Dynamical Model of Variable Speed WECS: Attend of Simplification

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***Abstract*— In this paper, a simplified model that can be used 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 PMG supplying voltage-stiff buss 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, two study cases was simulated to remote area power installed in rural area on Venezuela: light and heavy load, and some results obtained by simulation of the dynamic behavior are shown in this paper.**

***Index terms*— Modeling, power system dynamics, simulation, variable speed wind turbine.**

I. Introduction

As result of increasing environmental concern, the impact of conventional electricity generation on the environment is being minimized and efforts are made to generate electricity from renewable sources. The main advantages of electricity generation from renewable sources are the absence of harmful emissions and the infinite availability of the prime mover that is converted into electricity [1]. One way of generating electricity from renewable sources is to use wind turbines that convert the energy contained in flowing air into electricity.

The working principle of a wind turbine encompasses two conversion processes, which are carried out by its main components: the rotor, which extracts kinetic energy from the wind and converts it into a mechanical torque, and the generating system, which converts this torque into electricity. This general working principle is depicted in figure 2.4. Many wind turbine types are on the market, each of this system has its own benefits and drawbacks. Recently, the wind energy industry has shown keen interest in variable speed system. Variable-speed operation can be increase the energy capture, alleviate mechanical stresses and reduce aerodynamics noise, especially in light winds. The use of the direct drive permanent-magnet generator (PMG), variable speed operation also provide economies by removing the need for special synchronism equipment and for damping both of which have found to be difficult and costly to implement.

However, the directly driven generator needs damping, either with mechanical springs and dampers or preferably with an electrical damping, i.e. variable speed operation. With directly driven generators, which are optimized for low speed operation, the performance (efficiency, reliability) of the systems can be improved whilst the cost can be reduced. The design of the drive train is also greatly simplified compared with a conventional drive train with gears and a high-speed generator [2].

In this paper, presents a simplified model for representation of variable speed wind turbines in power system dynamics simulations. The model has been developed to facilitate the investigation of the impact of large amounts of wind turbines on the behavior of an electric power system. And the main contribution in this paper is the use of controls-oriented model for PMG supplying voltage-stiff buss system, including intrinsic torque/load properties. Two study cases was simulated, both to remote area power installed in rural area on Venezuela: light and heavy load. The remote network is penetrated different levels, and results of simulation of the dynamic behavior are shown in this paper.

II. Model Requirements

The goal of the work is to develop a simplified model to represent the one of most interesting variable-speed wind turbine concepts in power system dynamics simulations. This concept is variable-speed operation enabled through the use of directly driven, three-phase permanent magnet synchronous generator (PMSG) with a frequency converter.

Derived model can be used in power system dynamics simulations; it should be possible to easily integrate the developed model into power system. To make this possible indeed, a number of requirements have to be posed on the model, namely

- Detail level of the wind turbine model should be similar to the models of the other system components.
- The overall wind turbine model would be simple with a minimum parameter to be characterized.

The main idea is reduce the order of the model to decrease in computation time, because the number of differential equations is substantially reduced and because a larger time step can be used due to the neglect of small time constants.

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III. SUBSYSTEM MODELS

The wind power conversion system studied has the configuration shown in Fig. 1.

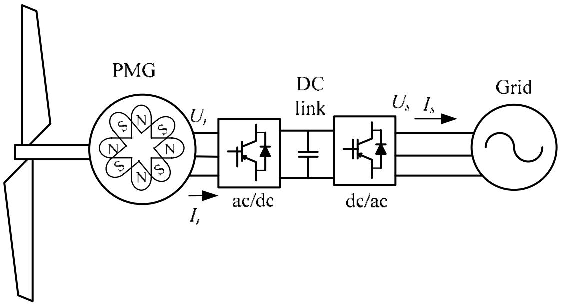

Fig. 1. PMG with DC link

The system consists, mainly, of a wind turbine, gearbox less, a high pole number modular PMG [1], [11], [14], [26], a modular rectifier system [28] and a controllable power electronics inverter [29], [26].

