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WEC'S UNSTEADY POWER OUTPUT SIMULATION

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A numerical method for the simulation of horizontal axis wind turbines (HAWT) was developed. Time-variable wind velocity, and induction generators in steady and transient states, connected to the utility grid (SEE) were considered.

1 - INTRODUCTION

Two main components, the turbine itself (wind rotor), and the induction generator were assumed. A method for the evaluation of the rotor's characteristic equation based on Glauert's Theory was developed. This equation was used in the wind turbine model to simulate the rotor's response to the variable wind. The saturation model of the induction generator's used, was based on the Von der Embse Theory.

The aim was to assess the working characteristics of a wind energy converter under different wind conditions and for induction generator steady and transient states, with limit conditions of the short-circuit power in the connection point, so these were the simulated situations.

To validate this model, some experimental data was collected from a *AEROMAN 12/20* HAWT connected to the utility grid and settled in *"LNETI's Wind Power Pilot Facility"*.

2 - WEC'S MODEL

2.1 - Analytical Model

The model was developed to a HAWT in CSCF working mode (which rotational speed, is actually not constant, but variable in the stable ranges of the wind rotor and the electric generator), equipped with an induction generator connected to the utility grid through a transmission line, with a local reactive source [3]. This model takes into account the variable wind speed and the short circuit power in the grid.

The wind turbine's analysis is based on the Glauert's Theory for propellers, also considering the influence of variable rotational speed [9] and the induction generator's model is based on the Von der Embse's Circuit Theory and was proposed by Ferreira de Jesus [6].

Wind Rotor's Model

The typical wind rotor's models based on the Glauert's Theory, as the *PROPSHAFT* code proposed by Hibbs and Radkey [7] that compute the interference velocity factors in a blade previously divided into sectors, are neither well suited to simulate the performance of a wind turbine under variable wind speed, nor to "connect" to an electric generator's saturation dynamic models. An alternative method to perform dynamic's simulation of wind rotors was then developed, after the blade aerodynamic characteristics and taking into account the effects of variable rotational speed, that enable to estimate the mechanical torque produced by a WEC. This method consists in determining a wind rotor's torque characteristic equation, $Q_m=f(\Omega, V_0)$ in the form:

$$Q_m(\Omega, V_0) = A(V_0)\,\Omega + B(V_0)$$

equated, taking separately the functions $Q_m(\Omega)$ and $Q_m(V_0)$, where Q_m is the mechanical torque, Ω is the rotational speed and A and B are parameters which depend on the wind speed, V_0, and for the *AEROMAN 12/20*, assume the values:

$$A(V_0)=117.9V_0^{0.772}-328.6V_0^{0.463}+274.4$$

$$B(V_0)=-595.2V_0^{1.46}+4013.1V_0^{0.79}-6794.3$$

represented in Figure 1.

Induction Generator and Electrical Equipment Models

The model adopted to simulate the induction generator was developed by Ferreira de Jesus [6] and includes the effects of the magnetic circuit saturation. The basis of this model is the Von der Embse Circuit Theory [2] and the hypothesis of a unique magnetic characteristic, without hysteresis.

The model enables to simulate the performance of a WEC connected to the utility grid through a transmission line with local reactive source, as represented in Figure 2.

