THE ANNALS OF “DUNAREA DE JOS” UNIVERSITY OF GALATI
FASCICLE III, VOL.34, NO.2, 2011, ISSN 1221-454X
ELECTROTECHNICS, ELECTRONICS, AUTOMATIC CONTROL, INFORMATICS

AN ANALYSIS OF DYNAMICS REGIMES OF PARALLEL GENERATORS OPERATION IN WIND TURBINE SYSTEMS

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Abstract: The parallel connection of different types of AC generators, used as example in isolated sites, represents a difficult problem due to the different particularities of the that generators involved. This paper analyses the specific dynamic processes that may occur with the development of such systems. Although some dynamic processes that not affect the magnetic and/ or electric symmetry of the system can be excellent modelled through (d,q) models, most of them cannot take into account such symmetry, reason to resort the models in phase coordinates, often implemented with professional Software (Psim). The dynamical particularities obtained by simulations revealed different dynamics in most of the regimes, prefigured by the different nature of the generators: asynchronous and synchronous. Further development using automatic control techniques will allow uniform integration of such systems with different dynamics.

Keywords: dynamical regimes, permanent magnet synchronous generator, induction generator, wind turbine systems, numerical simulation

1. INTRODUCTION

Continuous development of wind systems is claimed by the potential expansion of the consumers at isolated grids also by the progress of the technologies that created manifold equipments that are becoming much cheaper.

For three decades, the technical solution of generator used in the conversion of wind energy in electricity is the induction one (Burton *et al*, 2001). Therefore, nowadays the induction generator is the most popular generator used in renewable systems, at wind farms and also at isolated sites. However, the problem that cannot be overcome is related to the exclusion of gear box (Blaabjerg Chen, 2006), the device cannot be physically designed at these requirements. It has been observed that the presence of the mechanic reducer incur a multitudinous of disadvantages that significantly increase the maintenance costs and reducing the lifecycle of the turbine (Burton *et al*, 2001). For this purpose, the multi-polar generators with permanent magnet excitation have been developed.

The permanent magnet generators represent a great opportunity (Boldea, 2005) in the conversion systems of wind energy, because of the gearbox elimination, the insulated operation without additional excitation devices (as in the case of induction generator with short-circuit rotor). The wind energy systems development by connecting in parallel of different types of AC generators can be determined by the seasonal growth/ expansion of important loads and the extension of wind farms, where often removing the turbines equipped with asynchronous generators it is not justified due to the high amortization period of initial investment.

2. THE MATHEMATICAL MODELLING OF PARALLEL CONNECTED SYSTEM

We consider a structure system composed by parallel connection of different types of AC generators: induction and permanent magnet synchronous generator (Fig 1).

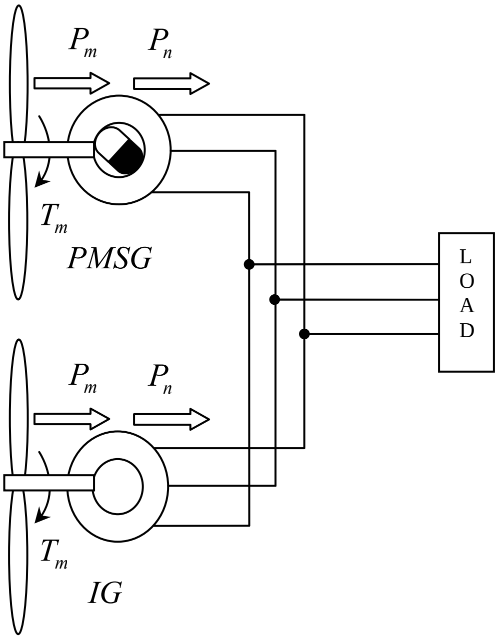

Fig.1. The structure of connected system

The system composed by generators which define the two successive generations of turbines.
The mathematical model of induction generator is defined by (Babescu and Paunescu, 2001) :

$$(1)\quad \begin{cases} \dfrac{d\varphi_s}{dt} = -R_s i_s - u_s \\ \dfrac{d\varphi_{rs}}{dt} = -R_r i_{rs} + jp\omega_m \varphi_{rs} \\ \varphi_s = L_{\sigma s} i_s + \varphi_u = L_s i_s + L_m i_{rs} \\ \varphi_{rs} = L_{\sigma r} i_{rs} + \varphi_u = L_r i_r + L_m i_s \\ \varphi_u = L_m (i_s + i_{rs}) = L_m i_{ms} \\ T_a - T_{em} = J \dfrac{d\omega_m}{dt} = \dfrac{J}{p} \cdot \dfrac{d^2\theta_{eg}}{dt^2} \end{cases}$$

