dt} \quad \textbf{(5)}$$

$$E_q = \frac{\int (Q_m - Q_s)^2\, dt}{\int Q_m^2\, dt} \quad \textbf{(6)}$$

Calculating E_p and E_q is the selected way to verify P_s and Q_s congruencies with P_m and Q_m. Simulations results were taken as valid when $E_p \leq 5\%$ and $E_q \leq 5\%$. Also, P and Q Quadratic Error blocks of **Fig. 1** smoothed measured and simulated P and Q, by passing these quantities through a first order filter of 5 seconds of time constant to obtain the following variables: Filtered Active power, measured and simulated (P_{m_f} and P_{s_f} respectively) and Filtered Reactive power, measured and simulated (Q_{m_f} and Q_{s_f} respectively). Then, small load variations due to intrinsic load characteristics that are not depending on feeding voltage variations were filtered.

C. Results

Table I summarizes results of tests and simulations carried out for a representative subset of typical loads tested.

Table I. Test and Simulation results**.**

Type	Power Factor	P_0 (MW)	n_P	E_P (%)	Q_0 (MVAr)	n_Q	E_Q (%)	Fig.
P_1	0.936	7.04	0.4	4.3	2.64	3.6	2.8	2
P_2	0.966	3.68	0.0	5.0	0.98	3.4	3.1	3
R	0.915	2.95	1.1	0.9	1.30	4.5	1.7	4
I	0.891	3.816	0.1	1.5	1.94	2.0	0.8	5
P_1=0.6/**R**=0.4	0.964	11.28	0.8	1.2	3.12	6.0	0.9	6
P_1=0.9/**R**=0.1	0.997	25.36	0.4	1.7	2.10	15	4.7	7
P_1=0.9/**R**=0.1	0.874	25.36	0.4	1.7	14.10	4.0	0.8	8

Where load Type is:

- P_1: of Petroleum Extraction Fields using Rod Pumps.
- P_2: of Petroleum Extraction Fields using Submersible Electrical Pumps.
- R: Residential
- I: Industrial (Petrochemical).

Fig. 2 to **Fig. 11** show records of some made tests and their simulations. Variables in gray and black traces were obtained from test records and from simulations respectively.

Fig. 2.a to **Fig. 2.c** show test records and simulations for a test made at 132/33/13.2 kV feeding transformer of a "P_1" load type. P and Q were recorded at 132 kV side, meanwhile U was recorded at 132 kV and 33 kV. Simulation was made by taking into account Q absorbed by transformer (Q_T) by means of:

$$Q_T = \frac{P_m^2 + Q_m^2}{U_{Im}^2} * X_T * \frac{U_{Im}^2}{S_n} \qquad [VAr] \quad \textbf{(7)}$$

Where:

- P_m/Q_m [W/VAr]: Recorded Active/Reactive power at 132 kV
- U_{Im}[V]: Recorded Voltage at 132 kV
- X_T [pu]: Transformer longitudinal reactance between 132 kV and 33 kV
- S_n [VA]: Nominal transformer VA at 132 kV side

For this test, simulation yields $E_P \leq 4.3$ % and $E_Q \leq 2.8$ % for $n_P = 0.4$ and $n_Q = 3.6$, at 33 kV transformer side.

Fig. 3.a to **Fig. 3.c** show test records and simulations for a test made at 132/33/13.2 kV feeding transformer of a "P_2" load type. P, Q, U and dF were recorded at 33 kV. Simulation shown in **Fig. 3.b** was made with nP = 0.05. It can be seen that P does not have dependence on U. For this test, simulation yields $E_P \leq 5.0$ % and $E_Q \leq 3.1$ % for $n_P = 0.0$ and $n_Q = 3.4$.

Fig. 4.a to **Fig. 4.c** show test records and simulations for a test made at 132/33/13.2 kV feeding transformer of "R" load type. P, Q, U and dF were recorded at 13.2 kV. For this test, simulation yields $E_P \leq 0.9$ % and $E_Q \leq 1.7$ % for $n_P = 1.1$ and $n_Q = 4.5$.

Fig. 5.a to **Fig. 5.e** show test records and simulations for a test made at 132/33 kV feeding transformer of an "I" (Petrochemical) load type. P, Q, U and dF were recorded at 33 kV.

