Models of different generators for wind power generations

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Abstract - **Wind power generation has grown in the last three decades and it is considered as a one of the most promising renewable energy sources. And its integration into power systems has a number of technical challenges concerning security of supply, in terms of reliability, availability and power quality. In this paper suitability of different generators according to their reliability is considered as well as simulation results of all generators are observed. The mathematical models of all Generators permit to analyze their response under generic conditions. However, their mathematical complexity does not contribute to simplify the analysis of the system under transient conditions, and hence do not help to find straight-forward solutions to enhance their FRT.**

keywords - **Generators, Wind system, Wind turbines, modeling.**

I. INTRODUCTION

The first windmill was installed in 1980s to generate electricity in the rural U.S.A. Today, number of wind power plants is competing with electric utilities in supplying economical clean power in the world. The wind turbine capture the wind's kinetic energy in a rotor. Wind turbine rotor consists of two or more blades and it is mechanically coupled with an electric generator. The wind turbine system consists of two main parts: mechanical and electrical parts. Mechanical part consists of aerodynamic and gearbox model. And electrical part consists of generator model. In this paper we have discussed about suitability of different Generators for wind application. The power captured from the wind with a wind energy converter with effective area A is given by

$$PV=1/2\rho A V^3. \qquad (1.1)$$

The average energy available in the wind is obtained by integrating above (1.1) during a time interval Tp, typically for one year:

$$\text{Average energy} = \frac{1}{2}\rho A \int_0^{T_p} V^3 dt. \qquad (1.2)$$

II. INDUCTION GENERATOR

It is very important challenge for wind power industry to Improving the Fault Ride Through capability (FRT) of Induction Generators (IG) in wind power application.

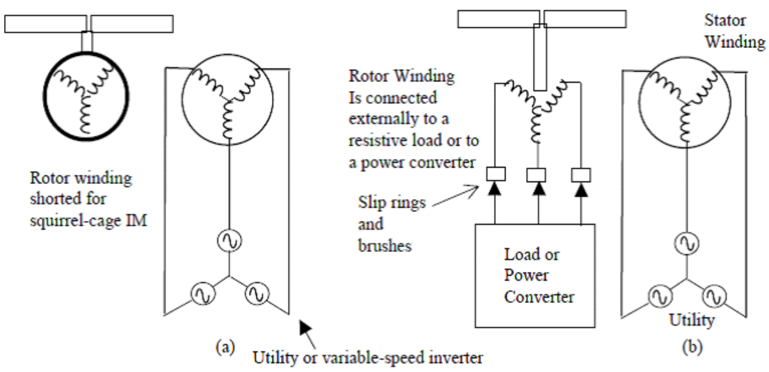


Fig.(i) Physical diagram of IG in WTG applications
(a) Squirrel-cage induction machine
(b) Wound rotor induction machine

During start-up, due to slip the rotor circuit branch presents a much lower impedance (almost short circuit) than the magnetizing branch. The starting current is about 5 to 8 times rated current. Although the rotor current is large, the magnetizing current is small. When the rotor speed increases, the slip decreases. And when total impedance of the induction machine increases, the stator current decreases, and the magnetizing current and the torque increases. The slip at which the peak torque occurs is:

$$Slip\_peak = \frac{R_r^{'}}{\sqrt{R_s^2 + (X_{ls} + X_{lr}^{'})^2}}$$

From the above equation, the peak-torque slip can be increased by using a higher rotor resistance.

Modeling of a Squirrel Cage Induction Generator:

The mechanical output power of a wind turbine can be expressed by

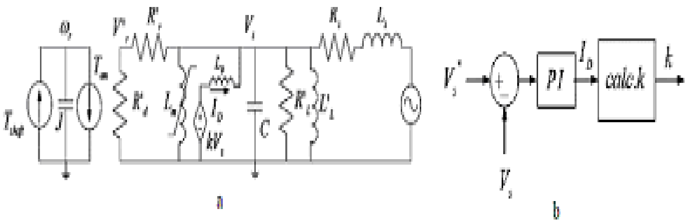
$$P = \pi\rho V^3 R^2 C_p / 2 \qquad (1.3)$$

where: ρ- air density, V- wind speed, R- rotor radius and Cp represents the fraction of aerodynamic wind power extracted by a turbine. The power coefficient Cp varies with the wind speed, the turbine rotational speed and the turbine blade pitch angle parameter β.The approximate equation for Cp is

$$C_p = (0.44 - 0.0167\beta) * \sin[\frac{\frac{\pi}{2}(\lambda - 3)}{7.5 - 0.15\beta}] - (\lambda - 3) * (0.00148\beta) \qquad (1.4)$$

