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Modelling of a Wind Turbine with Permanent Magnet Synchronous Generator

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Abstract— **This investigation presents the implementation and simulation of a Simulink-based controlled permanent magnet synchronous generator (PMSG) wind turbine in the dq0 reference frame. The model consists of a current control subsystem, a PMSG model, a mechanical subsystem, a pitch angle controller and a wind turbine model. The current control subsystem makes use of PI controllers governing the wind turbine speed, the direct and quadrature stator currents and the pitch angle of the turbine blades. The pitch angle controller measures the speed and the active power from the generator limiting both in case of high-speed wind conditions. In order to verify the functioning and the effectiveness of the proposed controllers, simulations- for different operation conditions- are presented and discussed.**

Keywords— Permanent magnet synchronous generator, Wind Turbine, Control, Modeling.

I. INTRODUCTION

Throughout history the use of wind energy has been a constant for human kind. Such energy comes from a renewable source, namely, the natural and continuous atmospheric processes [1]. The use of wind energy has increase notably in recent years, especially for generation of electric power [2]. This is because the increasing need of finding less polluting alternatives for energy production has found in wind power system a realizable option, with the power-electronic controlled variable speed wind turbines as the most efficient scheme. The speed and the pitch angle of the blades of these turbines are controlled by digital algorithms in all time [3].

One of the problems associated with variable-speed wind systems today is the presence of the gearbox coupling the wind turbine (WT) to the generator, which have proven to require maintenance constantly and replacement well before its design life [4][5]. To improve reliability of the WT and reduce maintenance expenses the gearbox should be eliminated [6]. Because of this need, direct drive variable speed wind turbines based on multi-pole permanent magnet synchronous generator (PMSG) with full-scale converter, have began to gain acceptance among wind turbine developers such as Vestas, GE Wind, Goldwind, Siemens and Gamesa, specially for offshore wind farm developments. The advantages of using variable-speed with PMSG, are: better reliability, longer life and improved performance [7] however, since the blades of a PMSG WT are direct-coupled to the generator, the speed of its rotor (i.e. 5-25 rpm) is much more slower than the gearbox generators (which is around 1500 rpm), this conveys the need of higher torque in the PMSG to produce the same amount of power of a gearbox generator, which is translated in larger rotor diameters (around 7 times) to sustain the tangential stress produced by the increased torque [7].

This investigation presents the model of a PMSG WT able to work under low and fast wind speed conditions and during wind gusts. The PMSG has the benefits of high power density, low losses, no need of gearbox, and the characteristic of not requiring a rotor field excitation. The modeling and simulations are carried out using Simulink with a sample time of 50e-6 sec.

II. MODELING OF THE PMSG WT

A. Current Controller

The control of the i_d and i_q stator currents are carried out indirectly by controlling the d and q voltages of the machine, where [8]:

$$L_d \frac{di_d}{dt} + R_s i_d = u_d \tag{1a}$$

$$L_q \frac{di_q}{dt} + R_s i_q = u_q \tag{1b}$$

where L_d, L_q, i_d, i_q, u_d and u_q are the d and q components of the stator inductances currents and voltages respectively and R_s is the stator resistance.

The current control makes use of the compensators K_d and K_q for i_d and i_q respectively. The i_d compensator obtains the error signal $e_d = i_{dref} - i_d$ and commands the injection of a control voltage u_d. In a similar way, the i_d compensator obtains the error signal $e_q = i_{qref} - i_q$ and commands the injection of a control voltage of u_q. Assuming that the transfer function of the closed-loop systems I_d / I_{dref} and I_q / I_{qref} are first-order with a time constant of τ_i then K_d and K_q are defined, using the Laplace operator s, as:

$$K_d = \frac{L_d s + R_s}{\tau_i s} \tag{2a}$$

$$K_q = \frac{L_q s + R_s}{\tau_i s} \tag{2b}$$

Fig. 1 shows a block diagram of the current control subsystem, where $P = 1/s$.

