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A Simplified Model for Dynamic Behavior of Permanent Magnet Synchronous Generator for Direct Drive Wind Turbines

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***Abstract*-- In this paper, a simplified model to represent variable speed wind turbines in power system dynamics simulations is presented. This model is based in the use of controls-oriented model for permanent magnet synchronous generator supplying voltage-stiff bus system, including intrinsic torque/load properties. First, the modeling approach is commented upon and models of the subsystems of which a variable speed wind turbine consists are discussed. Then, time-domain simulations have been performed for one study case in order to demonstrate the suitable use of the model proposed in this paper. Results have shown that the model developed performs satisfactorily for slow dynamic when compared with the results obtained from simulation considering the detailed model.**

***Index Terms*—Direct drive, modeling, permanent magnet synchronous generator, power system dynamics, simulation, variable speed wind turbine.**

I. INTRODUCTION

IN the early 1990s most installed wind turbines operated at fixed speed; regardless of wind speed [1]. The turbine's rotor speed is fixed at a speed determined by the nominal frequency of the power grid that the turbine is connected to. The gear ratio and generator design allow the rotor to operate at this fixed speed for variable wind speeds [2]. A wind turbine with a generator operating at variable speeds connected to the grid via a full-scale frequency converter (see Fig. 1) is superior to these fixed speed designs as it provides reactive power compensation and a smoother grid connection.

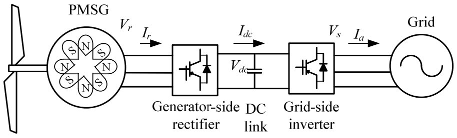

Fig. 1. General structure of a variable-speed wind turbine with a direct-drive synchronous generator with full-scale frequency converter.

The full variable-speed wind turbine system has no gearbox and a directly driven multi-pole generator with a large diameter is used [1], [3]. The use of the direct drive permanent-magnet synchronous generator (PMSG) for variable speed operation also provide economies by removing the need for special synchronism equipment and damping; both of which have been found to be difficult and costly to implement [4].

This paper presents a simplified model for the representation of variable speed wind turbines suitable for the analysis of slow dynamic in power system. This model has been developed to facilitate the investigation of the impact of high penetration levels of wind power on the slow dynamic behavior of electrical power systems. The main contribution of this paper is the development of a model of the PMSG that incorporates the control of the voltage regulation characteristic and torque/load properties. The shaft torque is represented as a quadratic function of the current in the DC link, this assumption make the model suitable for dynamic that not involve large exclusion in the rotor speed. This is a basic model that avoids the use of the classical flux linkage equations. It thus provides a fast way to simulate PMSG, with all of the necessary parameters being obtained easily from experimental results of steady-state tests.

The paper is organized as follows. Section II describes the mathematical model of the direct drive PMSG. Section III presents the results of time-domain simulations that confirm the validity of the proposed model for slow dynamic and demonstrate the suitable use of the model proposed in this paper. Finally, the advantages of this novel model are discussed in Section IV.

II. WIND TURBINE MODEL

Fig. 2 depict the general structure of a model of a variable-speed wind turbine with a direct-drive synchronous generator. Various subsystems of a variable-speed wind turbine with PMSG are modeled [1], [3], [5], [6].

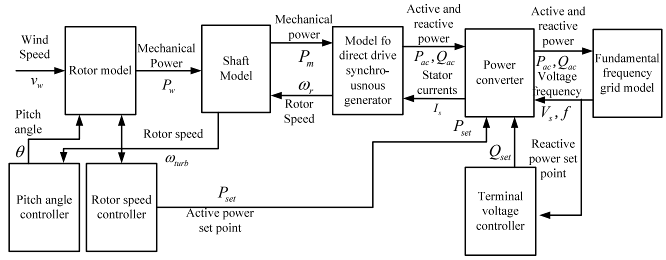

Fig. 2. General structure of a model of a variable-speed wind turbine with a direct-drive synchronous generator.

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A. Wind Speed

This model is used to generate a wind speed sequence in form of a time series to simulate wind model on the location of the wind turbine and its values are applied to the rotor, $v_w(t)$.