Fig. 5.a and **Fig. 5.b** show P, Q, U and dF complete test records. This industrial plant has a cyclic working time as it can be seen in **Fig. 5.b**.

Simulation was made during a stable part of working time, without sudden P variation.

Fig. 5.c and **Fig. 5.e** show P, Q, U and dF partial test records and corresponding simulations. For this test part, simulation yields $E_P \leq 1.5$ % and $E_Q \leq 0.8$ % for $n_P = 0.1$ and $n_Q = 2.0$.

Fig. 6.a to **Fig. 6.c** show test records and simulations for a test made at 132/13.2 kV feeding autotransformer of a combination of 60 % "P_1" and 40 % of "R" load types. P, Q, U and dF were recorded at 13.2 kV. For this test, simulation yields $E_P \leq 1.2$ % and $E_Q \leq 0.9$ % for $n_P = 0.8$ and $n_Q = 6.0$.

Fig. 7.a to **Fig. 7.c** show test records and simulations for a test made at 132/35/10.4 kV feeding transformer of a combination of 90% of "P_1" and 10 % of "R" load types. P, Q, U and dF were recorded at 35 kV. For this test, simulation yields $E_p \leq 1.7$ % and $E_q \leq 4.7$ % for $n_P = 0.4$ and $n_Q = 15$.

Fig. 8. shows corrected test records and a new simulation for Q of the previous test, by discounting the shunt capacitor - of 3x4 MVAr at 35 kV bus - effects over Reactive power.

Capacitor was simulated like a load given by **(4)** with $n_Q = 2$. For this Q corrected test, simulation yields $E_Q \leq 0.8$ % for $n_Q = 4.0$.

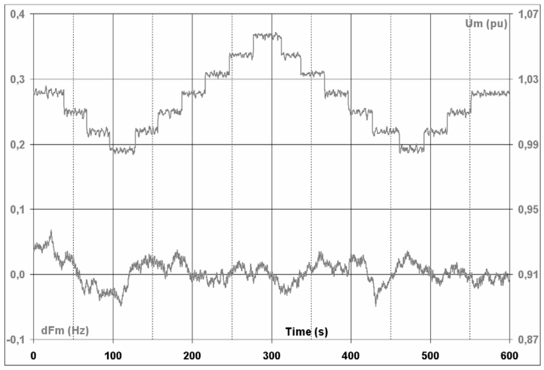

Fig. 2.a. ***P_1 load***. Measured feeding Voltage (U_m, upper gray trace, right scale) and measured Frequency deviation (dF_m, lower gray trace, left scale).

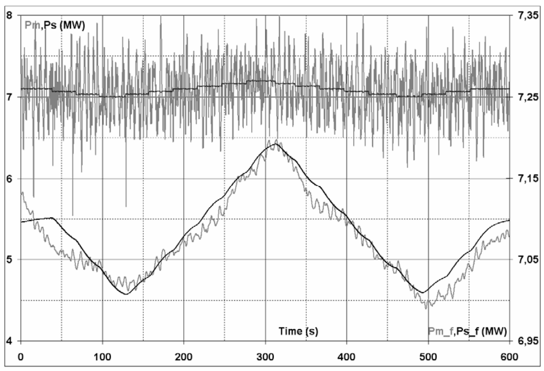

Fig. 2.b. ***P_1 load***. Measured/Simulated Active power without filtering (P_m/P_s, upper gray/black traces, left scale) and with filtering (P_{m_f}/P_{s_f}, lower gray/black traces, right scale).

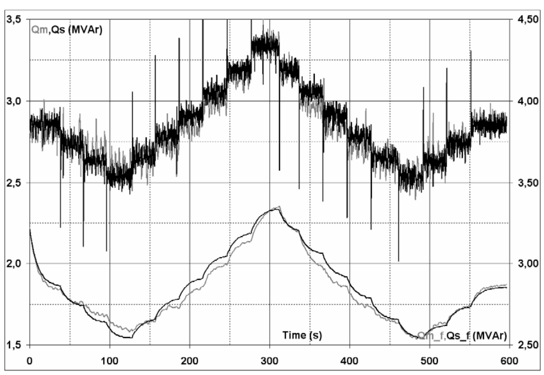

Fig. 2.c. ***P_1***. Measured/Simulated Reactive power without filtering (Q_m/Q_s, upper gray/black traces, left scale) and with filtering (Q_{m_f}/Q_{s_f}, lower gray/black traces, right scale).