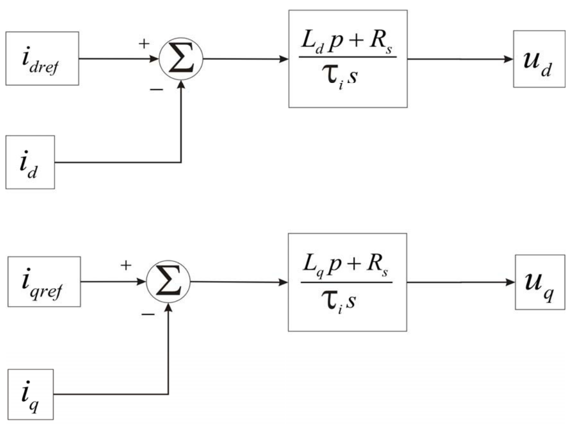

Figure 1. *d* and *q* current controllers

B. *Modeling of the permanent magnet synchronous generator*

The dynamic model of the PMSG is carried out using the synchronous *dq* reference frame, where the dynamic behavior of the PMSG currents can be defined as [9]:

$$\frac{di_d}{dt} = -\frac{R_a}{L_d} i_d + \omega_e \frac{L_q}{L_d} i_q + \frac{1}{L_d} u_d \tag{3a}$$

$$\frac{di_q}{dt} = -\frac{R_a}{L_q} i_q - \omega_e \left(\frac{L_d}{L_q} i_d + \frac{1}{L_q} \lambda_0 \right) + \frac{1}{L_q} u_q \tag{3b}$$

where, u_d, u_q, i_d and i_q are the *d* and *q* components of the stator voltage and current respectively, R_a is the armature resistance, ω_e is the electrical rotor speed (which is related to the mechanical speed, ω_g, as $\omega_e = n_p \omega_g$ with n_p as the pole pairs), and λ_0 is the flux of the permanent magnet. The electrical frequency is given by $f_e = \omega_e / 2\pi$, the inductances L_d and L_q are the sum of the generator inductances in the *d* and *q* axes.

The *q* axis current counterbalance the electrical potential $e_q = \omega_e \lambda_0$, and the d axis current counterbalance the electrical potential $e_d = 0$. Assuming that $L_d = L_q = L$ then (3a) and (3b) can be written as:

$$\frac{di_d}{dt} = -\frac{R_a}{L} i_d + \omega_e i_q + \frac{1}{L} u_d \tag{4a}$$

$$\frac{di_q}{dt} = -\frac{R_a}{L} i_q - \omega_e \left(i_d + \frac{1}{L} \lambda_0 \right) + \frac{1}{L} u_q \tag{4b}$$

Fig. 2 shows a block diagram of the PMSG model based in (4a) and (4b), where $P = 1/s$. Past model requires the rotor speed (which is obtained from the mechanical system) and the voltages coming from the current controllers.

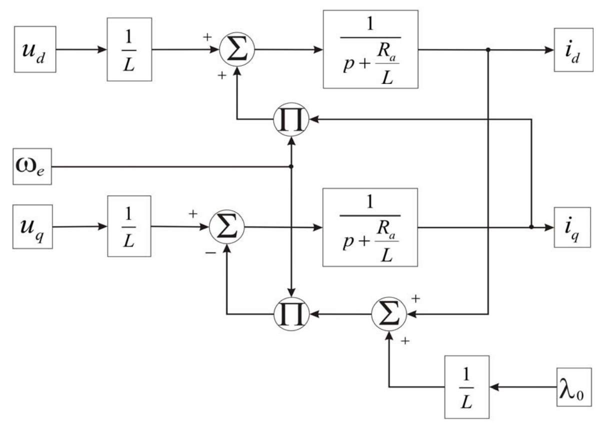

Figure 2. PMSG model

C. *Modeling of the mechanical system*

The model of the mechanical system uses the PMSG currents as an input variable and provides as outputs the rotor speed and the electromagnetic torque of the PMSG.