γ is the trip speed ratio and defined as : $\lambda = \omega_H R / V$ (1.5)

where ωh is the rotating speed of the wind turbine. Equation (1.3)-(1.5) shows that mechanical output power of a wind turbine is a function of turbine speed ωh , wind speed V and the β .The reference current can be changed into a voltage which its value is calculated by Eq. 1.6.



Fig(ii) a) The improved model for controlling the voltage b) the control

$$kV_s - V_s = L_D I_D$$
$$k = \frac{L_D I_D + V_s}{V_s} \qquad (1.6)$$

Wound rotor induction machine:

In order to derive the control strategies of grid-connection, mathematical model of DFIG in two-phase synchronous speed rotating coordinate system should be established firstly [7].

The spatial relationship of different coordinates is shown in Fig. α1, β1 is two-phase stationary coordinate system, α1 axis is on the positive direction of A phase winding axis of stator. α2 β2 is two-phase rotor speed rotating coordinate system, α2 axis is on the positive direction of A phase winding axis of rotor. The angle between α2 axis and α1 axis is θr. mt is two-phase synchronous speed rotating coordinate system, and the angle between m axis and α1 axis is θs . Using the rule of generator, DFIG(doubaly fed induction generator) mathematical model in mt coordinate system is as follows.

$$\begin{cases} u_{m1} = -R_1 i_{m1} - p\psi_{m1} + \omega_1 \psi_{t1} \\ u_{t1} = -R_1 i_{t1} - p\psi_{t1} - \omega_1 \psi_{m1} \end{cases} \qquad (1.7)$$

$$\begin{cases} u_{m2} = R_2 i_{m2} + p\psi_{m2} - \omega_s \psi_{t2} \\ u_{t2} = R_2 i_{t2} + p\psi_{t2} + \omega_s \psi_{m2} \end{cases} \qquad (1.8)$$

$$\begin{cases} \psi_{m1} = L_1 i_{m1} - L_m i_{m2} \\ \psi_{t1} = L_1 i_{t1} - L_m i_{t2} \end{cases} \qquad (1.9)$$

$$\begin{cases} \psi_{m2} = L_2 i_{m2} - L_m i_{m1} \\ \psi_{t2} = L_2 i_{t2} - L_m i_{t1} \end{cases} \qquad (1.10)$$

where, R_1 and R_2 are the stator and rotor winding resistances (1 corresponds to stator, while 2 corresponds to rotor); L_1, L_2 and L_m are the equivalent self and mutual inductances in m_t coordinate system; u_{m1} , u_{t1} , u_{m2} and u_{t2} are the *m*, *t* axis components of the stator and rotor voltage respectively; i_{m1} , i_{t1} , i_{m2} and i_{t2} are the *m*, *t* axis components of the stator and rotor current respectively; □$_{m1}$.

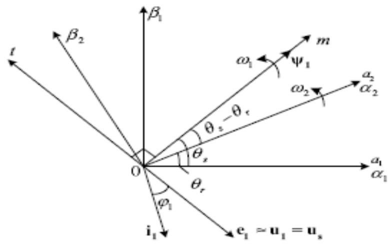


Fig.2.3.Relation of coordinates

$\square_{t1}$,$\square_{m2}$ and $\square_{t2}$ are the *m*, *t* axis components of the stator and rotor flux linkage respectively; ω_1, $\square_r$ and $\omega_s=\omega_1-\omega_r$ are the synchronous angular velocity, rotor angular velocity and slip angular velocity respectively, and *p* corresponds to the derivative operation.The stator current of DFIG without load is zero, by substituting $i_{m1}= i_{m1} = 0$ to (1.7)~(1.10), the mathematical model of DFIG without load can be get:

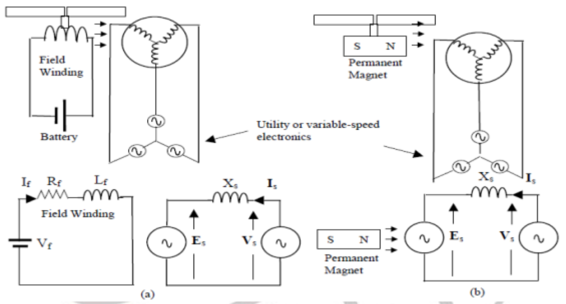
$$\begin{cases} u_{m1} = -p\,\psi_{m1} + \omega_1\psi_{t1} \\ u_{t1} = -p\,\psi_{t1} - \omega_1\psi_{m1} \end{cases} \quad (1.11)$$

$$\begin{cases} u_{m2} = R_2 i_{m2} + p\,\psi_{m2} - \omega_s\psi_{t2} \\ u_{t2} = R_2 i_{t2} + p\,\psi_{t2} + \omega_s\psi_{m2} \end{cases} \quad (1.12)$$

$$\begin{cases} \psi_{m1} = -L_m i_{m2} \\ \psi_{t1} = -L_m i_{t2} \end{cases} \quad (1.13)$$

$$\begin{cases} \psi_{m2} = L_2 i_{m2} \\ \psi_{t2} = L_2 i_{t2} \end{cases} \quad (1.14)$$

III. SYNCHRONOUS GENERATOR:



Fig(iii)Physical diagram and equivalent circuits ofa syn machine: (a)wound field excitation (b) permanentmagnet excitation

Synchronous Generator Model:

The mathematical model of SG in the rotor reference frame can be derived as (3.2)-(3.8) based on the assumptions that,

(i) Core losses and magnetic saturation are negligible;
(ii) There are three dampers on the rotor
(ii) Rotor shaft stiffness is infinite

$$v_{qs} = r_s i_{qs} + \frac{d}{dt}\varphi_{qs} + \omega_e\varphi_{ds} \quad (3.1)$$

$$v_{ds} = r_s i_{ds} + \frac{d}{dt}\varphi_{ds} - \omega_e\varphi_{qs} \quad (3.2)$$

$$v'_{fd} = r'_{fd} i'_{fd} + \frac{d}{dt}\varphi'_{fd} \quad (3.3)$$

$$v'_{kq1} = r'_{kq1} i'_{kq1} + \frac{d}{dt}\varphi'_{kq1} = 0 \quad (3.4)$$

$$v'_{kq2} = r'_{kq2} i'_{kq2} + \frac{d}{dt}\varphi'_{kq2} = 0 \quad (3.5)$$

$$v'_{kd1} = r'_{kd1} i'_{kd1} + \frac{d}{dt}\varphi'_{kd1} = 0 \quad (3.6)$$

$$T_e = \frac{3}{2}P(\varphi_{ds}i_{qs} - \varphi_{qs}i_{ds}) \quad (3.7)$$

$$T_m - T_e = J\frac{d\omega_r}{dt} + B\omega_r \quad (3.8)$$

Equation which represents the mechanical coupling between SG and wind turbine is pertaining not only to SG but also to the mechanic part of wind turbine.

Direct-drivepermanent magnet synchronous Generator:

At present, the wind turbine generation system requires large capacity, good power quality, high material utilization, noise reduction, low cost and high efficiency etc. With the rapid development of high-power semiconductor devices and permanent magnetic materials, and because of the direct-drive PMSG system eliminates the gear box, reduces energy losses and maintenance costs, no direct connection between motor and the grid, easy to implement for active and reactive power control, low harmonic and so on. The direct-drive PMSG variable speed constant frequency wind power generation system has become a trend. In MW-class direct-drive wind power generation system, because of the PMSG used to surface mounted and outer rotor multi-level structure [10], it becomes difficult for installing speed sensor, even if speed sensor can be installed in some system, it will increase the connection between motor and control system and the interface circuit is needed, which making the control systems vulnerable to external environment disturbance and then reducing the reliability. As a result, the MW-class direct-drive wind power generation system need to adopt non speed sensor technology.