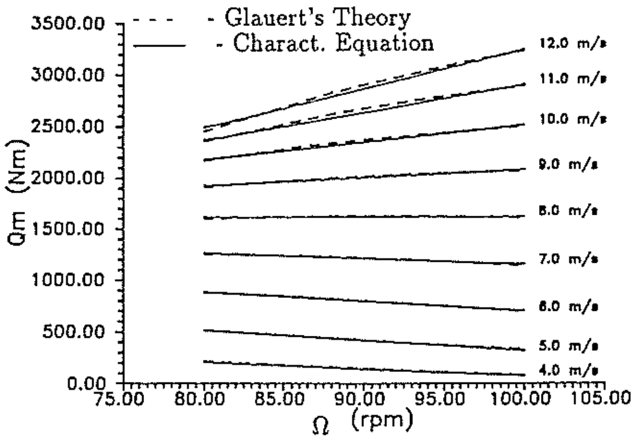

Fig. 1 - Torque vs rotational speed
for variable wind speed

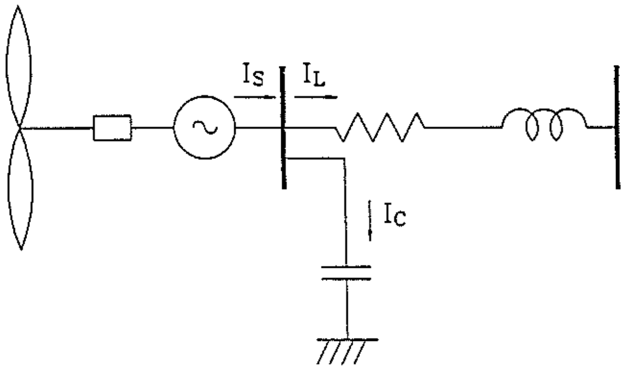

Fig. 2 - WEC's connection to the utility grid.

The equations that describe the induction generator's performance in (d,q,o) coordinates in a referential sincronous with the electromagnetic's torque angular velocity ω, are, to the stator:

$$v_{ds} = - r_s i_{ds} + \omega l_{qs} i_{qs} - \omega \Psi_{qs} - l_{ds} \frac{\partial i_{ds}}{\partial t} + \frac{\partial \Psi_{ds}}{\partial t}$$
$$v_{qs} = - r_s i_{qs} - \omega l_{ds} i_{ds} + \omega \Psi_{ds} - l_{qs} \frac{\partial i_{qs}}{\partial t} + \frac{\partial \Psi_{qs}}{\partial t}$$

and, to the rotor:

$$0 = r'_r i'_{dr} - (\omega - \omega_r)\lambda'_{qr} \quad + \frac{\partial \lambda'_{dr}}{\partial t}$$
$$0 = r'_r i'_{qr} + (\omega - \omega_r)\lambda'_{dr} \quad + \frac{\partial \lambda'_{qr}}{\partial t}$$

where, v and i are respectively the current intensity and the voltage, r represents the coil resistance and l the induction coefficient, Ψ is the magnetisation flux and λ the rotor's total flux. The subscripts d e q refer to the direct and quadrature components and the subscripts s e r correspond to rotor and stator variables.

The equations above enable to achieve the induction's generator state equations. The state equations for the capacitors in the same reference frame, are:

$$\frac{\partial v_{ds}}{\partial t} = \frac{1}{C}(i_{ds} - i_{dL} + \omega C v_{qs})$$
$$\frac{\partial v_{qs}}{\partial t} = \frac{1}{C}(i_{qs} - i_{qL} + \omega C v_{ds})$$

where i_{dL} e v_{qL} correspond to the direct and quadrature components of the line intensity current.

This model assumes that the line transmission can be adequately represented by a resistance and a reactance. In the same coordinate system and referential, one may obtain to the transmission line state equations:

$$\frac{\partial i_{dL}}{\partial t} = \frac{1}{L_L} (v_{ds} - v_{dR} - r_L i_{dL} - \omega L_L i_{qL})$$
$$\frac{\partial i_{qL}}{\partial t} = \frac{1}{L_L} (v_{qs} - v_{qR} + r_L i_{qL} - \omega L_L i_{dL})$$

where v_{dR} e v_{qR} represent the voltage components and, r_L e L_L, represent respectively the equivalent resistance and induction coefficient of the transmission line. Another variable that needs to be defined is the slip:

$$s = \frac{\omega_s - n_p \omega_r}{\omega_s}$$

where n_p represents the number of induction generator's pairs of poles, ω_r the shaft's rotational speed - referred to the induction generator rotational speed and ω_s the sincronous speed.

Shaft's equation

The wind rotor's shaft and the induction shaft are connected by a gear box, which is considered as ideal. The dynamic shaft's equation was taken as:

$$J\frac{\partial^2 \theta}{\partial t^2} = Q_m - Q_{em}$$

where J is the inertia of the system, θ is the angle with respect to a reference, Q_m is already known and Q_{em} is the electromagnetic torque.