The electromagnetic torque, T_e, is calculated using [10]:

$$T_e = \left(\frac{3}{2}\right)\left(\frac{n_p}{2}\right)\left[\left(L_d - L_q\right) i_d i_q + i_q \lambda_0\right] \tag{5}$$

If $L_d - L_q$ is stated as L_{dq}, then T_e can be stated as:

$$T_e = (0.75) n_p i_q \left(L_{dq} i_d + \lambda_0\right) \tag{6}$$

Using (6) the dynamics of the generator speed ω_g can be stated as:

$$\frac{d\omega_g}{dt} = (T_e - T_{\omega,g} - B_m \omega_g) / J_{eq} \tag{7}$$

where the sub index g represents the generator parameters, J_{eq} is the moment of inertia of the WT, (where $J_{eq} = J_g + J_\omega / n_g^{\,2}$ with n_g is the gearbox ratio) B_m is the damping coefficient of the turbine, $T_{\omega,g}$ is the aerodynamic torque (defined as: $T_{\omega,g} = T_\omega / n_g$) and ω_g is the mechanical speed of the generator.

Fig. 3 shows the block diagram of the mechanical system based on (6) and (7). The model requires as an input, the mechanical torque extracted from the wind, as seen in Fig. 3.

D. *Modeling of the speed controller*

Fig. 4 shows the speed controller of the WT. Such controller sets the *q*-current reference by using a PI. The proportional constant of the controller is $K_{p\omega}$ and the integral constant is $K_{i\omega}$.

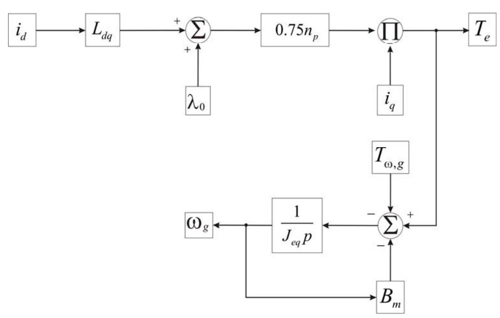

Figure 3. Schematic diagram of the mechanical system

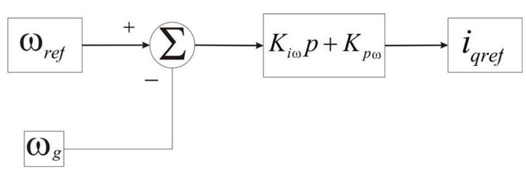

Figure 4. Schematic diagram of the speed controller

E. *Modeling of the pitch angle controller*

The pitch angle controller modifies the power coefficient (*Cp*) of the turbine which in turn affects the active power produced by the WT. Under low wind speed conditions, the pitch angle control is seldom activated; instead it remains fixed for an optimum value of *Cp*. Under high wind speed conditions the pitch angle controller limits the amount of energy extracted from the wind avoiding the overload of the PMSG. A schematic of the pitch angle controller is shown in Fig. 5.

This controller requires as an input the actual active power, *Pe,* generated, which is calculated as:

$$Pe = (i_d u_d) + (i_q u_q) \tag{8}$$

where *ud* and *uq* are the *dq* voltages coming from the current control model, *id* and *iq* are the *dq* currents of the PMSG. The active power calculation subsystem is shown in Fig. 6.

The pitch angle controller uses the nominal wind speed ω_{wnom} variable and the nominal active power reference *Peref* variable to the wind speed and active power values that will activate the pitch angle controller. A higher than nominal wind speed modifies the angle θ of the blades, the higher the winds the larger θ must become. Because of the past, the block MAX used in the diagram makes sure that the current winds peed is larger than ω_{wnom} before activating the pitch angle controller.

F. *Wind turbine Model*

The wind turbine model is taken from the *Simulink SimPower Systems* library. Such model requires the input variables wind speed, pitch angle and rotor speed to be in PU quantities, because of that, the block *convPU* is used to turn the input variables in PU. The mechanical torque produced by the wind turbine model is also given in PU so a block named *convSI* is used to convert the PU quantities to SI values. A schematic diagram of the wind turbine subsystem is shown in Fig. 7.