B. Rotor Model

The aerodynamic equation of a wind turbine that relates mechanical power (P_t) to wind speed (v_w) and mechanical speed of the turbine (ω_t) is given by [1]:

$$P_t = C_p\left(\lambda,\beta\right)\frac{\rho}{2}\pi R^2 v_w^3 \tag{1}$$

where is ρ the air density, R is the rotor radius, C_p is the power coefficient as a function of the blade pitch angle (β) and the tip speed (λ) which is calculated by [7]:

$$\lambda = \frac{\omega_t R}{v_w} \tag{2}$$

A quasistatic approach is used to describe the rotor of the wind turbine. In this case Instead of applying a functional or polynomial approximation to C_p a more cumbersome but direct approach by simply using a $C_p(\lambda,\beta)$ table [1], [8]. The value of C_p is specified for a number of combinations of λ and β values, then the values of C_p can be organized in a λ-β matrix. An interpolation-extrapolation method is applied between the λ-β nodes in this matrix. Fig. 3 show several curves for the power coefficient versus tip speed ratio, considering different pith angles, the detailed values of the matrix are shown in the appendix.

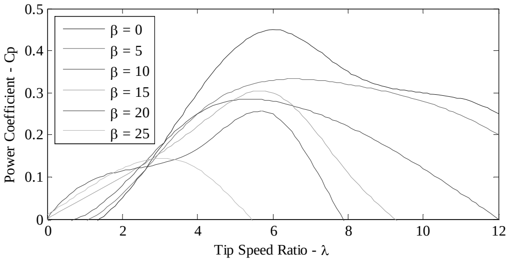


Fig. 3. Power coefficient (C_p) as function of tip-speed ratio (λ), considering several pitch angles (β).

C. Blade Angle controller

Blade pitch control is primarily used to limit the aerodynamic power (P_{wind}) above rated wind speed in order to keep the turbine shaft torque within its design limits. During the higher wind speed the torque or power can easily be limited to its rated value by adjusting the pitch angle β. However, in the variable-speed turbines, the design used for direct drive with PMSG, the pitch angle may be varied over a range of values for maximizing energy capture in light winds [7]. In this case, the active power is regulated according to the maximum power tracking (MPT) characteristic that define the maximum power depending on the shaft speed as power reference of the power controller. This ensures that the rotor can extract the maximum available power from the prevailing wind speed [9]. Fig. 4 shows the relationship between the rotor speed and power to arrive a set point for generated power.

The pitch angle is kept constant below rated wind speed at a value that maximizes the conversion efficiency then the blade angle control can be used to shed the aerodynamic power generated by the wind turbine [1], [8], [10].

The pitch actuator is a nonlinear servo that generally rotates all the blades – or part of them – in unison. In closed loop the pitch actuator can be modeled as a first-order dynamic system with saturation in the amplitude and derivative of the output signal [11].

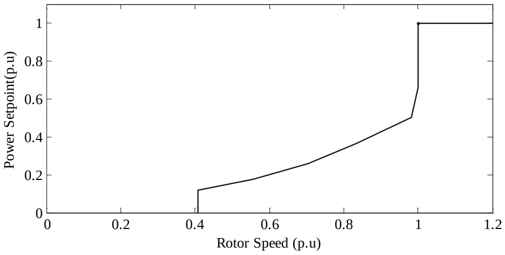


Fig. 4. Optimal Power-rotor Speed characteristic used for the variable speed wind turbine.

Fig. 5 shows the simplified block diagram of the blade angle controller and servomechanism.

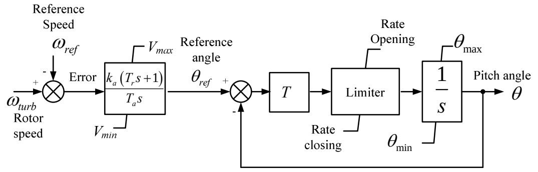


Fig. 5. Simplified Block Diagram for Blade Angle Control.

D. Shaft Model

When the impact of wind fluctuations is evaluated usually sufficient consider the simple-mass shaft model [12], [13]. During severe disturbances in the power system the shaft must be approximated by at least the two mass model, this is the typical case in stability analysis [14], [15].