For the distinguishing feature of the MW-class direct-drive wind power generation system, at first, this paper analyzes the PMSG resonant modulator control strategy detailedly, which is based on the rotor field-oriented vector control theory. After that we use the phase-locked loop (PLL) principle building the position detection controller.

Mathematical model of DDPMSG:

PMSM voltage equations are usually expressed as formula (3.9) in the d, q coordinates

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = -\begin{bmatrix} 0 & R_s \\ R_s & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} -\omega_s & p \\ p & \omega_s \end{bmatrix}\begin{bmatrix} \psi_d \\ \psi_q \end{bmatrix} \quad (3.9)$$

Where,u_d , u_q are stator voltage at d, q-axis component i_d , i_q are stator current at d, q-axis component Ψ_d , Ψ_q are magnetic flux at d, q-axis component L_d,L_q are inductor at d, q-axis component R_s is the stator resistance
The flux linkage equation:

$$\begin{bmatrix} \psi_d \\ \psi_q \end{bmatrix} = -\begin{bmatrix} 0 & -L_d \\ -L_q & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \psi_f \\ 0 \end{bmatrix} \quad (3.10)$$

Where, Ψ_f is the rotor flux excitated by permanent magnet Then, we can rewrite the voltage equations using the Ψ_d , Ψ_q which is calculated from the flux equation. As shown in formula (3.10).

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = -\begin{bmatrix} 0 & R_s \\ R_s & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \omega_s L_q & -L_d p \\ -L_q p & -\omega_s L_d \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_s \psi_f \end{bmatrix} \quad (3.11)$$

Now, we can take i_d , i_q as the state variable, so the state equation is shown in formula (3.12).

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}u \quad (3.12)$$

where,

$$A = \begin{bmatrix} -\frac{R_s}{L_d} & \omega_s \frac{L_q}{L_d} \\ -\omega_s \frac{L_d}{L_q} & -\frac{R_s}{L_q} \end{bmatrix} \qquad B = \begin{bmatrix} \frac{1}{L_d} & 0 & 0 \\ 0 & \frac{1}{L_q} & -\frac{\omega_s}{L_d} \end{bmatrix}$$

$u = [\, u_d \;\; u_q \;\; \psi_f]$

where torque equation is

$$T_e = \frac{3}{2}p(\psi_d i_q - \psi_q i_d) = \frac{3}{2}p[\psi_M i_q + (L_d - L_q)i_d i_q] \quad (3.12)$$

Where, p is the number of pole pairs of PMSG Analysis of the above formula (3.12), we can find that the first item in parentheses is the electromagnetic torque which is generated from the three-phase rotating magnetic field and permanent magnet magnetic field interaction; the second is reluctance torque caused by the salient-pole effect. For embedded rotor PMSG, $L_d<L_q$, both the electromagnetic torque and reluctance torque exist at the same time in the system. The maximum output torque will be got if the reluctance torque is used effectively. However, for the salient-pole rotor PMSG, $L_d = L_q$, now, only the electromagnetic torque is exist, the reluctance torque is disappeared. Then, the output electromagnetic torque of PMSG can be expressed as:

$$T_e = \frac{3}{2} p \psi_f i_q \quad (3.13)$$

Because that Ψ_f is a constant value, the electromagnetic torque is proportional with the i_q. There we use rotor flux orientation, putting synchronously rotating coordinate system on the rotor, rotate with the rotor synchronously. The direction of the d-axis coincides with the rotor magnetic field, and the q-axis counter-clockwise ahead of d-axis 90°.

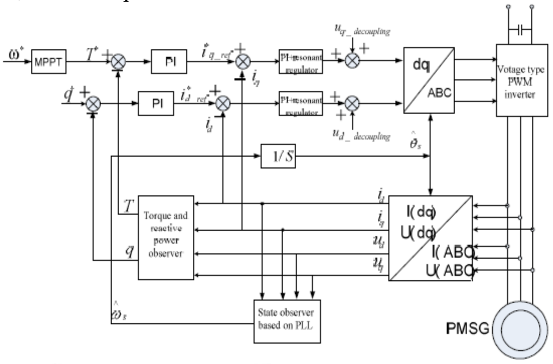


Figure.(iv) Direct-drive synchronous Generator control block diagram.