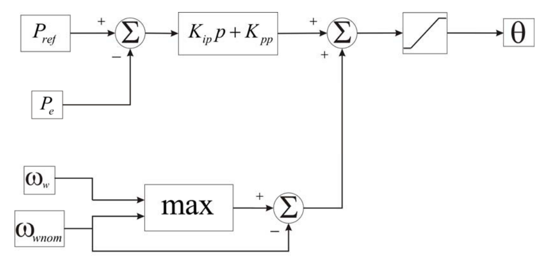

Figure 5. Schematic diagram of the pitch angle controller

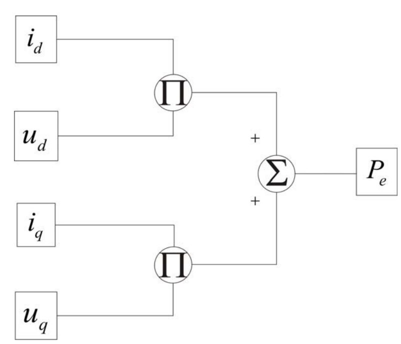

Figure 6. The active power calculation subsystem

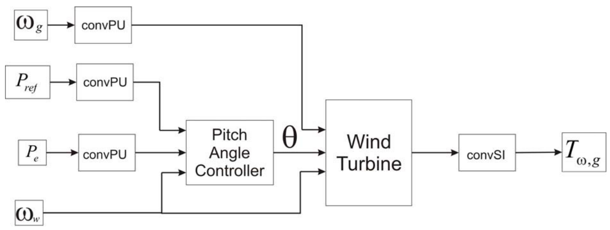

Figure 7. Schematic diagram of the wind turbine subsystem

G. *Full model integration*

The subsystems previously presented are interconnected to realize the full model of the WT as shown in Fig. 8.

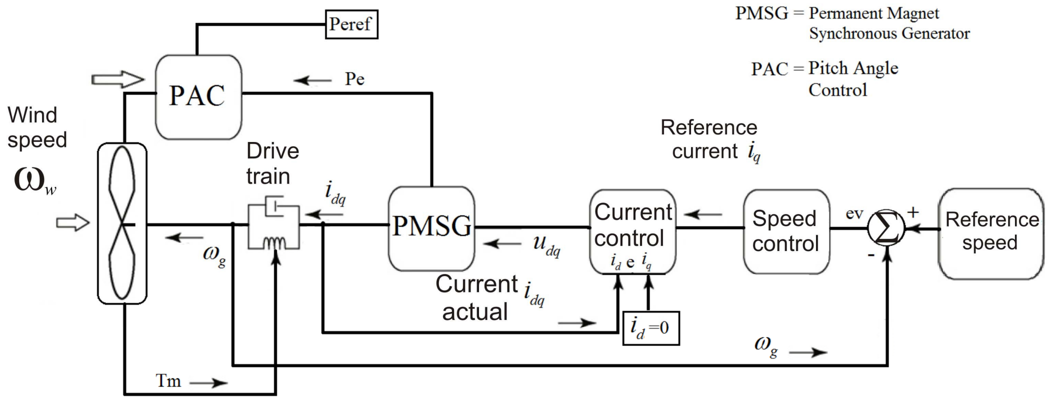

Figure 8. Schematic diagram of PMSG WT model

The generator speed controller in Fig. 8 requires has an input the difference between the reference and the actual generator speed and provides the i_q required by the current controller. The current controller also requires a i_d reference which is usually set to zero. The PMSG model uses the voltages produced by the current controllers to generate the real *dq* currents of the machine, which in turn are used to calculate T_e inside the mechanical subsystem. The T_e produced by the PMSG, along with the $T_{\omega,g}$ produced by the turbine are used to determine ω_g , which finally is fed to the speed controller.

III. SIMULATIONS

In order to evaluate the performance of the developed model, several simulations in both steady state and transient operation conditions are carried out. The parameters of the model are considered to be constant and time-invariant.

A. Change of rotor speed reference value

On this simulation, the ω_g reference of the controller is changed from 100 rad/s to 130 rad/s in the second 20. Fig. 9 shows the behavior of the PMSG rotor speed during the change of rotor speed reference value.