One mass is used to represent the turbine inertia, the other mass is equivalent to the generator inertia [13]. The two-mass representation is described by the following equations [14]:

$$\begin{aligned}
&\frac{d\omega_m}{dt} = \frac{T_m - T_e}{J_m} \\
&\frac{d\omega_{turb}}{dt} = \frac{T_{turb} - K_s\gamma}{J_{turb}} \\
&\frac{d\gamma}{dt} = \left(\omega_{turb} - \omega_m\right) \\
&T_m = K_s\gamma - D_{turb}\left(\omega_{turb} - \omega_m\right)
\end{aligned} \tag{3}$$

where T is the torque; γ is the angular displacement between the two ends of the shaft; J is the inertia; and K_s is the shaft stiffness. The subscripts r, m and e stand for wind turbine rotor, generator mechanical and generator electrical, respectively.

E. Generator Model

1) Full Detail Model

The electrical equations of a PMSG in the *d-q* (direct-quadrative) reference frame can be found in the literature [15], [16]. A second state-space model is used to representing the electrical and mechanical parts of the machine and is as follows:

$$\frac{di_d}{dt} = \frac{1}{L_d} v_d - \frac{R}{L_d} i_d + \frac{L_q}{L_d} p\omega_r i_q$$
$$\frac{di_q}{dt} = \frac{1}{L_q} v_q - \frac{R}{L_q} i_q + \frac{L_d}{L_q} p\omega_r i_d - \frac{\lambda p\omega_r}{L_d} \tag{4}$$
$$T_e = \frac{3}{2} p\left[\lambda i_q + \left(L_d - L_q\right) i_d i_q\right]$$

where L is inductance, R is the resistance of the stator windings, i is current and v voltage. The subscripts d and q stand direct and quadrative axis respectively. The amplitude of the flux induced by the permanent magnets of the rotor in the stator phases is represented by λ and p is the number of pole pairs. The sinusoidal model assumes that the flux established by the permanent magnets in the stator is sinusoidal, which implies that the electromotive forces are sinusoidal.

The dynamic of the mechanical system is described by:

$$\frac{d\omega_r}{dt} = \frac{1}{J_g}\left(T_m - F\omega_r - T_e\right)$$
$$\frac{d\theta_r}{dt} = \omega_r \tag{5}$$

where J_g is the inertia of the rotor, F the viscous friction of rotor, θ_r the angular position and T_m is the shaft mechanical torque.

2) *Enercon Concept*

The most common concept for the direct drive wind-generator is the Enercon-concept using a salient pole, electrically excited synchronous generator [13], [17]. The synchronous machine model used for the power system analysis is electrically excited (e_{fd}) using and Automatic Voltage regulator (AVR); this approach is used by Enercon concept. The PMSG can be modeled with the well known *d-q* frame model for the synchronous machine [15], [16], [18], by keeping the excitation current (i_{fd}) to a constant value ($i_{fd,ref}$) [13]. The AVR used to fed the field winding of the synchronous generator under the Enercon-concept is depicted on Fig. 6Fig. 6.

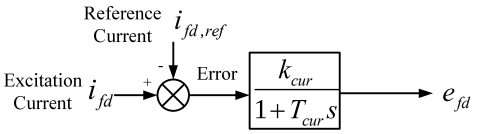


Fig. 6. AVR of constant current (i_{fd}).

3) *Proposed model*

The variable speed operation of wind turbines using direct drive synchronous generator is based on a synchronous machine with a high number pairs of poles and the use frequency converter to connect it into the grid. The number of possibilities realizing of frequency converters used for wind power applications is almost infinite [19]. The frequency-converter with generator-side diode-rectifier and grid-side pulse-width modulated (PWM) is the widest spread concept nowadays (see Fig. 7). The goal of the work is to develop a simplified model of one of the PMSG [4], [20]. In this way, generator-side converter is based on diode-rectifier which in turn supplies power to another converter, the grid-side inverter, that supplies constant-voltage, constant frequency power (Fig. 8) [4], [21].

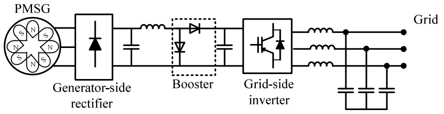


Fig. 7. Frequency converter with generator-side diode rectifier and grid-side PWM converter.

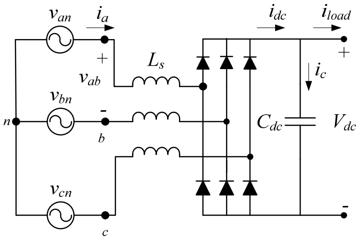


Fig. 8. Variable Speed PMSG Source for DC Link equivalent circuit.