A. Subsystems

Various subsystems of a variable-speed wind turbine with PGM will be modeled, namely [1], [32]:

- A wind speed signal generator, used to generate the wind model on the location of the wind turbine. This signal is applied to the rotor.
- Rotor model for converting the kinetic energy contained in the wind into mechanical power that can be applied to the generator;
- Model of the generator and the converter, converting mechanical power into electric power and determining the rotor speed;
- Model of the pitch angle controller is used to simulate the changing of the blade pitch angle above nominal wind speed preventing the rotor speed from becoming too high;

B. Wind Speed Model

The wind speed model consists of a source that generates a wind speed signal to be applied to the wind turbine. The wind speed signal is a time dependent variable, from a time series in the form of a table from real measures.

C. Model of the Rotor

The wind turbine rotor that extracts the energy from the wind and converts it into mechanical power is a complex aerodynamic system and depends on many factors [3], [4], [5], [6]. The modeling of wind turbine rotor presents a difficult challenge. The state-of-art in rotor modeling is the blade element theory, however, a number of drawbacks [1]. A simplified way of modeling the wind turbine rotor is use a quasistatic rotor model, which assumes an algebraic relationship between the wind speed and the mechanical power extracted from the wind.

The mechanical power extracted from the smooth wind flow condition is calculated from the following equation (1) [7], [8].

$$P_w = \frac{\rho}{2} C_p(\lambda, \theta) A_r v_w^3 \qquad (1)$$

in which P_W is the mechanical power extracted from the airflow [W], ρ the air density [kg/m^3], C_p the performance coefficient or power coefficient, A_r the area swept by the rotor [m2], and λ the tip speed ratio:

$$\lambda = \frac{v_t}{v_w} \qquad (2)$$

Where v_t [m/s] is the blade tip speed and v_w [m/s] is the wind speed upstream the rotor. Fig. 2 show the block diagrams representation of this static characteristic (1), where θ [deg] is the pitch angle. This is caused by the fact that variable speed wind turbines are assumed to be equipped with a pitch angle controller, as is normally the case [1], [30], [31].

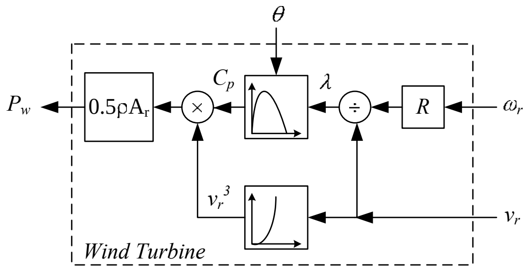

Fig. 2. Static Characteristic of Wind Turbine

The power coefficient, $C_p(\lambda,\theta)$ depends on the aerodynamics characteristic of wind turbine, as well as the operation conditions. For a variable pitch angle, the power coefficient can be expressed as a two dimensional characteristic. In this case, it is function of λ and θ [4], [6]. The rotor is modeled as a lumped mass and the shaft dynamics are neglected. It should be noted that this is only allowed when variable speed wind turbines are studied [1]. In variable speed wind turbines case, the shaft properties are hardly reflected at the grid connection due to the decoupling effect of the power electronic converter [9], [10].

D. Modeling of the Generator/Converter

A construction containing no gearbox offer several advantages, namely higher overall efficiency and reliability, reduced weight and diminished need for maintenance [11], [2], the present trend in wind power industry is to achieve such a construction. In order to produce a power frequency at such a low speed, a large number of magnetic poles are required [12].

With appropriate control, the generator and turbine speed can be adjusted as wind speed varies so that the optimum shaft/wind speed ratio is preserved and the maximum energy is collected. The PMG output varies in frequency and voltage. The output is then rectified to form a variable DC link witch sends power to the grid via an inverter [2], [11].

The wind turbines with a full-scale power converter between the generator and grid, which gives extra losses in the power conversion but it, will gain the added technical performance. Various power electronic interfaces may be used with permanent magnet wind power generators [16], [17], [18], [19]. PMG are used for the system shown in Fig.1, which are still becoming cheaper. This scheme has controllable characteristics since the generator is decoupled from the grid by a voltage-sourced dc-link [19]. Using the variable rotating speed system with a PMSG and AC-DC-AC link system, we achieve a high efficiency in the low wind-speed region and stable power output over the rated wind speed. The power converter to the grid enables a fast control of active and reactive power, and wind turbine systems behave like a power plant [20].