2.2 - Numerical Model

The characteristic equation found to this wind rotor was used in the numerical model to describe it. The numerical model of the induction generator used was based on Von der Embse Theory with the formal presentation proposed by Ramshaw and Xie [8] to the synchronous electric machines. The simulation of the electric equipment was developed by Castro [1]. The numerical model developed connects these two models, being all the variables referred to induction generator's rotational speed.

The steady state of the whole wind turbine under variable wind was considered as a sequence of induction generator's steady states. To perform this behaviour two time steps were considered, one mechanical and other electrical, Δt_m and Δt_e, respectively. In order to guarantee the validity of the model one has to assure that $\Delta t_m >> \Delta t_e$.

In the application of the model the inertia constant, is defined as:

$$H_i = \frac{\frac{1}{2} J (\frac{\omega_s}{n_p})^2}{S_b}$$

which is the ratio between the kinetic energy of the rotor and the base power, equated as:

$$S_b = \sqrt{3}\, U_N I_N$$

where U_N and I_N are respectively the nominals voltage and intensity current. The base torque is equated as:

$$T_b = \frac{S_b}{(\frac{\omega_s}{n_p})}$$

3 - WEC'S SIMULATION

The simulation range, corresponding to the constant attack angle to this WEC, goes from 3.5 m/s to approximately 14.0 m/s (the WEC begin in power control at 11-12 m/s).

The WEC's parameters simulated [3] are the following, to the wind rotor:

<u>Blades</u>: Two with variable chord and twist. The wind profiles are NACA 4415, 4418, 4421 and 4424.
<u>Rotor's diameter</u>: 12 meters. To evaluate the performance by the modified propshaft code the rotor was divided into 10 elements.

and to the induction generator and the electric equipment (the capacitors are always computed to compensate the reactive power in the linear range of the magnetic saturation circuit).

Nominal voltage $U_N = 380\ V$
Rotor's resistance, $R'_r = 0.140\ \Omega$
Nominal intensity current, $I_N = 35\ A$
Rotor's reactance, $X'_r = 1.2\ \Omega$
Number of pairs of poles, $n_p = 2$
Stator's resistance, $R_s = 0.223\ \Omega$
Base power, $S_b = 24{,}4\ KVA$
Stator's reactance, $X'_s = 1.2\ \Omega$
Base torque, $T_b = 156\ Nm$
Inertia constant, $H_i = 0.88\ s$

The resistance and the reactance of the transmission line, R_L e X_L, respectively, take the values, which correspond to the short-circuit ratios considered (r_{cc} - ratio between the short circuit power and the base power of the WEC, $r_{cc}=S_{cc}/S_N$):

$$r_{cc}=3 \Rightarrow R_L=0.172\ \Omega,\ X_L = 1.963\ \Omega;$$
$$r_{cc}=20 \Rightarrow R_L=0.0258\Omega,\ X_L=0.295\ \Omega;$$

The gear box transmission relation is 1:17.2.

The magnetic characteristic of the induction generator, equated was numerically simulated with the equation:

$$I_m = K_1\ E + K_m\ E^m$$

being I_m the magnetisation current, E the electromotrice force, and $K_1 = 0.3287$, $K_m = 0.0463$, $m=17$.

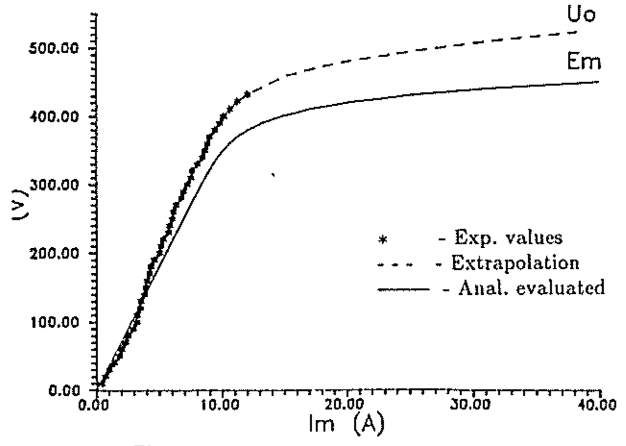

Fig. 3 - Electromagnetic Characteristic.