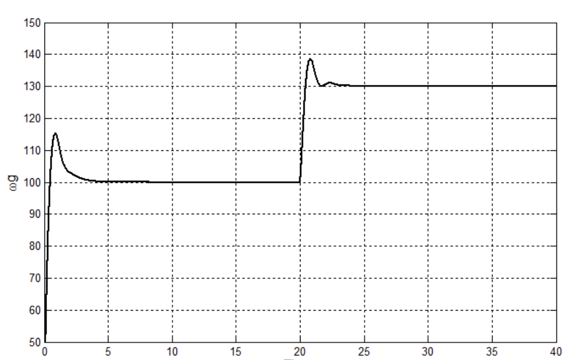

Figure 9. Generator speed behavior during a generator speed reference variation

The change of the rotor speed reference value does not have an effect in the pitch angle of the turbine blades because the wind speed remained in a value below the activation level of the pitch angle controller during the simulation time. The behavior of T_e , T_m , *ud*, *uq*, i_q and i_{qref} are shown in Figs. 10-12.

B. Wind speed variation

In order to test the performance of the pitch angle controller, on this simulation the wind speed is changed from 10 m/s to 14m/s at the second 15 and from 14 m/s to 13 m/s at second 30 as shown in Fig. 13. The rotor speed reference is kept constant at 150 rad/s during the simulation.

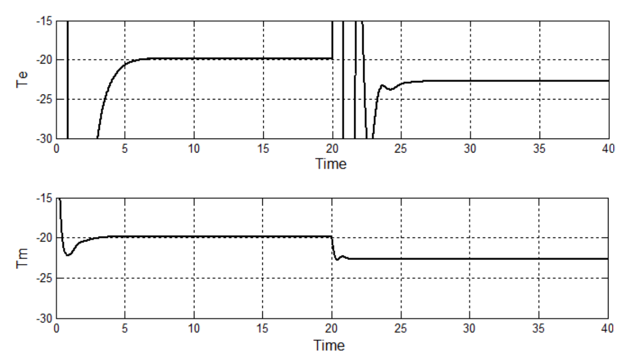

Figure 10. Electric and mechanical torque behavior during a generator speed reference variation

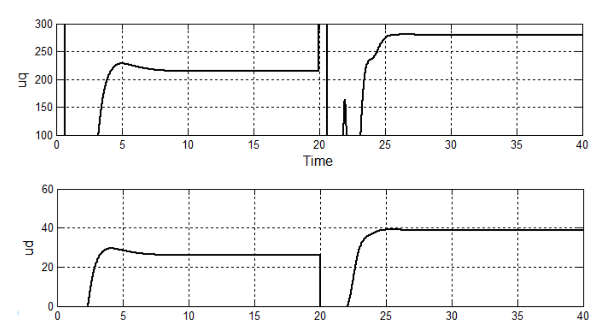

Figure 11. dq voltages behavior during a generator speed reference variation

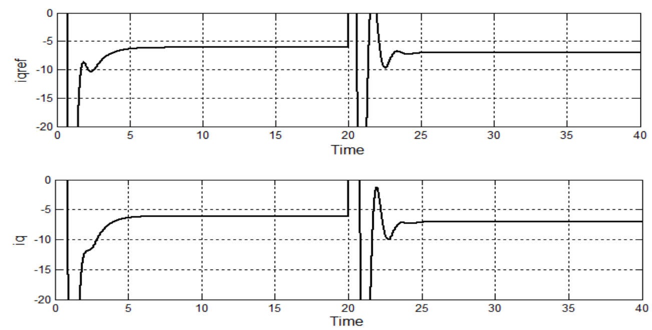

Figure 12. iqref and iq behavior during a generator speed reference variation

As seen in Fig. 14, the angle θ changes from a zero value when the wind speed exceeds the nominal wind speed value of the pitch angle controller, in this way the PMSG is protected from higher-than-nominal T_m product of the high wind speeds. Because of the past, ω_g remains constant during the wind gust, following its reference. The behavior of T_e, T_m, ud, uq, i_q and i_{qref} are shown in Figs. 15-17.