1) Generator

Permanent magnet machines are more efficient than the conventional synchronous machine and simpler because no exciter is needed. High energy permanent magnet material is expensive today and therefore this generator type will not yet be competitive in relation to standard synchronous generators. For low-speed gearless wind turbine generators the PMG is more competitive because it can have higher pole number than a conventional synchronous generator [21]. There are especially used in direct-drive wind turbines, which have the advantage that no gearbox is needed, which is favorable with respect to lifetime and maintenance [22].

Like other synchronous generators the AC output of the PMG is often converted into a DC link (using diode rectifiers), witch in turn supplies power to another converter, such as a inverter for supply constant-voltage, constant frequency power [10], [13], [14], [15]. This is displayed in Fig. 3.

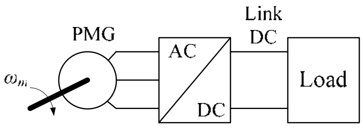

Fig. 3. Variable Speed PMG Source for DC Link

A typical PMG for low-speed gearless wind turbine application have reduced size and weight, and high pole number with small amount of saliency. Its is often modeled as a “voltage behind reactance” [23], and for reasons of simplify, efficiency, size and cost, the AC-DC interface between the PMG and the DC link is often accomplished with a simple, full-wave, diode bridge rectifier (FWBD), coupled directly to a DC bus capacitor (C_{dc}) as shown in Fig. 4. To generate a simplified model of the PMG with a FWDB, the system variables of speed, torque, DC bus voltage and DC bus current, are used to describe the dynamic behavior of the interaction between prime mover and the load.

For an ideal (unloaded and loss-less) PMG, the line-line voltage V_{LL} (rms volts), can be found as [11]:

$$V_{LL} = K_V \omega_e sen(\omega_e t) \left[\frac{rad}{seg} \right] \quad (3)$$

Where Kv is the voltage constant [V/(rad/s)], and ωe is the electrical frequency.

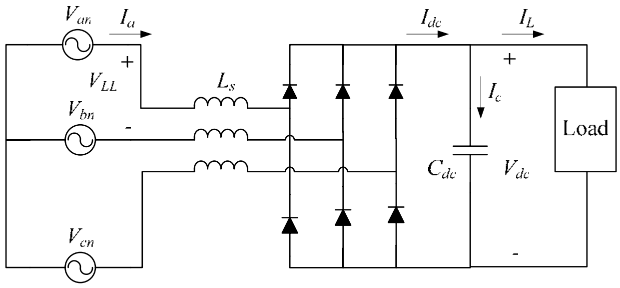

Fig. 4. FW Rectification into a stiff DC bus

The relationship between electrical frequency and mechanical speed is given by:

$$\omega_e = \omega_m \frac{p}{2} \left[\frac{rad}{seg} \right]$$

Where p is the number of poles in the PMG, and the mechanical angular velocity ω_m [rad/s] can be obtained from:

$$\frac{d\omega_m}{dt} = \frac{1}{J}\left(T_m - T_e\right) \quad (4)$$

With J the inertia constant of the rotor [kg-m^2] and T_m and T_e, the mechanical and electrical torque [Nm] respectively.

Bus voltage regulation is well understood for FWBR with constant output [24].

$$V_{dc} = \frac{3\sqrt{2}}{\pi} V_{LL} - \frac{3\omega_e L_s}{\pi} I_{dc} \left[\frac{rad}{seg} \right] \quad (5)$$

Combining (3), (4) and (5), result:

$$V_{dc} = K_e \omega_m - K_x \omega_m I_{dc} [V] \quad (6)$$

where:

$$K_e = \frac{3pK_V}{2\pi} \left[\frac{V}{rad/seg} \right] \quad (7)$$

$$K_x = \frac{3pL_s}{2\pi} \left[\frac{\Omega}{rad/seg} \right] \quad (8)$$

In (5), I_{dc} is the average rectified PMG current. The open circuit voltage of the PMG is found as:

$$V_{OC} = K_e \omega_m [V] \quad (9)$$

With this, an equivalent circuit model of the ideal PMG with FWDB can be constructed, and is shown below in Fig. 5.