Considering an ideal (unloaded and loss-less) PMSG, the line-line voltage V_{ab} (rms volts), can be found as [4], [21]:

$$V_{ab} = K_V \omega_e sen\left(\omega_e t\right) \tag{6}$$

where K_V is the voltage constant, and ω_e is the electrical frequency. Then, a PMSG operating at variable speed that is directly connected to a Full-Wave Diode Bridge Rectifier (FWBD) is a problem which can be addressed as the widely recognize modeling problem of a diode bridge with a constant voltage source [22].

The PMSG system shown in Fig. 8 has been found experimentally [21] that follow a nearly lineal voltage regulation curve, then the bus voltage with constant output [21], [23], [22], it can be written as:

$$V_{dc} = K_e \omega_m - K_x \omega_m I_{dc} \tag{7}$$

where I_{dc} is the average rectified PMSG current and the consntand in the model are defined as:

$$K_e = \frac{3pK_V}{2\pi}$$
$$K_x = \frac{3pL_s}{2\pi}$$

An equivalent circuit for the ideal PMSG with FWBD can be derived from (7) considering a model based on a voltage source being a variable resistance and it is depicted in Fig. 9.

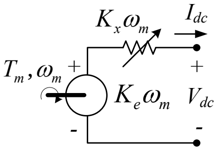


Fig. 9. Equivalent circuit model of the PMSG with FWBD.

All variables involved in the equivalent circuit model vary with the speed (ω_m). It is evident from the model that the open-circuit voltage (V_{oc}) of the combination PMSG and FWBD is giben by:

$$V_{oc} = K_e \omega_m \tag{8}$$

It is important noting on the Fig. 9 the equivalent resistance varies with speed buy the term $K_e\omega_m$ dissipate power and it represents the voltage regulation slope into model.

The electrical power output (P_{dc})for loss-less PMSG with

FWBD is calculated as a function of the average rectified current:

$$P_{dc} = V_{dc} I_{dc} = K_e \omega_m I_{dc} - K_x \omega_m I_{dc}^2 \qquad (9)$$

The electro-mechanical torque, T_e, (loss-less operation) can be calculated by the following quadratic function of I_{dc}:

$$T_e = \frac{P_{dc}}{\omega_m} = K_e I_{dc} - K_x I_{dc}^2 \qquad (10)$$

The torque reaches a maximum ($T_{e,max}$) when $V_{dc} = V_{oc}/2$, as:

$$T_{e,\max} = \frac{K_e^2}{4K_x} \qquad (11)$$

This value represents the maximum shaft torque than be applied back to the prime mover, it is the same torque value regardless of the rotor speed, and it is the torque limit.

The dynamic model should include the electro-mechanicals interactions of the PMSG with FWBD. One important aspect to be included is the dynamic behavior of the DC bus capacitor (V_{dc}), the model is depicted on Fig. 10.

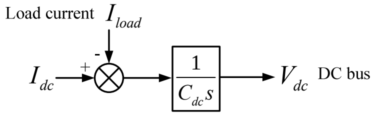


Fig. 10. Model of the Capacitor voltage dynamic.

On the other hand, the electromechanical dynamic of the PMSG can be described using the classic swing equation, which define the relationship between the between electrical frequency and mechanical speed:

$$\frac{d\omega_m}{dt} = \frac{1}{J_g}\left(T_m - T_e\right) \qquad (12)$$

with J_g the inertia constant of the rotor and T_m and T_e are the mechanical and electrical torque respectively, and the electrical frequency is calculated by:

$$\omega_e = p\omega_m \qquad (13)$$

where p is the number of pair of poles.

Finally the dynamic model of the rectified and DC bus is built considering the capacitor voltage (V_{dc}) as the state-variable in the model. The controllable quantities, such as the torque of the prime mover, the shaft speed [21], [20], [4], are related to physical quantities of the DC link the dynamic, it is shown in Fig. 11.