The mathematical model for dynamical regmies of induction generator is described by (Babescu and Paunescu, 2001):

$$(2)\begin{cases} \dfrac{di_d}{dt} = -\dfrac{r}{L_d} \cdot i_d + \dfrac{L_q}{L_d} \cdot p \cdot \omega_m \cdot i_q - \dfrac{1}{L_d} \cdot u_d \\ \dfrac{di_q}{dt} = -\dfrac{r}{L_q} \cdot i_q - \dfrac{L_d}{L_q} \cdot p \cdot \omega_m \cdot i_d - \dfrac{\Psi_m \cdot p \cdot \omega_m}{L_q} - \dfrac{1}{L_q} \cdot u_q \\ T_{em} = \dfrac{3}{2} \cdot p \cdot \left[\Psi_m \cdot i_q + \left(L_d - L_q \right) \cdot i_d \cdot i_q \right] \\ T_a - T_{em} = J \dfrac{d\omega_m}{dt} = \dfrac{J}{p} \cdot \dfrac{d^2\theta_{eg}}{dt^2}\ , \end{cases}$$

3. THE ANALYSIS OF DYNAMICS REGIMES

Due to the facilities offered by mathematical models for dynamic systems simulation, respectively, dedicated software, the analysis of dynamic regimes can be done in two stages:

- The analysis of connection processes (simultaneous start of both generators) based on orthogonal models (d,q);
- Failure process analysis (single-phase, two-phase and three phase short circuit) based on numerical dedicated software, in this case choosing Psim *(**)*.

Although they have a very high accuracy, the inefficiency of orthogonal models is related to the impossibility of taking into account the unbalances due to the assumptions that consider the model is valid (electric and magnetic symmetry).

For (d,q) models simulations, we consider for both generators (induction and synchronous) that at the time $t = 0[s]$ is applied a torque step by $0.5[Nm]$, and the voltage is maintain at the rated value.

The mathematical model of asynchronous machine in (d,q) coordinates, acquire through components development the following form (Babescu and Paunescu, 2001):

$$(3)\quad \begin{cases} L_{1d} \dfrac{dX}{dt} + \sqrt{L_{1d} L_{2d}} \dfrac{dZ}{dt} = U_d - R_d X + \omega_1 L_{1q} Y + \omega_1 \sqrt{L_{1q} L_{2q}} U \\ L_{1q} \dfrac{dY}{dt} + \sqrt{L_{1q} L_{2q}} \dfrac{dU}{dt} = U_q - \omega_1 L_{1d} X - R_q Y - \omega_1 \sqrt{L_{1d} L_{2d}} Z \\ \sqrt{L_{1d} L_{2d}} \dfrac{dX}{dt} + L_{2d} \dfrac{dZ}{dt} = \sqrt{L_{1q} L_{2q}} (\omega_1 - \omega) Y - R_{2d} Z + L_{2q} (\omega_1 - \omega) U \\ \sqrt{L_{1q} L_{2q}} \dfrac{dY}{dt} + L_{2q} \dfrac{dU}{dt} = -\sqrt{L_{1d} L_{2d}} (\omega_1 - \omega) X - L_{2d} (\omega_1 - \omega) Z - R_{2q} U \end{cases}$$

where: $X = I_d(t)$; $Y = I_q(t)$; $Z = I_{dr}(t)$; $U = I_{qr}(t)$; $s = s(t)$

In consequence, can be achieved the dynamical characteristics:

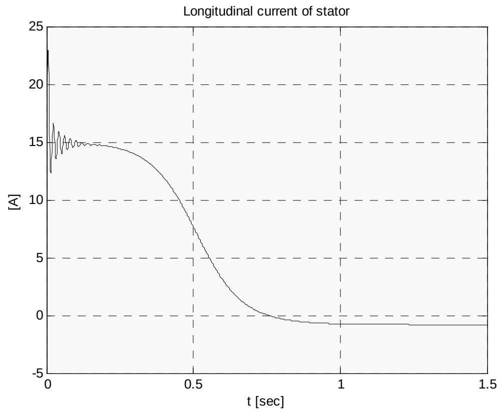

Fig.2. Longitudinal current of stator

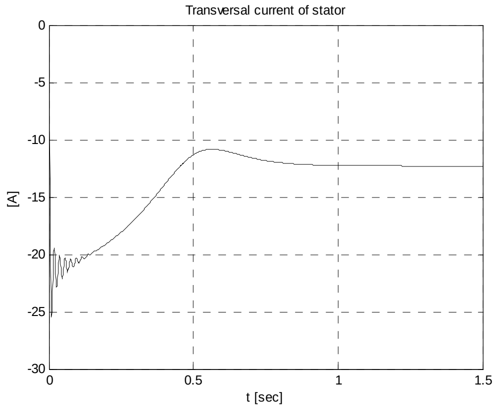

Fig.3. Transversal current of stator

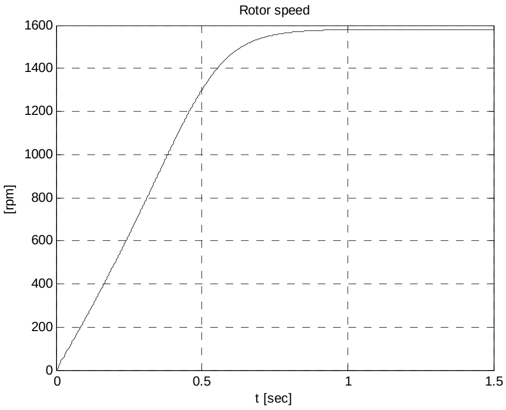

Fig.7. Rotor speed

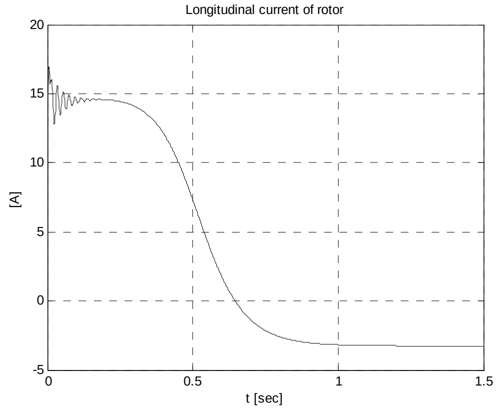

Fig.4. Longitudinal current of rotor

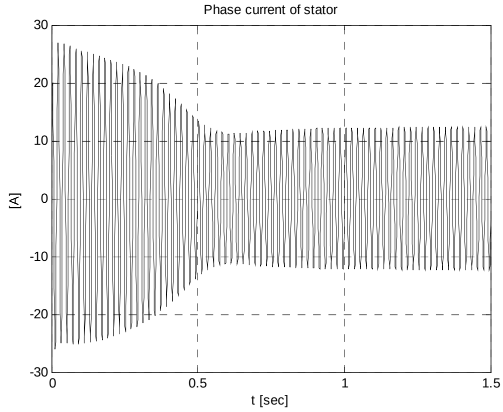

Fig.8. Phase current of stator

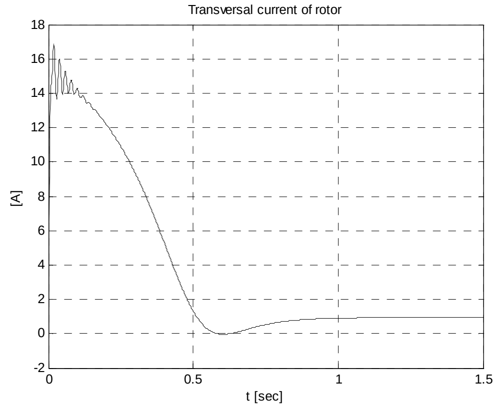

Fig.5. Transversal current of stator

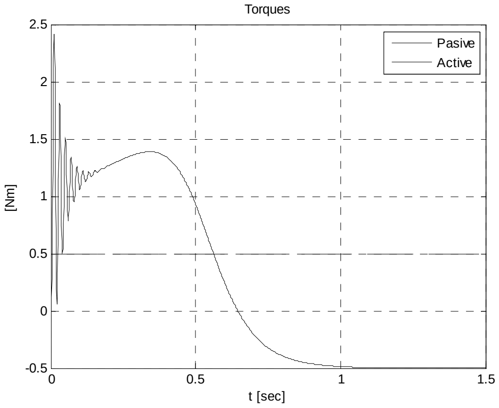

Fig.9. Active and passive torques

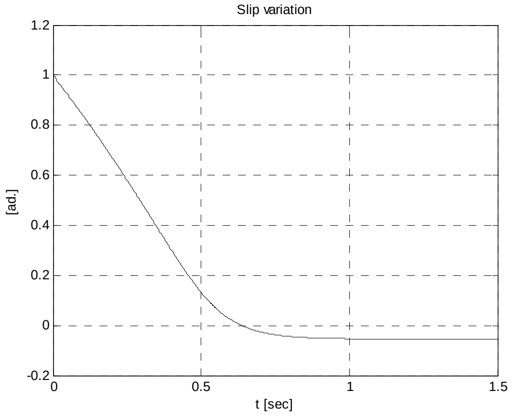

Fig.6. Slip variation

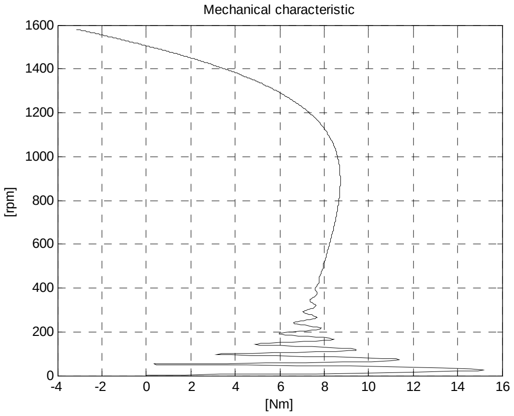

Fig.10. Mechanical characteristic