IV.SUITABILITYOFDIFFERENT GENERATORS

4.1. Table Comparison of wind turbine concept (+strength, - weakness)

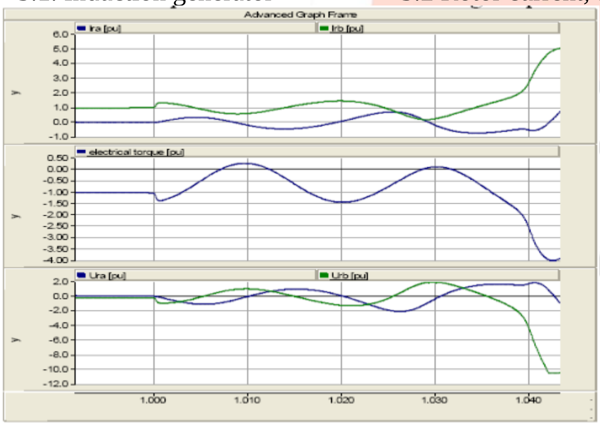
		CS	VTDI	VTDD
Cost, size and weight		+	+/-	-
Suitability for 50 and 60 Hz grid frequency		-	-	+
Audible noise from blades		-	+	+
Energy yield	Variable speed	-	+	+
	Gearbox	-	-	+
	Generator	+	+	-
	Converter	+	+/-	-
Reliability and Maintenance	Brushes	+	-	- (PM:+)
	Gearbox	-	-	+
	Mechanical loads	-	+	+
	Complexity	+	-	-
Power quality	'Flicker'	-	+	+
	Grid V&f control possible	-	+	+
	Harmonics	+	-	-
Grid faults	Fault currents	+	+	+/-
	Restoring voltage	-	+	+

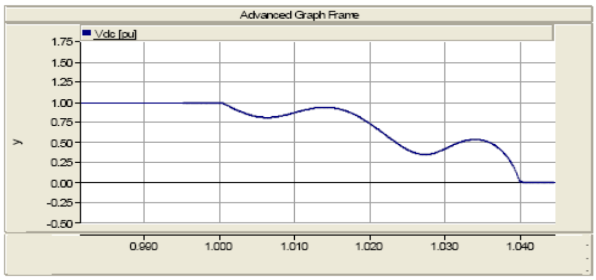
4.2. Comparison of the Various Generators for Variable Speed Turbines √: Advantage ×: Disadvantage

Squirrel-cage Induction	Induction with coiled rotor	Synchronous with coiled field	Synchronous with Permanent Magnet
√ Simple and Robust	×Complex Structure	×Complex Structure	√Simple and Robust
√Reliable	×Slipping rings for DFIG	×Slipping Rings	√Reliable
√No Slipping Rings	√No Slipping Rings for BDFG	×Regular Maintenance	√No Slipping Rings
√Low Maintenance	High Cost	×High Cost	√Low Maintenance
√Low Cost	×Large and Heavy	×Large and Heavy	√Low Cost
×Low efficiency	√High efficiency with DFIG	√High efficiency in a wide range of load	√Small and lightweight
×Low power coefficient	×Low power coefficient	√High power coefficient	√High power coefficient
×Narrow speed range	√wide speed range	√wide speed range	×Narrow speed range
√Flat Torque	×Wavy Torque	√Wide-range torque	
		√Flat Torque	
Control and Regulation			
		√No need for Capacitors	
×Needs Capacitors	×Needs Capacitors	√Ease of Voltage Control	√No need for Capacitors
×Complex Voltage Control with static generator	×Complex Voltage Control with static generator	√Quick Torque Control	
×VAR or Capacitor	×VAR or Capacitor	√Easy control of Power Coefficient and reactive power	
√Stable operation in Unstable conditions	√Can be used as starter Motor		
√Can be used as starter Motor		√Can be used as recovery break	
Inverter Requirements			
×Large Scale Inverter	√Inverters for 25% to 50% of nominal power	×Large Scale Inverter	×Large Scale Inverter
√One controlling inverter	×Two controlling inverters	√One controlling inverter	√One controlling inverter
√Simple inverter control	×Complex inverter control	√Simple inverter control	√Simple inverter control
1 rectifier + 1 inverter		1 field controller + 1 inverter	1 Rectifier + 1 inverter