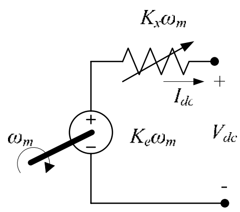

Fig. 5. Equivalent circuit model of the PMG with FWDB rectifier

For a given PMG, values of K_e and K_x, can be determined. Controllable quantities, such as the torque of the prime mover or the shaft speed [11], [14], can be relate to physical quantities of the dc link quantities by (10) y (11).

$$P_{dc} = V_{dc} I_{dc} = K_e \omega_m I_{dc} - K_x \omega_m I_{dc}^2 [W] \quad (10)$$

$$T_m = \frac{P_m}{\omega_m} = \frac{P_{dc}}{\omega_m} = K_e I_{dc} - K_x I_{dc}^2 \left[Nm\right] \qquad (11)$$

The dynamic model of the rectified PMG and DC bus capacitor is shown in Fig. 6, where capacitor voltage will be a fundamental state of the system.

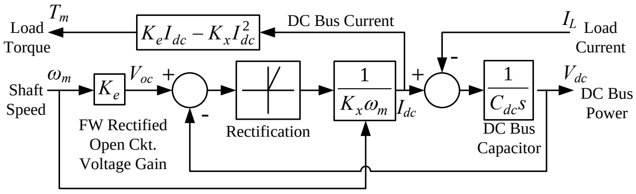

Fig.6. Non Linear State Block Diagram of Ideal (Loss-Less) PGM and DC Bus Model

2) Converter

The low-speed gearless wind turbine generators use a PMG that have high pole number connected to a three-phase rectifier followed by boost converter [25], [26], [27]. The boost converter may be use to control the electromagnet torque [6]. The supply side converter regulates de DC link voltage as well as control the input power factor. One drawback of this configuration is the use of diode rectifier that increases the current amplitude and distortion of the PMSG [27].

a) DC-DC converter

Many circuit topologies could be used for dc-dc conversion. Of the options available, a half bridge converter is the easiest to simulate. However, regardless of the topology, the same basic principle applies: dc-dc converters regulate the dc voltages of generator-rectifier units by varying the switching ratio (duty cycle), so that the optimum dc voltage profile [24]. Meanwhile an appropriate dc voltage is maintained at the dc bus to enable the voltage source inverters to perform the optimal real power transfer and reactive power regulation [26]. The simplified model of the dc-dc boost converter is shown in the Fig. 7 [34], [35], considering the inverter like a load.

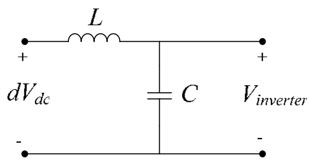

Fig. 7. Simplified model of dc-dc converter with filer

The control strategy used, maintain the dc bus voltage at a fixed set point. The load current make instantaneous jumps in value and the controller track these and adjust the duty cycle appropriately. The output voltage of the inverter determines the lower limited for the dc bus voltage. However, if vars are to be supplied by the inverter an over-voltage of least 5% is required [24].

b) Current-Controlled VSI

CC-VSIs can generate an ac current which follows a desired reference waveform and so can transfer the captured real power (P_s) along with controllable reactive power (Q_s) and with minimal harmonic pollution [24]. The real and reactive power supplied to the grid is:

$$P_s = V_s I_s \cos\phi[W] \qquad (12)$$

$$Q_s = V_s I_s sen\phi[VAR] \qquad (13)$$

Where V_s, I_s are the inverter ac voltage and current respectively (fundamental component, harmonics are neglected). With a given ac line voltage, P_s and Q_s can be controlled by regulating the magnitude of Is and the angle ϕ. The equation (12) and (13) are used to represent the CC-VSI for steady state analysis. Control of the inverter require a important conservation energy approach, that the inverter be the master, dictating the rate of load change, and the dc-dc converter be the slave. The main idea is adequate the dc-dc power output to the inverter requirement, and an correct dc bus voltage. The inverter sets the rate at which the load is tracked, and the dc-dc converter ensures that the dc bus voltage remains within tolerances, thus tracking the load at the rate set by the inverter.