The mathematical model of permanent magnet synchronous generator in (d,q) coordinates (Babescu and Paunescu, 2001) is:

(4)

$$\begin{cases} L_{1d}\dfrac{dX}{dt}+\sqrt{L_E}\dfrac{dU}{dt}+\sqrt{L_D}\dfrac{dW}{dt}+\dfrac{R_d}{\sqrt{L_d}}X-\omega\dfrac{\sqrt{L_Q L_q}}{L_d}Q-\omega\dfrac{L_q}{\sqrt{L_d}}Z=\dfrac{U_d}{\sqrt{L_d}} \\ \sqrt{L_d}\dfrac{dX}{dt}+\sqrt{L_E}\dfrac{dU}{dt}+\sqrt{L_D}\dfrac{dW}{dt}+\dfrac{R_E}{\sqrt{L_E}}U=\dfrac{U_E}{\sqrt{L_E}} \\ \sqrt{L_d}\dfrac{dX}{dt}+\sqrt{L_E}\dfrac{dU}{dt}+\sqrt{L_D}\dfrac{dW}{dt}+\dfrac{R_D}{\sqrt{L_D}}W=0 \\ \sqrt{L_Q}\dfrac{dQ}{dt}+\sqrt{L_q}\dfrac{dZ}{dt}+\omega\dfrac{L_d}{\sqrt{L_q}}X+\omega\dfrac{\sqrt{L_d L_E}}{\sqrt{L_q}}W+\dfrac{R_d}{\sqrt{L_q}}Z=\dfrac{U_d}{\sqrt{L_q}} \end{cases}$$