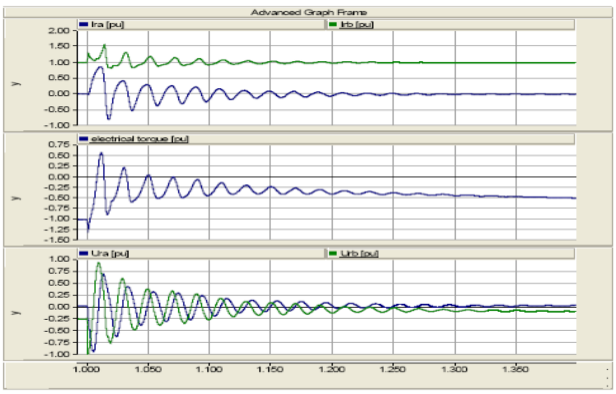
V. Simulation results:

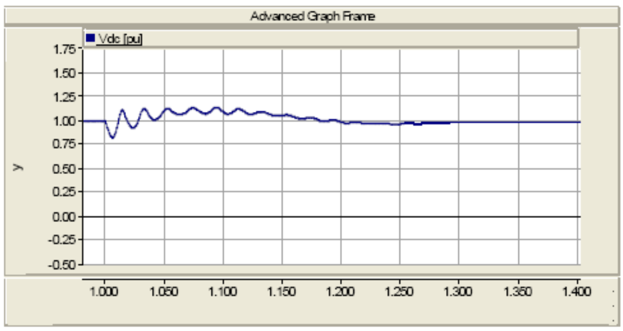
5.1. Induction generator 5.2 Rotor current, torque and rotor voltage during a transient voltage drop



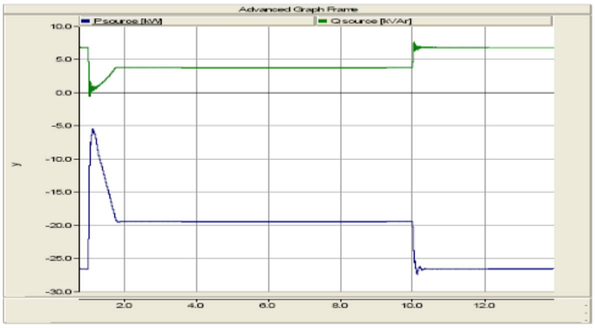


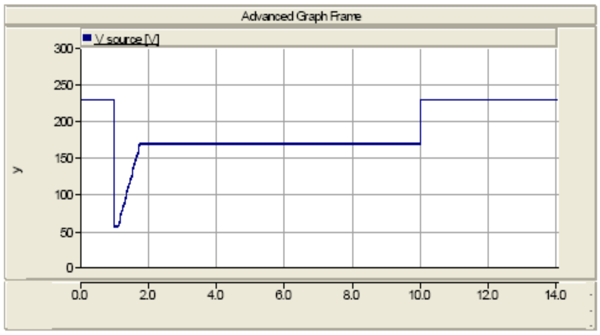
5.3 Dc-link voltage during a transient voltage drop 5.4. Rotor currents, Torque and Rotor Voltages during a transient voltage drop.