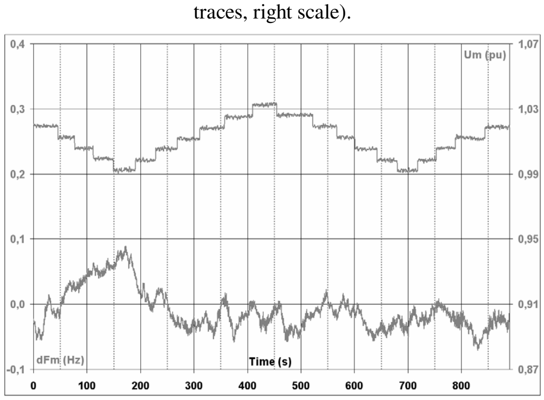

Fig. 3.a. ***P_2 load***. Measured feeding Voltage (U_m, upper gray trace, right scale) and measured Frequency deviation (dF_m, lower gray trace, left scale).

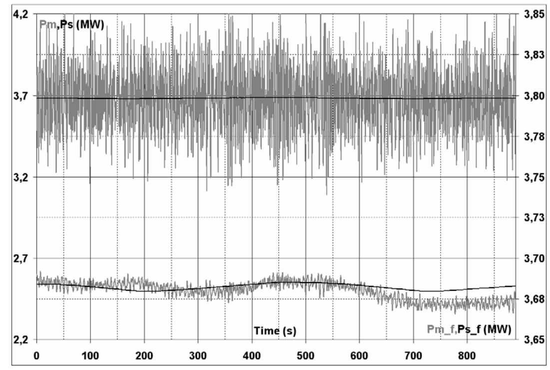

Fig. 3.b. ***P_2 load***. Measured/Simulated Active power without filtering (P_m/P_s, upper gray/black traces, left scale) and with filtering (P_{m_f}/P_{s_f}, lower gray/black traces, right scale).

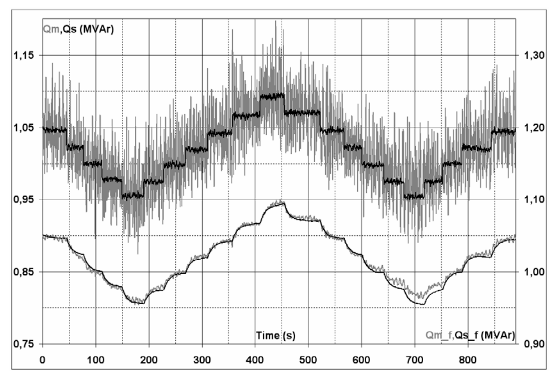

Fig. 3.c. ***P_2 load***. Measured/Simulated Reactive power without filtering (Q_m/Q_s, upper gray/black traces, left scale) and with filtering (Q_{m_f}/Q_{s_f}, lower gray/black traces, right scale).

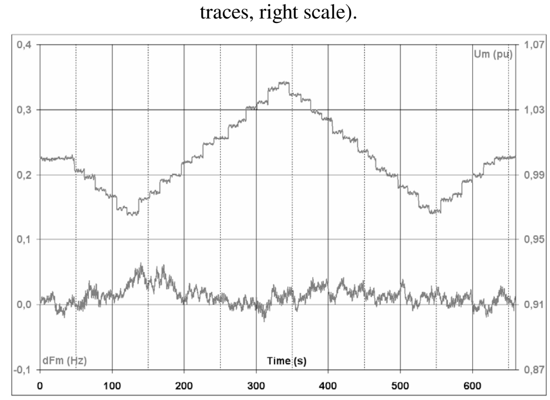

Fig. 4.a. ***R load***. Measured feeding Voltage (U_m, upper gray trace, right scale) and measured Frequency deviation (dF_m, lower gray trace, left scale).