where: $X=I_d(t)$; $Z=I_q(t)$; $Q=I_Q(t)$;
$W=I_D(t)$; $U=I_E(t)$

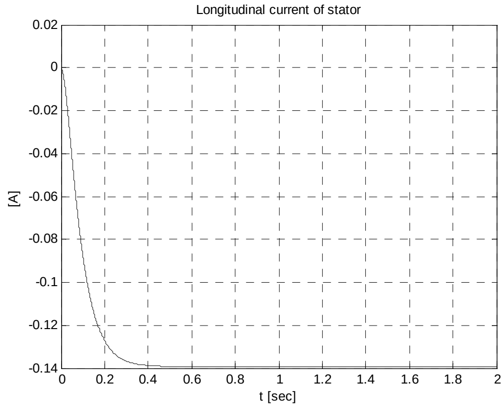

Fig.11. Longitudinal current of stator

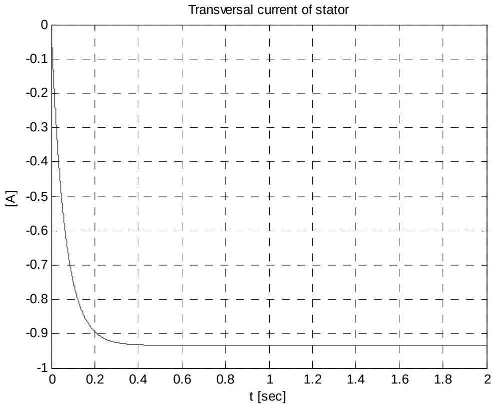

Fig.12. Transversal current of stator

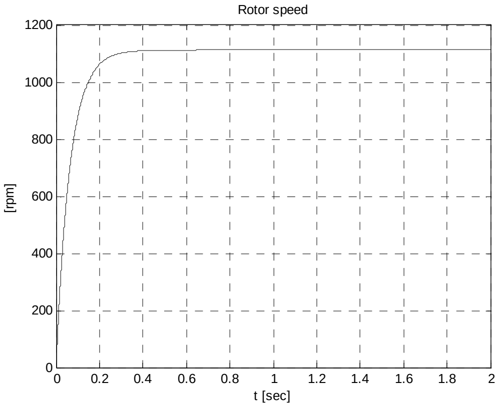

Fig.13. Rotor speed

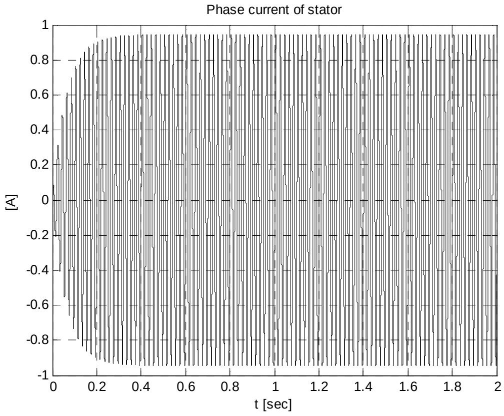

Fig.14. Phase current of stator

It can be observed the high starting currents of asynchronous generator compared to synchronous permanent magnet generator.

After starting-up process, will be analysed the default processes. The schema for single-phase short circuit of connected generators, implemented in Psim software, it is presented in Fig. 15. The wind torque was simulated by a DC motor. All the faults will use the same Psim implementation scheme.

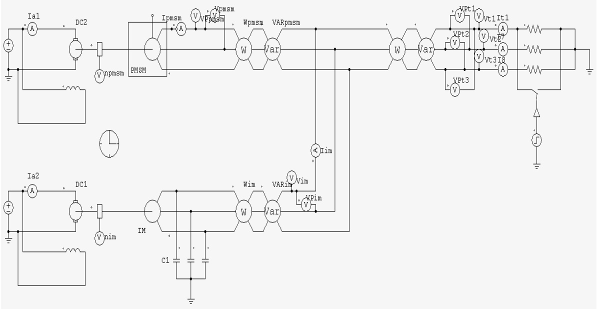

Fig.15. Simulation system

The first studied fault process was the single-phase short circuit. It has been considered that at the time $t=1s$ the phase has been short circuited (Fig.16). It can be observed that the asynchronous generator is frailer, the current absorption being higher than for the permanent magnet device.

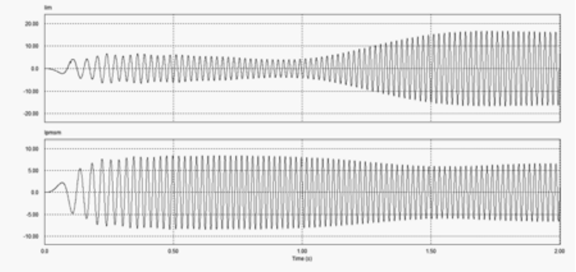

Fig.16. Output currents of generators

Excepting short-circuited phase, where a peak voltage occurs in the first moments of the fault, on the other phases, the voltages at the load remain unchanged in relation to the situation before the occurrence of defect (Fig. 17).

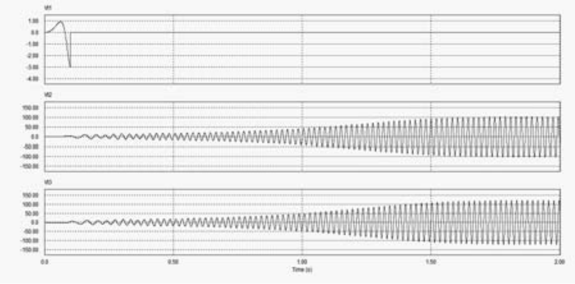

Fig.17. Load voltages

Load currents are changing adequate to produced unbalance (Fig. 18). The other results having the behaviour of common short-circuit.