The torque's electromechanical characteristic of this induction machine was determined in the generator working mode, and his represented, as well as the experimental values in Figure 4.

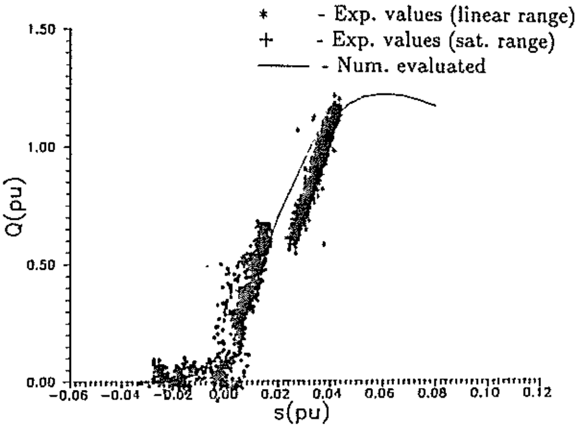

Fig. 4 - Electromechanical torque's characteristic of the induction generator.

The wind records simulated correspond to the situation of *medium* and *strong* wind, respectively with mean values of 7.8 m/s and 10.0 m/s, represented in Figure 5.

The situations presented correspond to an induction generator in steady state, with *medium* wind and low short circuit ratio, (r_{cc}=3) presented in Figure 6. Two transient simulation are also shown: connection to the utility grid under *strong* wind and low short-circuit (Fig. 7), and a three phase fault at the generator's busbar, (Fig. 8) under *medium* wind and high short circuit ratio, (r_{cc}=20).

The variables are all presented in *per unit values*.

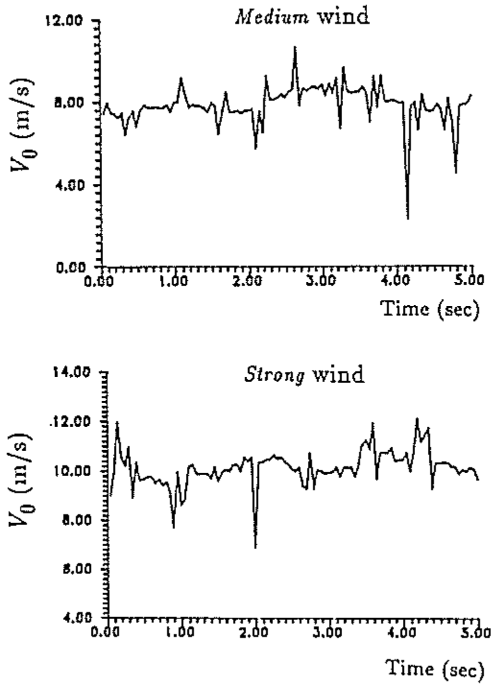

Fig. 5 - Wind time records.