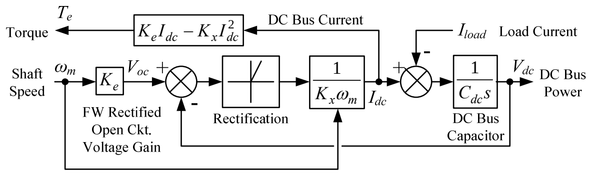


Fig. 11. Non Linear State Block Diagram of Ideal (Loss-Less) PGM and DC Bus Model.

F. Converter Model

Low-speed gearless wind turbine generators use a PMSG that has a high number of poles connected to an intermediate DC-circuit by a diode rectifier. The grid-side connection is realized by a self-commuted PWM converter that imposes a pulse-width modulated voltage to the AC-terminal.

This paper is focused on the power system stability so the centre of interest is on the control behavior of PWM-converter instead of switching frequencies, or high frequencies phenomenon. For this reason, the equivalent to the fundamental frequency models is used to PWM converter which operated in a stator-voltage oriented refernce frame. Hence, d-axis represents the active and q-axis the reactive component.

The line-line AC voltage (rms value, $U_{AC} = U_{AC,d} + jU_{AC,q}$) and DC voltage ($U_{dc}$) are related by:

$$\begin{aligned} U_{AC,d} &= \frac{\sqrt{3}}{2\sqrt{2}} m_d V_{dc} \\ U_{AC,q} &= \frac{\sqrt{3}}{2\sqrt{2}} m_q V_{dc} \end{aligned} \qquad (14)$$

where m_d and m_q are the real and imaginary part of the modulation index. Proportional integral (PI) control loop regulates the d and q-axis current components (I_d, I_q) based on a PI controller regulating the active and reactive power (P, Q), these are shown in Fig. 12.

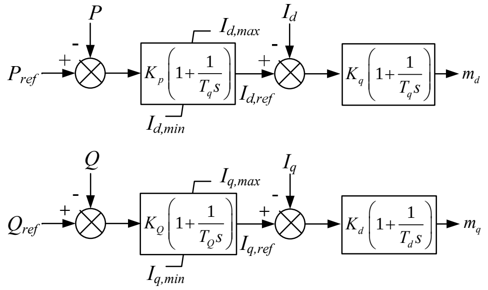


Fig. 12. Grid-side current controllers.

The active power reference (P_{ref}) is defined from the MPT-characteristic discussed in previous section.

III. SIMULATION AND RESULTS

A. Generator Parameters

The controls-oriented model for PMSG proposed in this paper is characterized by K_e and K_x constants. These constants are determined from the steady-state voltage regulation for different speed (ω_r). The main data of a real PMSG is presented in the Table I (complete set of parameters are shown in Appendix).

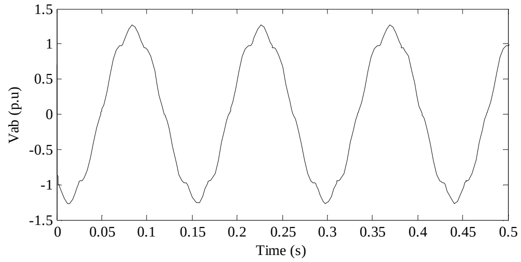
TABLE I
CHARACTERISTICS OF PMSG SIMULATED

Characteristic	*Variable*	*Value*
Rated Power	P_{PMSG}	1.5 MW
Rated Speed	ω_{PMSG}	18 rpm
Number of Poles	pf	80
Rated Voltage	U_n	3300 V
Inertia constant H	H_{gen}	0.91 s

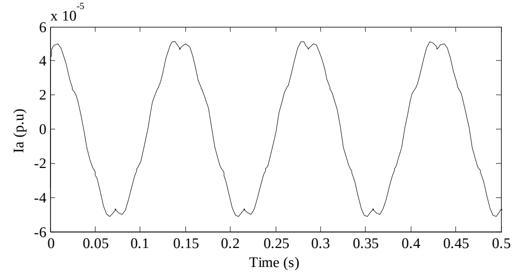
This generator was tested using a MATLAB® program integrated into a SIMULINK® model. The PMSG with FWDB is operated at constant speed; Fig. 13 and Fig. 14 show the terminal waveform for no-load and heavy-load conditions.

Fig 13a show the line-line voltage of the PMSG at no-load, this waveform display some content of harmonic. For heavy-load conditions the diode commutation of the phase current Fig. 14b, produce a heavy content of harmonic. This time-domain simulations show the complex waveform of the

PMSG with FWDB and demonstrate the inconvenience of the use the full detailed model for power system stability analysis.