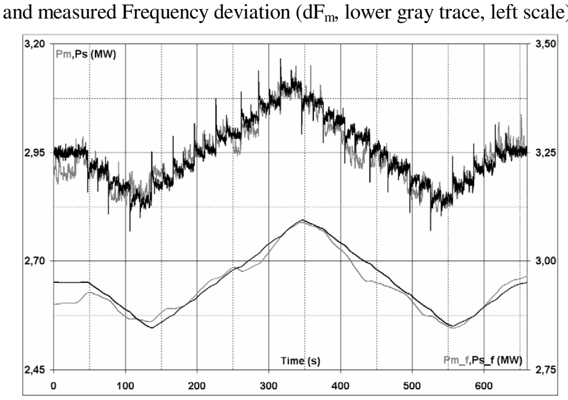

Fig. 4.b. ***R load***. Measured/Simulated Active power without filtering (P_m/P_s, upper gray/black traces, left scale) and with filtering (P_{m_f}/P_{s_f}, lower gray/black traces, right scale).

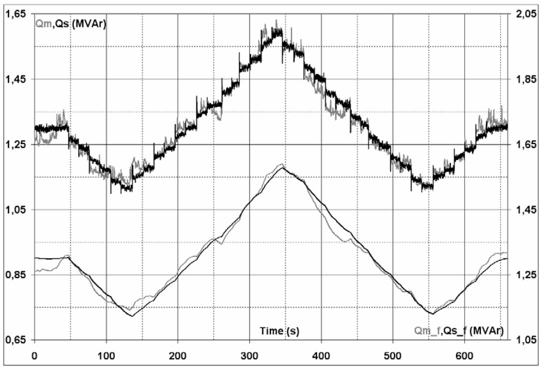

Fig. 4.c. ***R load***. Measured/Simulated Reactive power without filtering (Q_m/Q_s, upper gray/black traces, left scale) and with filtering (Q_{m_f}/Q_{s_f}, lower gray/black traces, right scale).

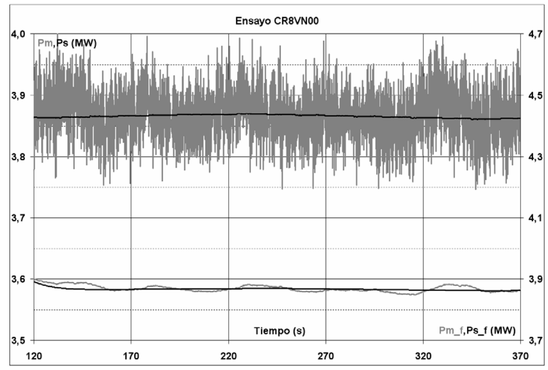

Fig. 5.d. ***I load***. Measured/Simulated Active power without filtering (P_m/P_s, upper gray/black traces, left scale) and with filtering (P_{m_f}/P_{s_f}, lower gray/black traces, right scale). Partial test records.

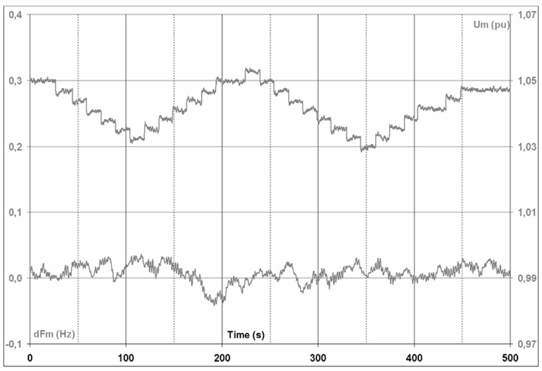

Fig. 5.a. ***I load***. Measured feeding Voltage (U_m, upper gray trace, right scale) and measured Frequency deviation (dF_m, lower gray trace, left scale). Complete test records.