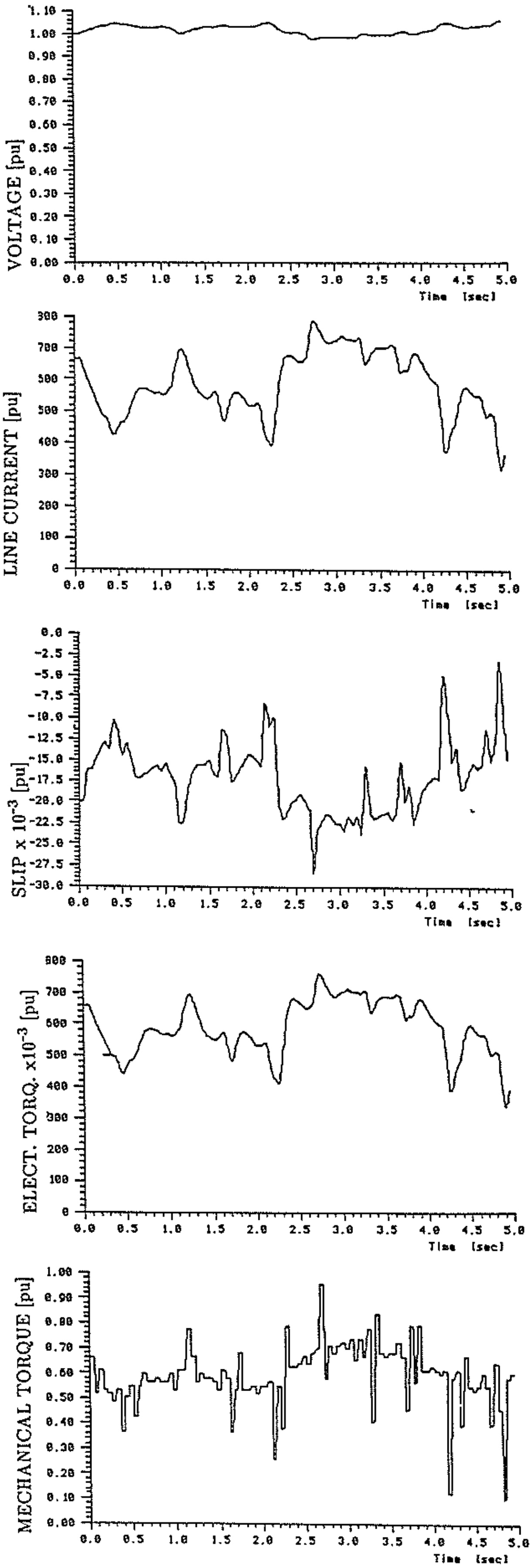

Fig. 6 - Steady state. *Medium wind*, r_{cc}=3. Voltage, line current, slip, electromagnetic and mechanical torque.