3) Modeling of the Pitch Angle Controller

Variable pitch control can be used to shed the aerodynamic power generated by the wind turbine [1], [32]. When the wind speed is higher than the nominal value, the blades are pitched in order to limit the power extracted from the wind and the rotor speed [33]. The pitch angle controller is only active in high wind speeds. In those circumstances, the rotor speed can no longer be controlled by increasing the generated power, as this would lead to overloading the generator and/or the converter. To prevent the rotor speed from becoming too high, which would result in mechanical damage, the blade pitch angle is changed in order to reduce C_p [1], [30], [31]. The power captured by the wind turbine may be written as (2). From (1), it is apparent that the power production from the wind turbine can be maximized if the system is operated at maximum C_p [32]. Using (1) and (2), the pitch angle needed to limit the power extracted from the wind to the nominal power of the wind turbine can be calculated for each wind speed. From these equations, it can be concluded that the optimal pitch angle equals zero below the nominal wind speed and from the nominal wind speed on increases steadily with increasing wind speed. This observation greatly facilitates pitch control.

Fig. 8 shows the simplified block diagram of the pitch controller system [3]. There are three modes: If the turbine produces more than rated power, the switch "SW" is in position "*a*" and the angle θ is constantly increased with its maximum speed of θ'_{max}. If the power is near the rated power, the pitch drive is stopped and θ remains constant. If the power is below rated power, the switch is the position "*c*" and a closed control loop with proportional controller (K_p) is formed. This controller gets its reference from a characteristic, which gives the optimum angle θ as a function of the power [3]. The pitch angle cannot change immediately, but only at a finite rate, which may be quite low due to the size of the rotor blades [1], [3], [30], [31], [32]. The maximum rate of change of the pitch angle is in the order from 3 to 10 deg/s, depending on the size of the wind turbine.

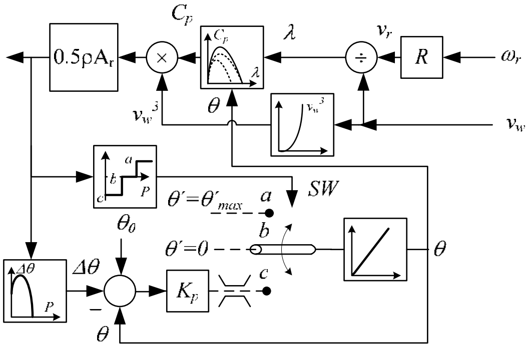

Fig. 8. Simplified Block Diagram for Pitch Angle Control

Because the blade pitch angle can only change slowly, the pitch angle controller works with a sample frequency f_{ps} which is in the order of 1 to 3 Hz. In Fig. 9, the pitch angle controller is depicted for power below rated power.

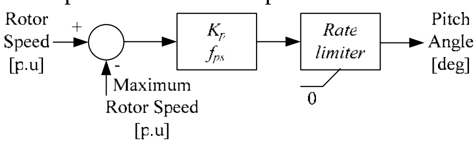

Fig. 9. Pitch angle controller model

IV. Simulation and Results

A. Model Parameters

All model parameters of the wind turbine for remote application are presented in this section. It is essential to use a consistent set of parameters when using the wind turbine model presented before, because otherwise incorrect results may be obtained. Table 1, show the rotor characteristic parameters for a wind turbine model consistent with numerical approximations developed to calculate the $C_p(\lambda,\theta)$ curve.

TABLE 1
CHARACTERISTICS FOR ROTOR MODEL OF WIND TURBINE SIMULATED

Rotor Characteristic	*Value*
Minimal Rotor Speed	9 rpm
Nominal Rotor Speed	19 rpm
Rotor Diameter	75m
Rotor swept area	4418 m^2
Nominal wind speed	14 m/s
Inertia constant	2.5 s

The following equations are used to approximate de power coefficient [1], [30]:

$$C_p(\lambda,\theta)=\left(\frac{110.23}{\lambda_i}-0.43\theta-0.001\theta^{2.14}-9.63\right)e^{-\frac{18.4}{\lambda_i}} \quad (14)$$

$$\lambda_i=\frac{1}{\dfrac{1}{\lambda-0.02\theta}-\dfrac{0.003}{\theta^3+1}} \quad (15)$$

Fig. 10 show the C_p-*TSR* curve for several pitch angle -θ, and the optimal power coefficient C_{pmax} , curve was plotted for different pitch angles.