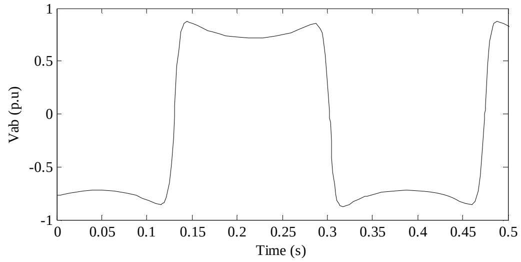


(a) Line-line voltage

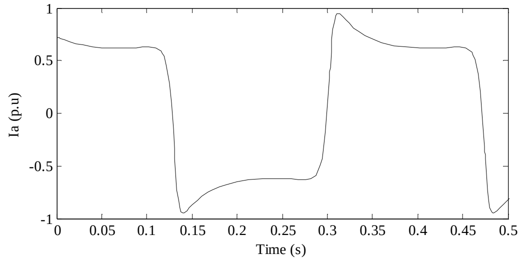


(b) Phase current

Fig. 13. No-load voltage phase-phase and phase current, 18 rpm.



(a) Line-line voltage



(b) Phase current

Fig. 14. Heavy-load voltage phase-phase and phase current, 18 rpm.

The full model was tested under steady-state, constant-speed conditions; and the voltage regulation of the DC bus was tested under various load conditions. Fig 15 plot the actual values obtained from the test and ideal voltage regulation using the model described in this paper.

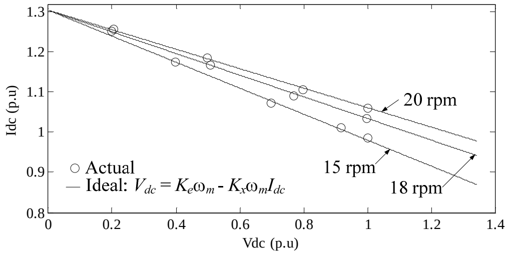
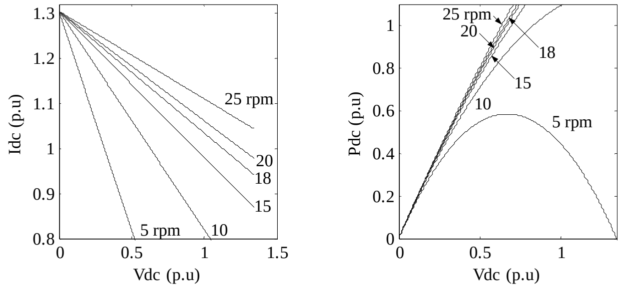


Fig. 15. PMSG voltage regulation for several speeds.

A basic fitting function has been used to find the coefficients (K_e and K_x) of the polynomial function $V_{dc}(I_{dc})$ that fits the data obtained from the tests, the least squares method has been used to obtain K_e = 8.5944x10^3 and K_x = 13.372.

The constant speed voltage regulation curves are plotted (Fig 16a) and power properties versus voltage for several constants speed (Fig 16b) has been plotted (loss-less operation).



(a) Constant speed voltage regulation curves.

(b) PMSG Shaft Torque as a function of V_{dc}.

Fig. 16. Characteristic curves for the PMSG with FWDB.

B. Network Parameters

The simple portion of transmission/distribution system depicted in Fig. 17 is used for the evaluation of the dynamic behavior of the model proposed in this paper. An equivalent of 30x1.5MW direct drive wind turbine using PMSG is connected on the bus WTGen.

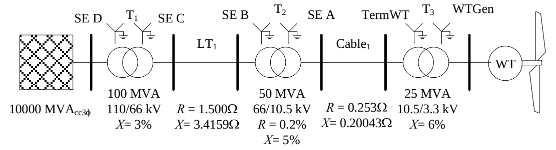


Fig. 17. Test system.

C. Results

A measured wind speed sequence (Fig. 18) which can be found in the literature[1], [3] and whose results have been clearly demonstrated is used to evaluate the correct performance of the model presented in this paper.