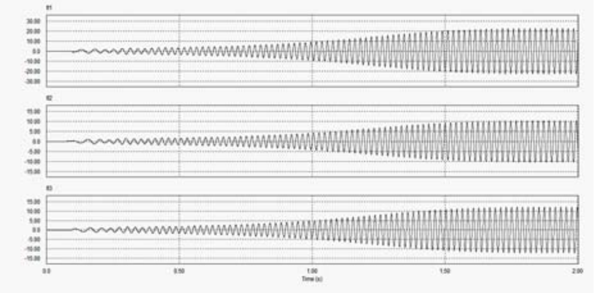

Fig.18. Load currents

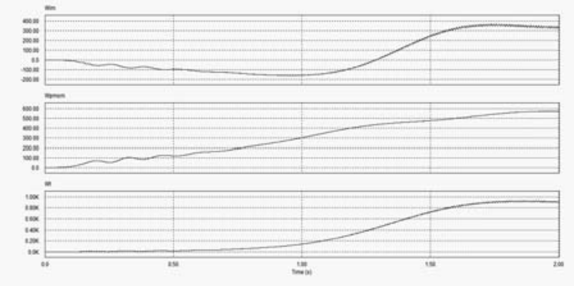

Fig.19. Active power

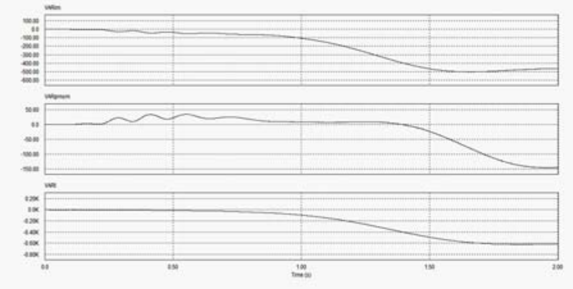

Fig.20. Reactive power

If the case of two-phase short-circuit (Fig. 21) was determined that the synchronous generator deliver a much higher current at the load.

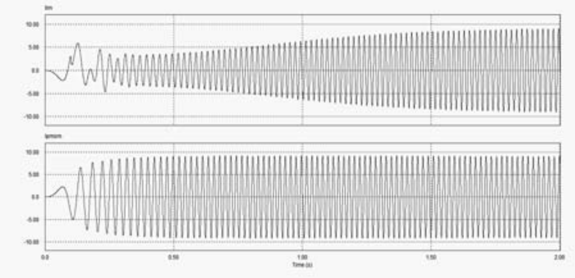

Fig.21. Output currents of generators

The other measurements (currents and voltages of load, powers) presents a identically aspect with those founded in conventional networks.

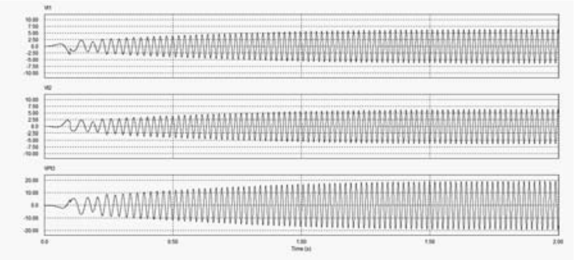

Fig.22. Load voltages

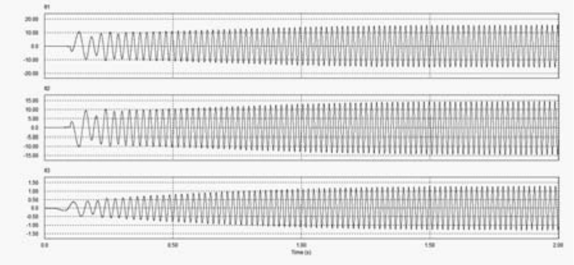

Fig.23. Load currents

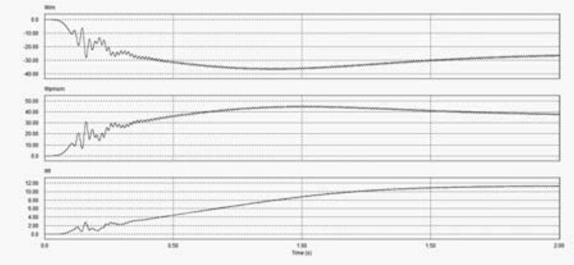

Fig.24. Active power

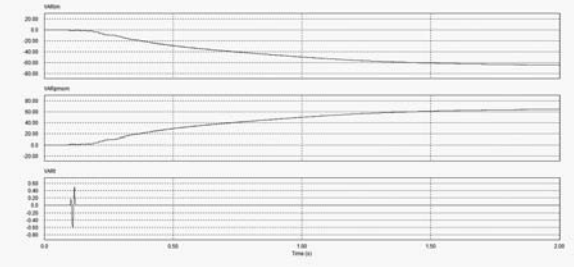

Fig.25. Reactive power

In the case of three-phase short-circuit (Fig. 26) it has been observed the existence of peaks currents in the first moments of coupling, the synchronous generator does not deliver current, the entire current being provided only by the synchronous generator.