5.5. Dc - link voltage during a transient voltage drop. 5.6. Reactive and Active Power under a transient Voltage drop

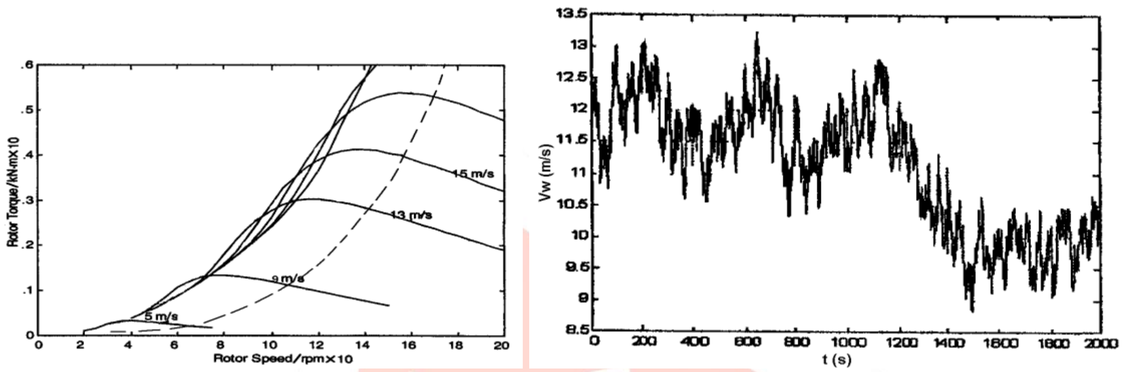




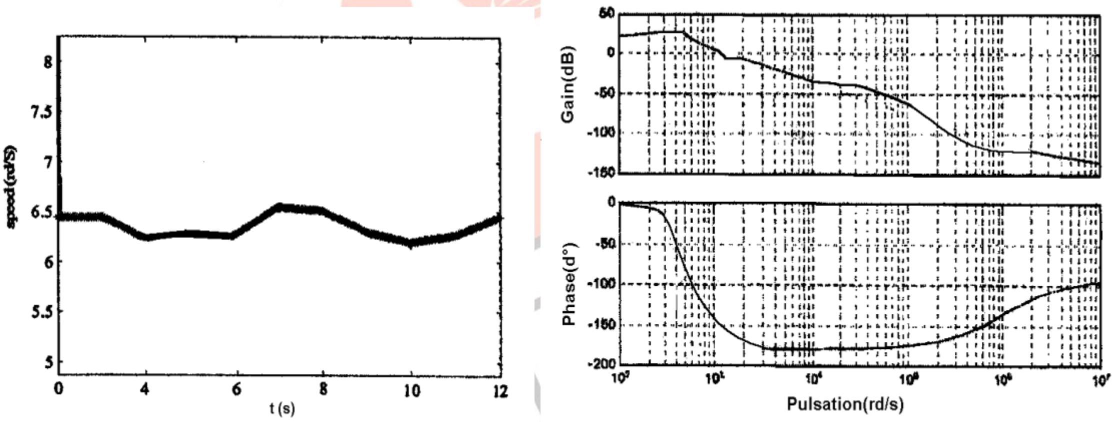
Transient Voltage drop.

Synchronous generator:

The complete model of the system has been implemented on matlab–simulink environment for different values of the load. Stochastic wind model has been used for this purpose, Fig. 5.[9]

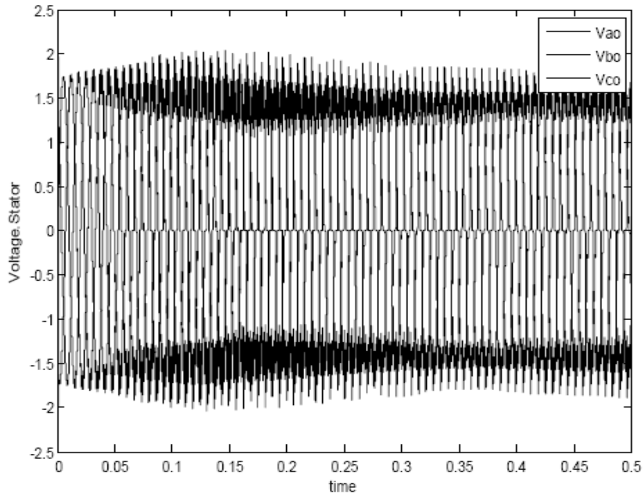


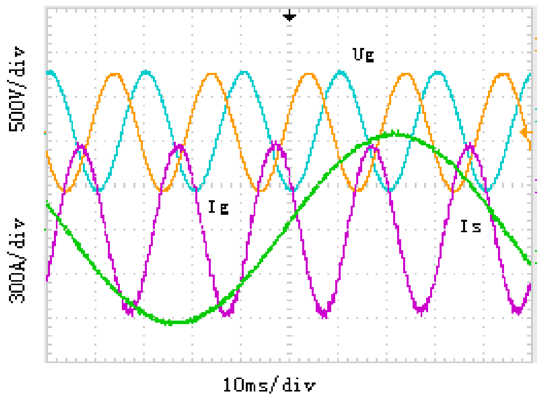
5.7. WT torque as function as rotor speed velocity issued from Betz's characteristics *5.8 Stochastic wind speed evolution*