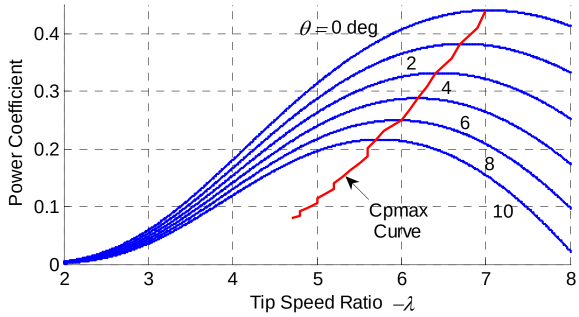

Fig. 10. Power coefficient versus tip-speed ratio for different pitch angles

The wind turbine system, use a directly driven PMSG such main characteristics are shown in the Table 2.

TABLE 2
CHARACTERISTICS PMSG SIMULATED

Generator Characteristic	*Value*
Nominal Power	2 MW
Nominal Speed	19 rpm
Number of Poles	80
Nominal Voltage	3000 V

The controls-oriented model for PMSG is characterized by K_e and K_x constants. For this PMSG, values of K_e and K_x constants were determined and the steady-state voltage regulation for different speed was plotted (Fig. 11)

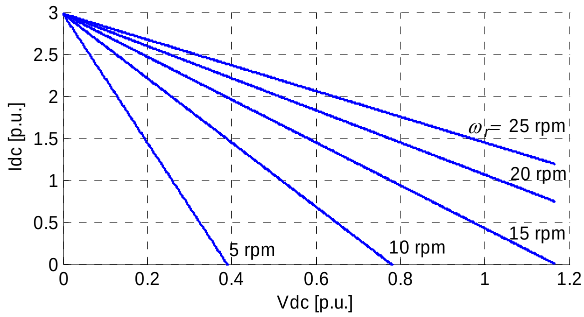

Fig. 11. Constant Speed Voltage Regulation of PMSG with FWDB

The intrinsic torque/load properties versus voltage for several constants speed are shown in the Fig. 12 (loss-less operation).

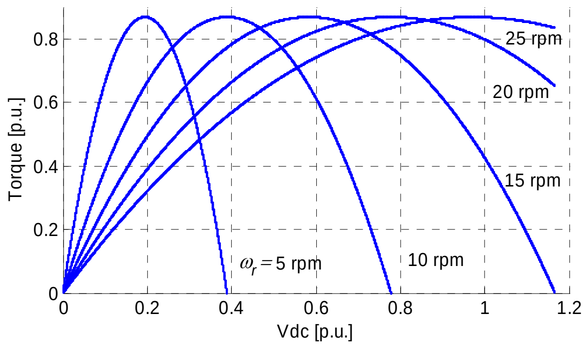

Fig . 12. PMSG Shaft Torque as a function of V_{dc}

B. Study Case

A typical remote network area installed in rural area on Venezuela was used for this paper. This is a typical distribution, radial, and supply power to residential loads with high power factor; and connected to a robust transmission system by step-up transformer at distribution station. Bus 1, is connected to a robust system and considered as an infinite power bus. The network was reduced to a 15 nodes system (Fig. 13), each bus has a load simulated by impedance constant model. The total load of the distribution system is P_{load} = 6.301MW, Q_{load} = 0.446 MVAR, with V_{rated} = 13.8kV. The detailed network parameters are not due to space limits.

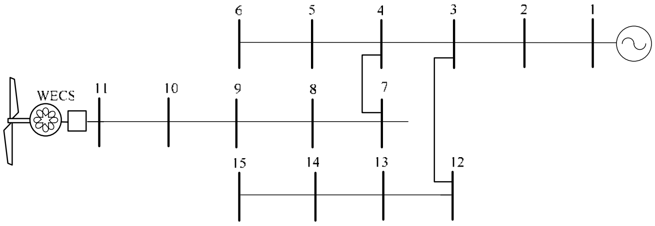

Fig. 13. 15 Buses Network, with WECS simulated

The preliminary studies about wind energy resources over supply area of this distribution network reveal the possibility to install a wind energy conversion system, about 2MW at bus 11.

This wind turbine, is considered that work to reinforce the local voltage profile, and to attend to the local demand, to congress-less the transmission network, working as distributed energy resource. God wind speeds are present on such location

For simulation purpose, two wind speed time series was used. One with low variability, and other with high variability (instantaneous speed up to 22m/s), as shown on the top of Fig. 14 and 15 respectively. The idea is evaluate the behavior of the wind turbine system developed on more favorable and adverse canaries of wind speed.