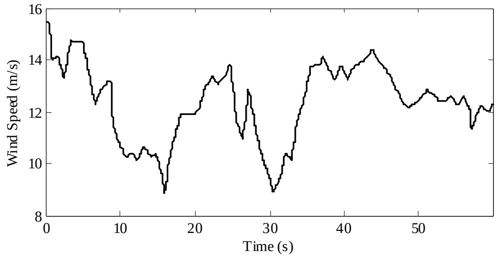


Fig. 18. Measured wind speed sequence [1].

The simulated rotor speed, terminal voltage, and the output power are depicted on Fig 19. Simulation results obtained from the proposed model have been compared with results the dynamic behavior of full model, it is clear that every single variable exhibit satisfactory correspondence.

In general terms, the dynamic behavior of the terminal voltage exhibit the same behavior in both models, however, a little difference is evident, and the AC voltage produced by the proposed model is below of those obtained from the full model. The reactive power has adjusted to constant power factor, unity, at connection busbar. The wind speed time-series used to test the proposed model is lower than the nominal rotor speed, for this reason, the active power production is below the nominal power. The rotor speed of the proposed model exhibits high variability; it is especially true during large changes of the wind speed.

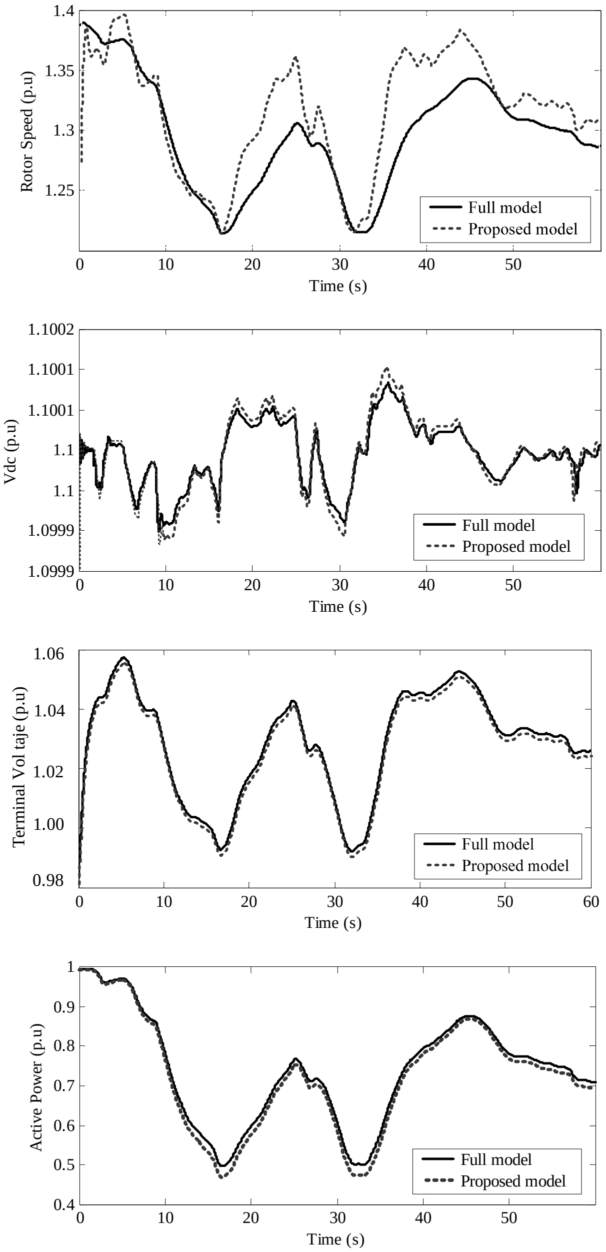


Fig. 19. Simulated results.

Dynamic behavior in both models exhibit some differences in terms of peaks but the overall behavior is pretty good considering that the model only considers a differential equation instead of the five equations used in the detailed model.

IV. CONCLUSIONS

A simplified model for representing variable-speed wind turbines with PMSG directly driven for the simulation of slow dynamic of power system dynamics is presented. Models of the subsystems of the variable speed wind turbine have been presented in this paper with its practical values. The main contribution of this paper is the development of a model of the PMSG that incorporates the control of the voltage regulation characteristic and torque/load properties. This model avoids the use of the classical flux linkage equations and its complexity. It thus provides a fast way to simulate PMSG, with all of the necessary parameters being obtained easily from experimental results of steady-state tests.