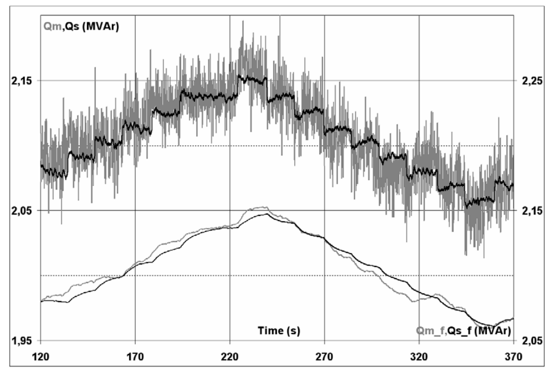

Fig. 5.e. ***I load***. Measured/Simulated Reactive power without filtering (Q_m/Q_s, upper gray/black traces, left scale) and with filtering (Q_{m_f}/Q_{s_f}, lower gray/black traces, right scale). Partial test records.

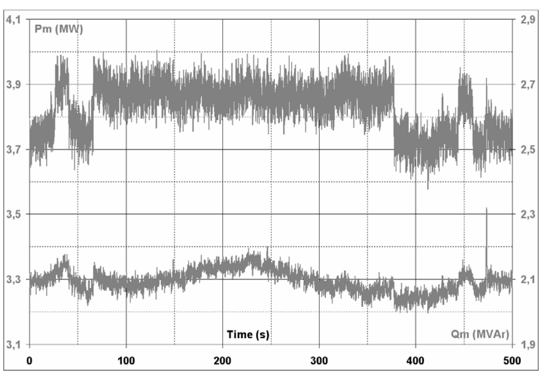

Fig. 5.b. ***I load type***. Measured Active power without filtering (P_m, upper gray trace, left scale) and Measured Reactive power without filtering (Q_m, lower gray trace, right scale). Complete test records.

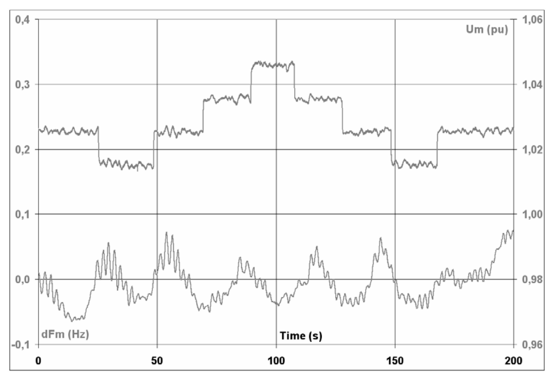

Fig. 6.a. ***$P_1 = 60$ % and R = 40 % load***. Measured feeding Voltage (U_m, upper gray trace, right scale) and measured Frequency deviation (dF_m, lower gray trace, left scale).

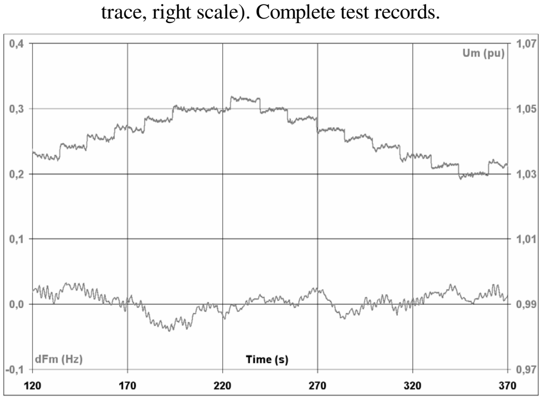

Fig. 5.c. ***I load***. Measured feeding Voltage (U_m, upper gray trace, right scale) and measured Frequency deviation (dF_m, lower gray trace, left scale). Partial test records.

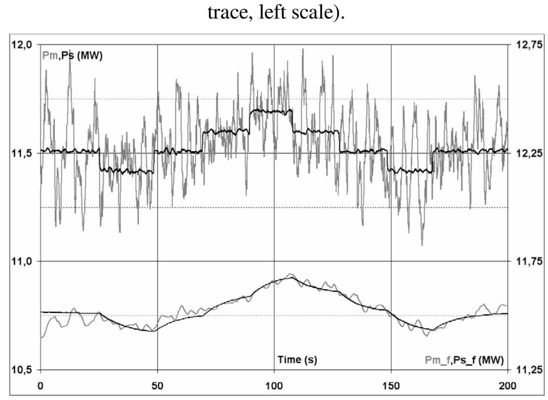

Fig. 6.b. ***$P_1 = 60$ % and R = 40 %*** load. Measured/Simulated Active power without filtering (P_m/P_s, upper gray/black traces, left scale) and with filtering (P_{m_f}/P_{s_f}, lower gray/black traces, right scale).