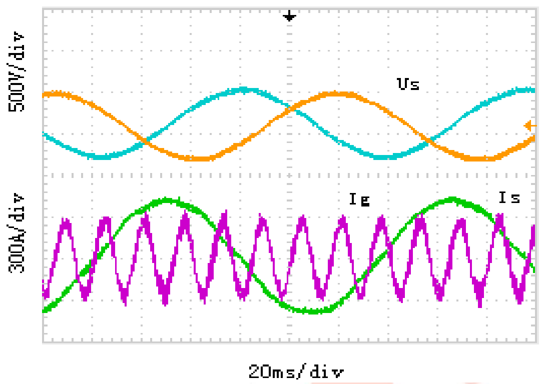
5.9 Bode diagram in open loop case

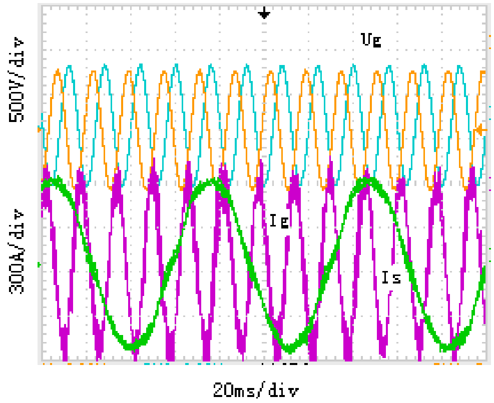
The detailed modeling of the Generator, the rectifier and dc-dc converter is very important for obtaining the accurate picture of all the system waveforms (voltages, currents, torque, power, speed), this is necessary for dimensioning of semiconductors, and for validating the average value models used in the control system design. Besides, electromagnetic oscillations can rise from Generator current harmonics, which could alter the mechanical characteristics of the WECS. Fig. 6 shows the mean Generator shaft speed as function of the time.[9]





5.10. Direct Drive synchronous Generator *5.11 the grid voltage, stator current and grid-side current (11HZ)*





5.12. the stator voltage, stator current and grid-side current (6HZ) *5.13. the grid voltage, stator current and network-side current (20HZ)*

A direct-drive PMSG variable speed constant frequency wind power generation simulation system platform is employed to verify the validity and usefulness of the above-mentioned control strategy. A PMSG with rated values of 380V, 20KW and 22 ~ 45rpm, the number of pole pairs is 20, the stator resistance Rs = 0.2Ω, the AC-DC-axis inductance is 3.2mH and the rotor flux 2.5Wb. The net side converter has rated power of 30KW, rated current of 90A, DC bus voltage of 400V. The smoothing capacitor of DC side is 6600μF and the net side inductor is 0.7mH. The platform used Emerson inverter TD3000 to drive a three phase squirrel-cage induction motor as wind turbine emulator. Motor side and net side converters are controlled by the dual-DSP controller (TMS320LF2407A). Figure 6 shows the grid voltage and stator current and network-side current waveform when the Generator frequency is 11HZ; Figure 7 is the grid voltage and stator current and network-side current waveform when the Generator frequency is 6HZ; Figure 8 is the grid voltage and stator current and network-side current waveform when the Generator frequency is 20HZ.

VI. CONCLUSION

In this chapter we have discussed about wind energy system & wind turbine. Also we have presented a dynamical simulation model for the IG, SRG, and the PMSG which are the main types of generators or variable speed wind generators that we will see in wind farms in following years, DFIG being the most common nowadays. First we presented a wind able to simulate the evolution of its speed for a given wind turbine location. Then we have introduced a simple model that describes the dynamic behavior of the wind turbine mechanical components and the generator electrical dynamics. Finally we have briefly discussed the control of both wind turbine topologies and how we can model a series of electrical disturbances of interest with the model.
We have also discussed about suitability of all the Generators depending on their advantages, disadvantages & economic point of view.

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