Time-domain simulations have been performed for one study case in order to demonstrate the suitable use of the model proposed in this paper. The model has been tested using a short-term wind speed time-series, results of this simulation allow evaluate slow dynamic of the model. Results of this show that the developed model performs satisfactorily when compared with the results achieved with the detailed model.

Initial results demonstrate the suitable use the model for slow dynamic as power quality assessment as consequences of short-time variations of the wind speed.

Further evaluations on the dynamic behavior of the model proposed should be done, it include the effect of turbulence on the power quality, and an assessment of large disturbances. Short circuit is a challenge to be considered, although the DC capacitor must provide a fast response and the grid-side converter as well, PMSG capacity to sustain fault currents is compromised, fault current produces a demagnetizing effect on the generator, at first glance effect is not directly considered in the model presented in this paper.

V. APPENDIX

TABLE A.1
TABLE REPRESENTATION OF THE WIND TURBINE (λ-β MATRIX)

		Tip Speed ratio (λ)						
		0	2	4	6	8	10	12
β	0	0.00	0.05	0.3	0.45	0.35	0.30	0.25
	5	0.00	0.06	0.25	0.33	0.32	0.28	0.20
	10	0.00	0.08	0.25	0.28	0.22	0.12	0.00
	15	0.00	0.10	0.22	0.30	0.11	-0.05	-0.20
	25	0.01	0.12	0.12	-0.05	-0.20	-0.50	-0.70

TABLE A.2
CHARACTERISTICS FOR ROTOR MODEL OF WIND TURBINE SIMULATED

Rotor Characteristic	*Value*
Minimal Rotor Speed	9 rpm
Rated Rotor Speed	18 rpm
Rotor Diameter	60m
Rotor swept area	2827 m^2
Rated wind speed	14 m/s
Inertia constant	0.72 s

TABLE A.3
CHARACTERISTICS OF SHAFT SIMULATED

Shaft Characteristic	*Variable*	*Value*
Rated Power	Ps_{haft}	1.5 MW
Rated Speed	ω_n	18 rpm
Turbine Damping	D_{turb}	14×10^{6} Nms/rad
Rotor Inertia	J_{turb}	6.1×10^{6} Kg mm
Shaft Stiffness	K_s	83×10^{6} Nm/rad

TABLE A.4
CHARACTERISTICS OF PITCH ANGLE CONTROLLER SIMULATED

Characteristic	*Variable*	*Value*
Blade angle controller gain	k_a	100 deg/p.u
Lead time constant	T_r	5
Speed reference	ω_{ref}	1.25 p.u
Servo time constant	T	0.5 s
Closing rate of change limit	Rate Closing	-15 deg/s
Opening rate of change limit	Rate closing	15 deg/s
	V_{min}	0
	V_{max}	70
Min. Blade angle	β_{min}	0 deg
Max. Blade angle	β_{max}	70 deg

TABLE A.5
CHARACTERISTICS OF PMSG

Characteristic	*Variable*	*Value*
Startor Resistance	R_s	1.7850 Ω
d-axis inductance	L_d	8.5mH
q-axis inductance	L_q	8.5 mH
Magnet Flux Linkage	λ_{fd}	0.57 V.s
Inertia	J_{gen}	8.5×10^6 Nm/rad
d-axis subtransient reactance	X''_d	0.17 p.u
q-axis subtransient reactance	X''_q	0.17 p.u
d-axis subtransient time constant	T''_{d0}	0.02 s
q-axis subtransient time constant	T''_{q0}	0.05 s

VI. BIOGRAPHIES

Francisco M. González-Longatt (S'01, M'03, SM' 2009) was born in Cagua-Venezuela, on July 30, 1972. He graduated on Electrical Engineering of Instituto Universitario Politécnico de la Fuerza Armada Nacional, Venezuela (1994), and Master of Business Administration of Universidad Bicentenaria de Aragua, Venezuela (1999) and PhD of Universidad Central de Venezuela (2008). His main area of interest is the dynamic behavior of smartgrid with high penetration of renewable energy resources. He is former associate professor on Electrical engineering Department of Universidad Nacional Politécnico de la Fuerza Armada Nacional, Venezuela. He is currently a Post Doctoral Research Associate at School of Electrical and Electronic Engineering, The University of Manchester.

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