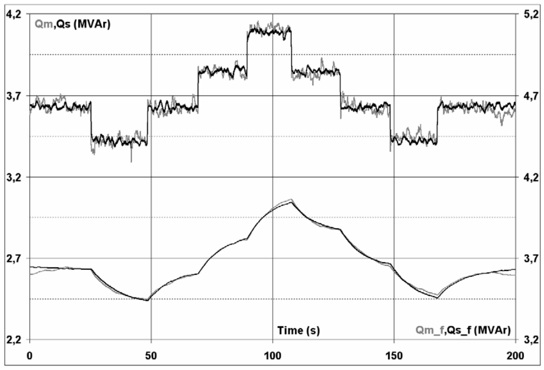

Fig. 6.c. ***P_1 = 60 % and R = 40 % load***. Measured/Simulated Reactive power without filtering (Q_m/Q_s, upper gray/black traces, left scale) and with filtering (Q_{m_f}/Q_{s_f}, lower gray/black traces, right scale).

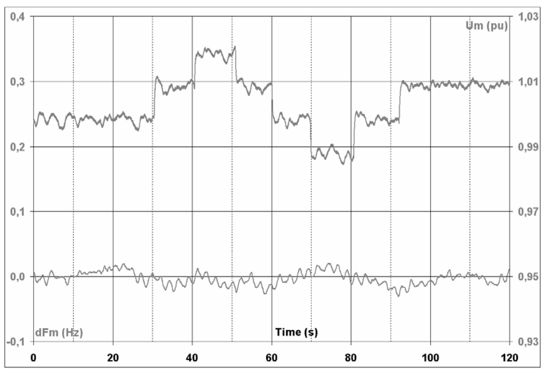

Fig. 7.a. ***P_1 = 90 % and R = 10 % load***. Measured feeding Voltage (U_m, upper gray trace, right scale) and measured Frequency deviation (dF_m, lower gray trace, left scale).

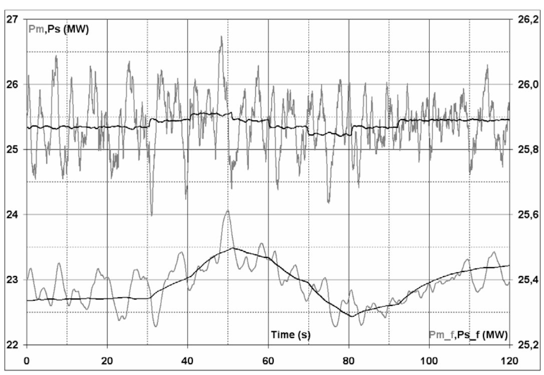

Fig. 7.b. ***P_1 = 90 % and R = 10 % load***. Measured/Simulated Active power without filtering (P_m/P_s, upper gray/black traces, left scale) and with filtering (P_{m_f}/P_{s_f}, lower gray/black traces, right scale).

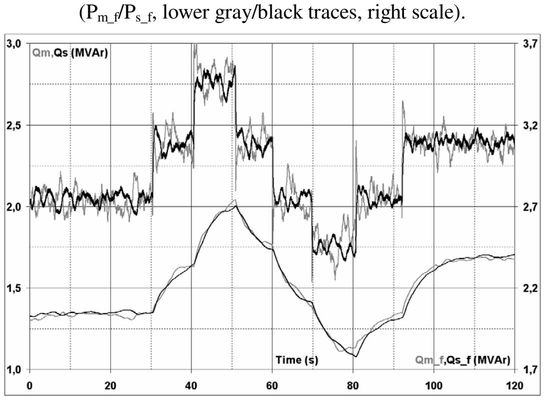

Fig. 7.c. ***P_1 = 90 % and R = 10 % load***. Measured/Simulated Reactive power without filtering (Q_m/Q_s, upper gray/black traces, left scale) and with filtering (Q_{m_f}/Q_{s_f}, lower gray/black traces, right scale).