C. Results

The wind energy conversion system developed in this paper was implemented and integrated to the traditional distribution system on rural application.

Considering a high variability wind speed (top of Fig 14), wind turbine was considered working with a local load constant equal at 90% of rated power of wind turbine, and the total load of the network was considered constant, the simulation results of the rotor speed, active power and terminal voltage are shown in Fig. 14.

The behavior of the model and the control system, look perfectly according with the theory. For wind speed below the nominal, the electrical variables (power, voltage) exhibit low dependence of the wind speed, when the win speed increases over nominal speed, the control system act, and the load following and power quality are good.

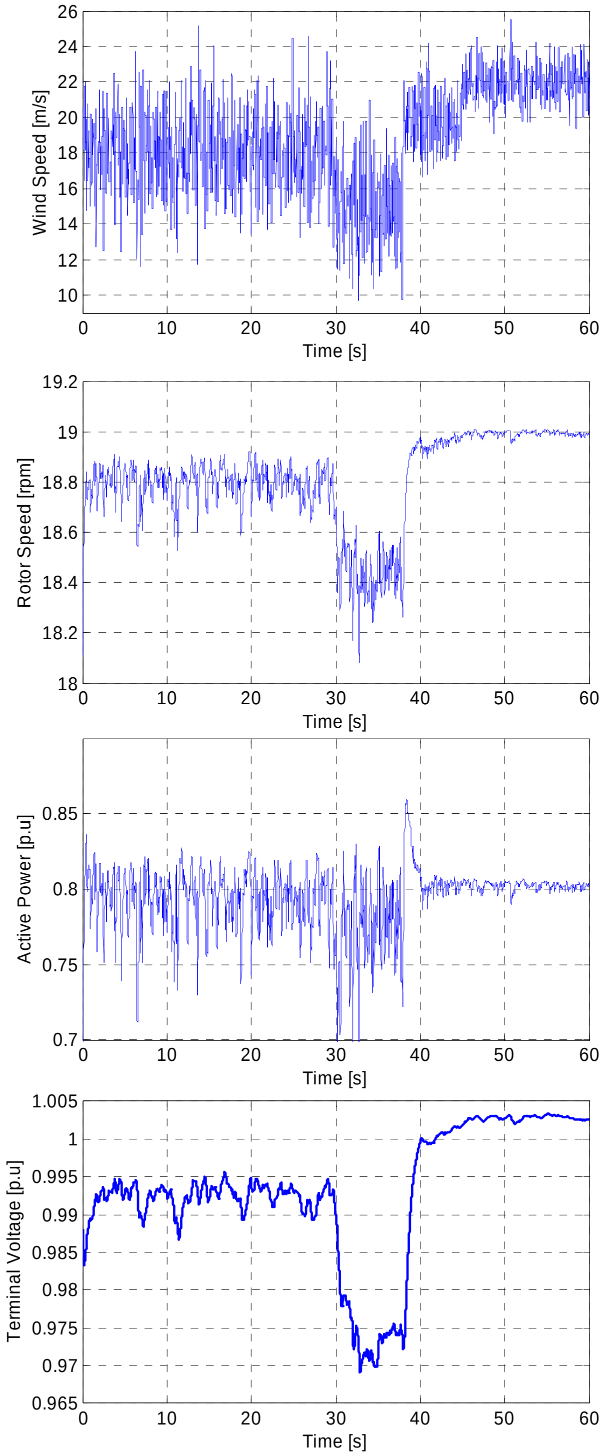

Fig. 14. Simulation results for constant local load and high variability wind speed, starting from above: rotor speed, active power, and voltage at the turbine's terminals

Later, a variable local load was considered to the wind turbine driven by low variability wind speed. The simulation results are shown in Fig. 15. The model exhibits a good load following behavior for variable load with a low rate of change on ramp slope. The rotor speed controller (by pitch angle) and the converter controller, permit a good time response, similar a real time controller.