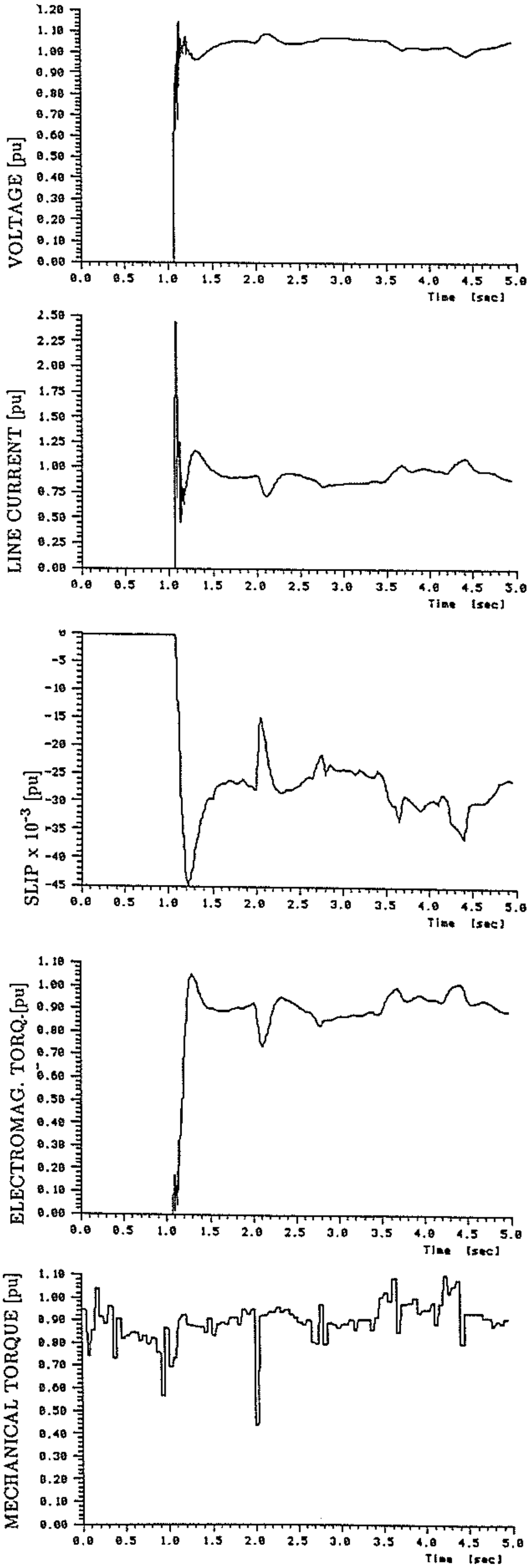

Fig. 7 - Utility grid connection. *Strong wind*, r_{cc}=3. Voltage, line current, slip, electromagnetic and mechanical torque.

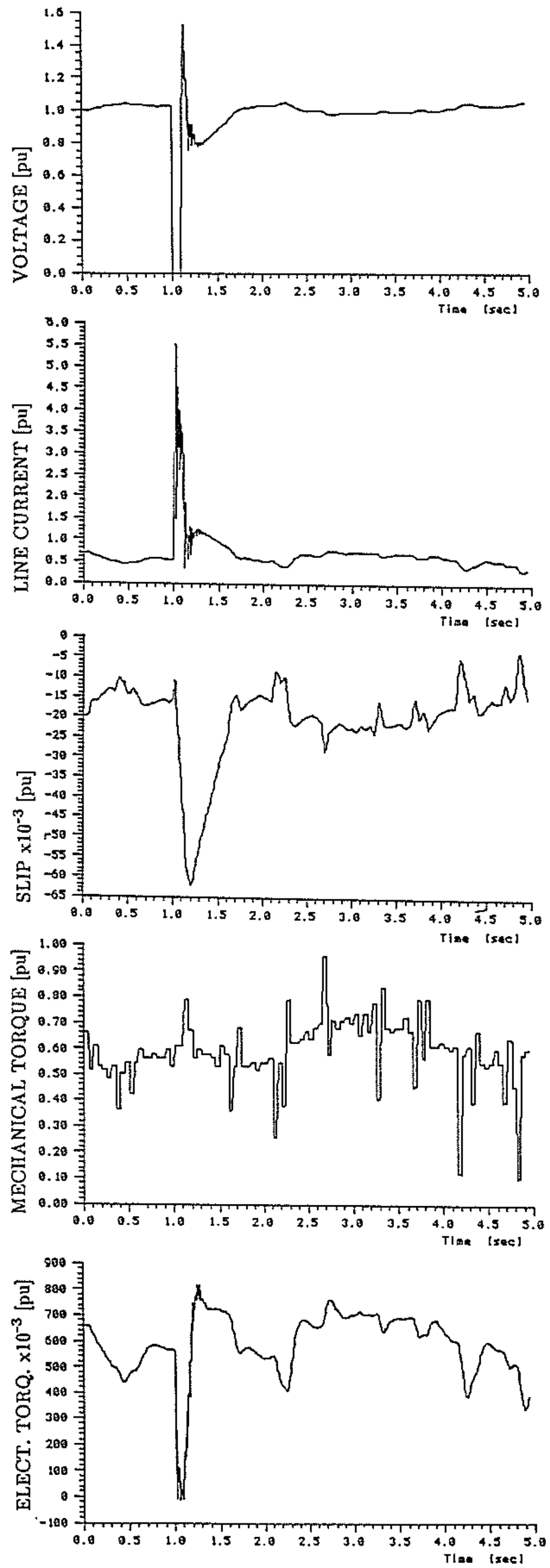

Fig. 8 - Three phase fault. *Medium wind*, r_{cc}=20. Voltage, line current, slip, mechanical and electromagnetic torque.

4 - CONCLUSIONS

The experimental work to confirm the results obtained with this model is being performed and points to a complete validation. Although, it is thought to be necessary to insert in the modelation a *transfer function* of the rotor and to develop methods that enable to know accurately the electric parameters of the induction generator in the saturation working range.

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