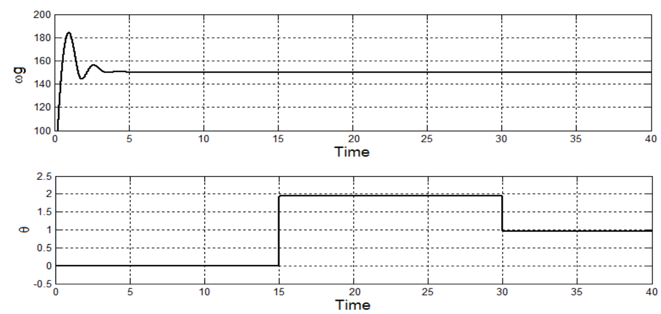

Figure 14. Generator speed and angle θ behavior during wind speed variations

IV. CONCLUSION

The results presented show that the speed and the pitch angle controller of the PMSG developed in this investigation produce satisfactory control actions and can be used to control a PMSG WT. The excessive power generated by the wind gusts was effectively balanced by the controllers, avoiding the overload of the generator. The time constants of the PI controllers must be chosen in order to avoid excessive control actions and unwanted current peaks, balancing between speed of response and the overshot of the control signals.

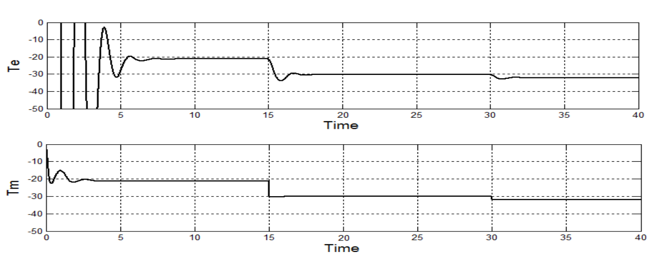

Figure 15. Electric and mechanical torque behavior during wind speed variations

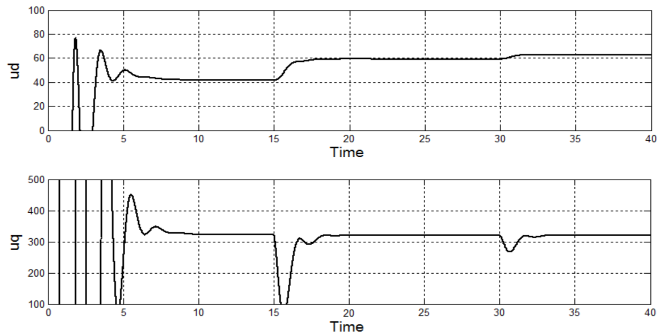

Figure 16. dq voltages behavior during wind speed variations

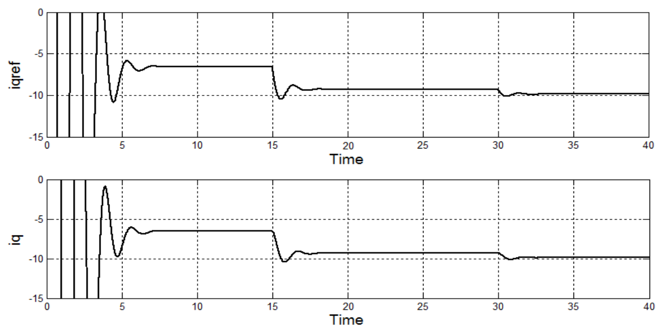

Figure 17. iqref and iq behavior during wind speed variations

V. APPENDIX

The parameters of the PMSG used in the paper are listed below:

Rated power: $6000W$
Generator reference speed: $153 rad/s$
Rated electrical torque: $40 N.m$
Permanent magnet flux: $0.433 Wb$
Number of pole pairs: 10
Rotational damping: 0
Equivalent inertia: $7.856 Kg.m^2$
Inductance: $8.5x10^{-3} H$
Armature resistance: 0.425Ω
Synchronous resistance: 0.45Ω

The parameters for the Control are:

$K_{p\omega} = 10$

$K_{i\omega} = 10$

$K_{pp} = 0.1$

$K_{ip} = 1000$

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