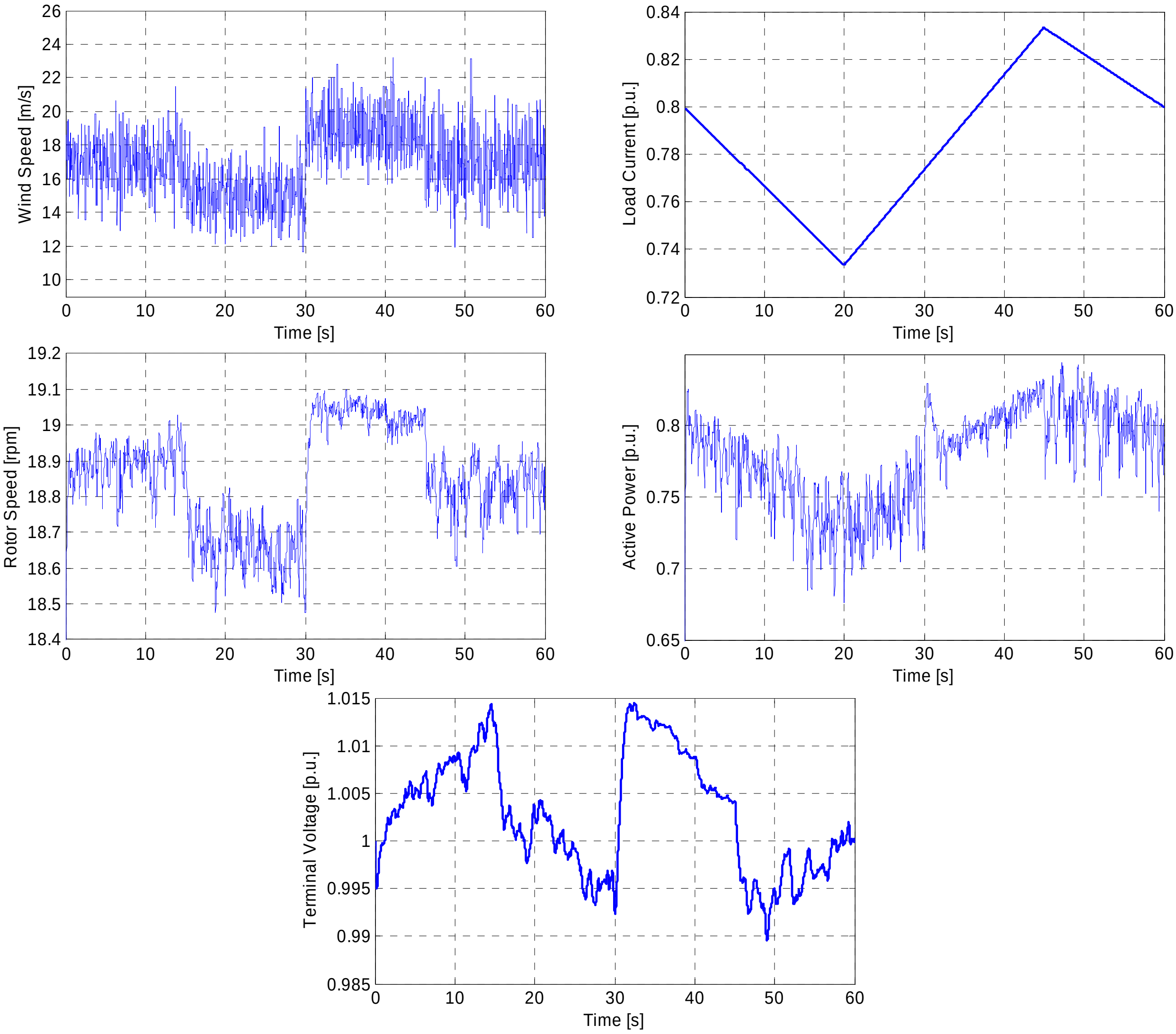

Fig. 15. Simulation results for variable local load and low variability wind speed.

V. Conclusions

In this paper, a particular model for representing variable-speed wind turbines with permanent magnet synchronous generator directly driven for power system dynamics simulation was presented. Models of the subsystems of which the variable speed wind turbine consists were developed from the works done by several authors and practical values for the various parameters shown in some paper was used. The main contribution of this paper is the use of controls-oriented model of the PMSG, and simplified model for the power converter to make a more simplified wind turbine model for the dynamic simulation on power system. Furthermore, this paper is relevant, because, simulate a typical rural application, on realistic scenarios, and the model work fine.

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