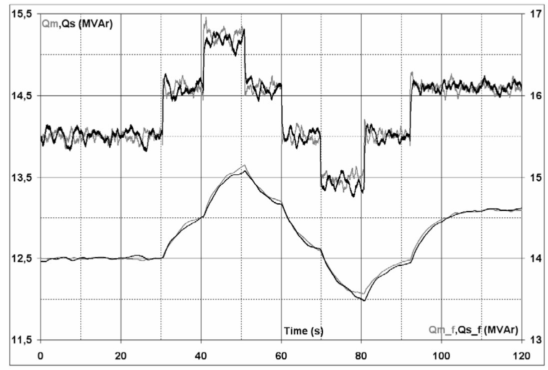

Fig. 8. ***P_1 = 90 % and R = 10 % load***, discounting 3x4 MVAr shunt capacitor effects. Measured/Simulated Reactive power without filtering (Q_m/Q_s, upper gray/black traces, left scale) and with filtering (Q_{m_f}/Q_{s_f}, lower gray/black traces, right scale).

D. Analysis

From all tests and simulations carried out, the following mean values for n_P were obtained on each load type:

- "P_1": $n_P \approx 0.4$
- "P_2": $n_P \approx 0.0$
- "R": $n_P \approx 1.1$
- "I": $n_P \approx 0.1$

On the other hand, n_Q factor strongly depends on load power factor compensation.

For the same load type, the higher power factor, the higher n_Q factor was obtained from tests.

Last example shown in **Fig. 8** yields an $n_Q = 4.0$ for power factor = 0.874, meanwhile an $n_Q = 15$ was obtained for power factor = 0.997 in the same example shown in **Fig. 7**.

In Argentina, it is a common practice to represent load Active power using **(1)** with the following parameters:

- $p_1 = 0$, $p_2 = 0.8$ and $p_3 = 0.2$
- $n_{P1} = 0$, $n_{P2} = 1$ and $n_{P3} = 2$

It means that Active power is represented by 80 % of Constant Current and by 20 % of Constant Impedance.

By using **(3)**, this load combination yields an equivalent $n_P = 1.2$ for small voltage variation.

This n_P factor value is similar to those obtained from tests for "R" type loads and it only represents loads of this kind.

Instead, in order to represent "P_1", "P_2" or "I" type loads, an n_P factor close to 0 must be used.

These load types normally have associated electronic control devices and have quasi-constant Active power.

In the same way, it is a common practice to represent load Reactive power using **(2)** with the following parameters:

- $q_1 = 0$, $q_2 = 0.5$ and $q_3 = 0.5$
- $n_{Q1} = 0$, $n_{Q2} = 1$ and $n_{Q3} = 2$

It means that Reactive power is represented by 50 % of Constant Current and by 50 % of Constant Impedance.

By using **(4)**, this load combination yields an equivalent $n_Q = 1.5$ for small voltage variation.

This low value used for n_Q supposes a very low power factor taking into account the n_Q values obtained from tests and displayed in **Table I**.

Then, the n_Q factor used to represent load Reactive power must be correlated with the load power factor. The higher power factor, the higher n_Q must be set.

IV. Conclusions

Models described in the technical literature and used to represent static loads were briefly presented.

Also, results of several tests made at feeding load transformers were reported and analyzed.

A procedure for model parameter validation was presented. This procedure uses the classical quadratic error technique.

Parameters for different load types were obtained by test simulation with the proposed model.

The following conclusions can be pointed out from test records and simulation presented:

- The used model reproduces test records in a good agreement for all load types tested.
- Active power exponents (n_P) obtained from tests for all load types are in agreement with those reported in technical papers.
- Reactive power exponents (n_Q) obtained from tests for all load types strongly depend on load power factor compensation.

In short, the static model described in the technical literature was validated by tests made at several feeding load transformers and for different load types.

The model and its corresponding parameters for each load type obtained from test simulations were incorporated to the Data Base for dynamic studies and were used to conduct modal analyses.

V. Acknowledgements

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They are also grateful to Mr. Roberto Molina from CAMMESA for his fruitful comments about model and test results.

VI. References

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VII. Biographies

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Elected Vice-Dean at Engineering School for 1997-1998 and re-elected for 1998-2001 terms.

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