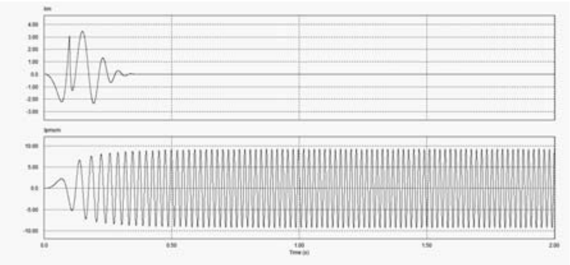

Fig.26. Output currents of generators

The other results were presented below:

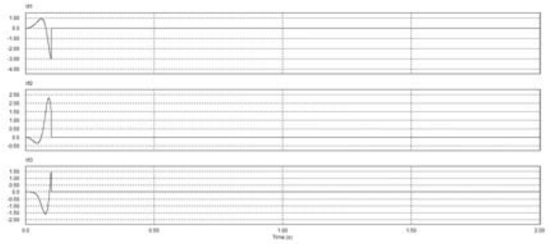

Fig.27. Load voltages

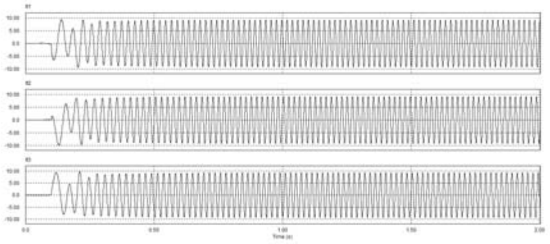

Fig.28. Load currents

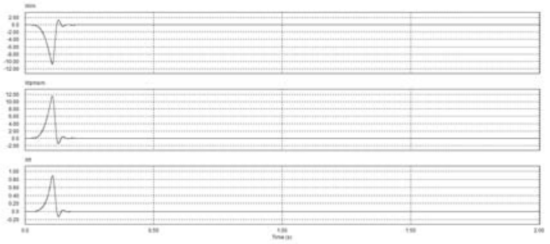

Fig.29. Active power

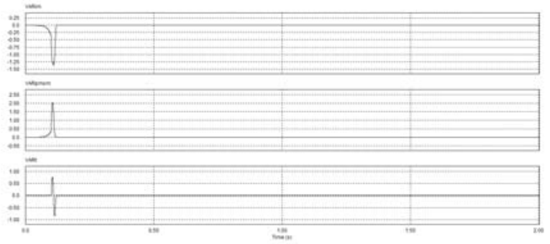

Fig.30. Reactive power

After the simulations it has been observed that the absorption of the currents from the two generators is realised differently depending on the nature of the fault (short-circuit).

4. CONCLUSIONS

In this paper were analyzed the dynamic regimes of parallel connecting of different types of AC generators and were presented important aspects due to dynamic particularities specific to the development of such systems.

Orthogonal models proved to be extremely viable in the starting process analysis, the high starting current of induction generator was presented in comparison to the current of permanent magnet synchronous generator when the voltage and a step torque are imposed.

The dynamic regimes due to the load unbalance have a different behaviour on the two generators. In the case of single-phase short-circuit, the asynchronous generator deliver a higher current (on short-circuit phase) than for the other phases (two-phase and three phase), the synchronous generator having a higher balance.

Dynamic processes are definitive for the situations encountered in practice of connected systems and the development of such systems must take into consideration these aspects in order to realise efficient protection and monitoring systems.

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**PSIM. Simulation software, POWERSYS-France-licence, 2007.

ACKNOWLEDGMENT

The work of Madalin Costin and Elena Voncila was supported by Project SOP HRD-EFICIENT 61445/2009.

Appendix 1. Simulation Parameters ((d,q) models)

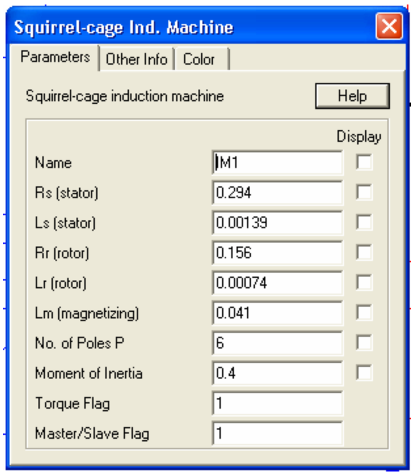
1. Induction generator (Babescu and Paunescu, 2001)

$$L_{1d} = L_{1q} = L_1 = 0.1[H]$$
$$L_{2d} = L_{2q} = L_2 = 0.1[H]$$
$$R_{1d} = R_{1q} = R_1 = 5[\Omega]$$
$$R_{2d} = R_{2q} = R_2 = 5[\Omega]$$
$$U_d = U = 220/380[V]$$
$$U_q = 0[V]$$
$$M_d = M_q = M = 0.08[H]$$
$$f = 50[Hz]$$
$$\omega_1 = 314[rad/s]$$
$$\omega_1 - \omega = \omega_1 s$$
$$\omega_1 L_1 = \omega_2 L_2 = 33.33[\Omega]$$
$$\omega_1 M = 27[\Omega]$$

2. Permanent magnet synchronous geneartor

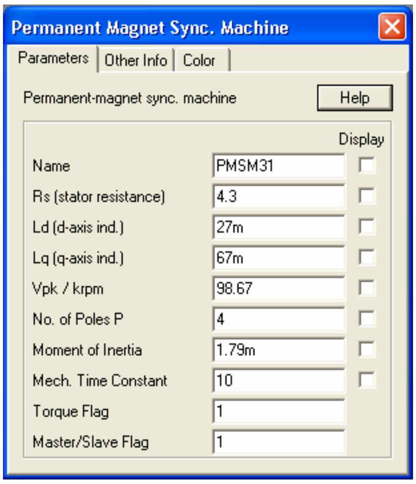
$$R_s = 1.6[\Omega]$$
$$L_d = 0.006365[H]$$
$$L_q = 0.006365[H]$$
$$\phi = 0.1852[Wb]$$
$$F = 5.35e^{-5}$$
$$P = 8$$
$$f = 50[Hz]$$
$$U = 220[V]$$

Appendix 2. Simulation Parameters –Psim (**)



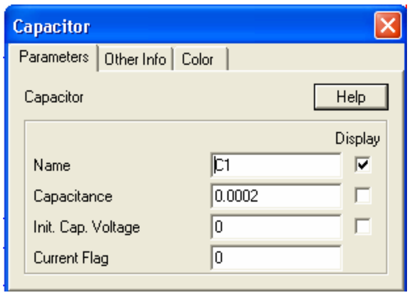
Squirrel-cage induction machine

		Display
Name	IM1	☐
Rs (stator)	0.294	☐
Ls (stator)	0.00139	☐
Rr (rotor)	0.156	☐
Lr (rotor)	0.00074	☐
Lm (magnetizing)	0.041	☐
No. of Poles P	6	☐
Moment of Inertia	0.4	☐
Torque Flag	1	
Master/Slave Flag	1	



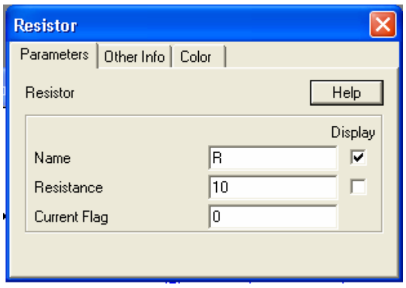
Permanent-magnet sync. machine

		Display
Name	PMSM31	☐
Rs (stator resistance)	4.3	☐
Ld (d-axis ind.)	27m	☐
Lq (q-axis ind.)	67m	☐
Vpk / krpm	98.67	☐
No. of Poles P	4	☐
Moment of Inertia	1.79m	☐
Mech. Time Constant	10	☐
Torque Flag	1	
Master/Slave Flag	1	



Capacitor

		Display
Name	C1	☑
Capacitance	0.0002	☐
Init. Cap. Voltage	0	☐
Current Flag	0	



Resistor

		Display
Name	R	☑
Resistance	10	☐
Current Flag	0	