Influence of Turbulence on Power Quality: Comparative study between Constant and Variable Wind Turbines

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***Abstract*--Turbulence is clearly a complex process, and one which cannot be represented simply in terms of deterministic equations. The main objective of this paper is a comparative study of impact on dynamic behavior on constant and variable speed wind turbines considering several turbulence sceneries. We consider integration on a test system of squirrel cage induction generator for constant speed wind turbine, and doubly fed induction generator for variable speed wind turbine. Several simulations with different intensity of turbulences were developed, and conclusions are presented. Good dynamic behavior is evident on doubly fed induction generator, with controls.**

***Index Terms*-- Wind speed turbulence model, electric dynamic behavior, power and voltage response.**

I. Introduction

THE wind consist of a mean wind speed determined by the seasonal, synoptic and diurnal effects described above, which varies on a time-scale of one to several hours, with turbulent fluctuations superimposed.

Turbulence refers to fluctuations in wind speed on a relatively fast time-scale, typically less than about 10 min; and its have a zero mean (when averaged over about 10 min). Turbulence is clearly a complex process, and one which cannot be represented simply in terms of deterministic equations.

There are many statistical descriptors of turbulence which may be useful, depending on the application. These range from simple turbulence intensities and gust factors to detailed descriptions of the way in which the three components of turbulence vary in space and time as a function of frequency.

The main objective of this paper is a comparative study of impact on dynamic behavior on constant and variable speed wind turbines considering several turbulence sceneries.

II. Modeling

The main interest of this paper is evaluate the dynamic behavior of two most important contemporary wind turbine types: the constant speed wind turbine with the squirrel cage induction generator and the variable speed wind turbine with a doubly fed (wound rotor) induction generator. The general structure of the constant speed wind turbine model is depicted in Fig. 1 and a doubly fed induction generator is more complex, there are a number of additional blocks in Fig. 2

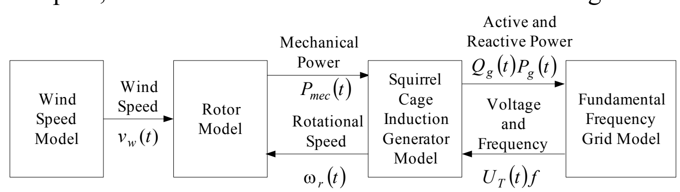

Fig. 1. General structure of constant speed wind turbine model.

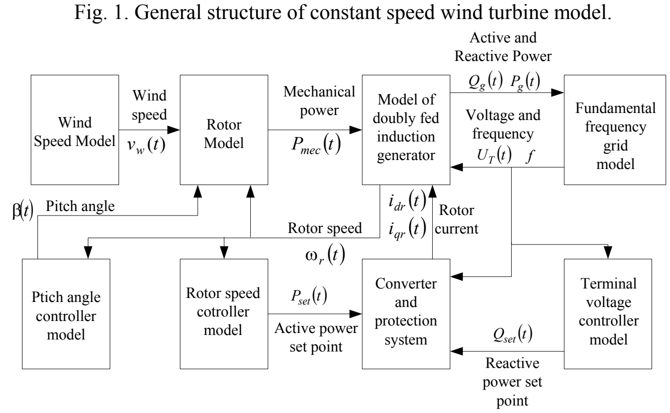

Fig. 2. General structure of a model of a variable speed wind turbine with a doubly fed induction generator

The main models used for simulations of both systems are developed in following sections.

A. Wind Speed

A wind speed sequence with characteristic controllable is generated by this model. Making possible simulate a wind speed sequence with desired characteristic, by setting the value of the corresponding parameters to an appropriate value.

In this paper the well-known model of four components is assumed. Wind speed (v_w) is the sum of following component [1]-[4]: the average value (v_{wa}), ramp component (v_{wr}), gust component (v_{wg}) and turbulence (v_{wt}).

$$v_w(t) = v_{wa} + v_{wr}(t) + v_{wg}(t) + v_{wt}(t) \tag{1}$$

The wind speed ramp is characterized by three parameters – amplitude of wind ramp A_r (in m/s), the starting time of the wind speed ramp T_{sr} (in s) and the end time of the wind ramp

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(in s) T_{er}; and following equation describe the ramp component [2]:

$$
\begin{aligned}
v_{wr} &= 0 && \text{for} \quad t < T_{sr} \\
v_{wr} &= A_r \frac{(t - T_{sr})}{(T_{er} - T_{sr})} && \text{for} \quad T_{sr} \le t \le T_{er} \\
v_{wr} &= A_r && \text{for} \quad T_{er} < t
\end{aligned}
\tag{2}
$$

The wind speed gust is characterized by: amplitude of gust A_g (in m/s), the starting time of the wind speed gust T_{sg} (in s) and the end time of the wind speed gust (in s) T_{eg}; and following equation describe the ramp component [1]-[2].

$$
\begin{aligned}
v_{wg} &= 0 && \text{for} \quad t < T_{sg} \\
v_{wg} &= A_g \left\{ 1 - \cos\left[2\pi \left(\frac{t - T_{sg}}{T_{eg} - T_{sg}} \right) \right] \right\}, && \text{for } T_{sg} \le t \le T_{eg} \\
v_{wg} &= 0 && \text{for} \quad T_{eg} < t
\end{aligned}
\tag{3}
$$

Turbulence component is complex, but use a model based on power spectral density $S_{wt}(f_i)$:

$$
S_{wt}(f_i) = \frac{\frac{1}{(\ln(h/z_o))^2} l v_{wa}}{\left(1 + 1.5 \frac{f_i l}{v_{wa}} \right)^{\frac{5}{3}}}
\tag{4}
$$

And the turbulence component is given by [4]:

$$
v_{wt}(t) = \sum_{i=1}^{n} \sqrt{S_{wt}(f_i)\Delta f} \cos(2\pi f_i t + \phi_i + \Delta\phi)
\tag{5}
$$

For detailed discussion of turbulence component see [5].

B. Rotor

A quasistatic approach is used to describe the rotor of the wind speed. In this case a well-known algebraic equation give the relation between wind speed and mechanical power extracted from the wind [1]-[2],[6]-[7]:

$$
P_w = \frac{1}{2} \rho_{AIR} A_{wt} C_p(\lambda, \beta) v_w^3
\tag{6}
$$

where ρ_{AIR} is the air density (typically 1.225Kg/m^3), A_{wt} is the area covered by the wind turbine rotor, C_p is the power coefficient, λ is the tip speed ratio, and v_w is the wind speed at hub height, and β is pitch angle [deg].

In this paper only stall controlled constant speed wind turbines are considered, and numerical approximation of the $C_p(\lambda,\beta)$ curve for controlled variable speed turbine. We use the following general equation to describe the rotor of constant-speed and variable-speed turbines:

$$
c_p(\lambda, \beta) = c_1 \left(\frac{c_2}{\lambda_i} - c_3 \beta - c_4 \beta^{c_5} - c_6 \right) e^{\left(\frac{-c_7}{\lambda_i} \right)}
\tag{7}
$$

Where:

$$
\lambda_i = \left[\left(\frac{1}{\lambda + c_8 \beta} \right) - \left(\frac{c_9}{\beta^3 + 1} \right) \right]^{-1}
\tag{8}
$$

The values of constant c_1 to c_9 used to approximate several types of wind turbines are given on Table I, according (7) and (8).

TABLE I
COEFFICIENT FOR POWER COEFFICIENT APPROXIMATION

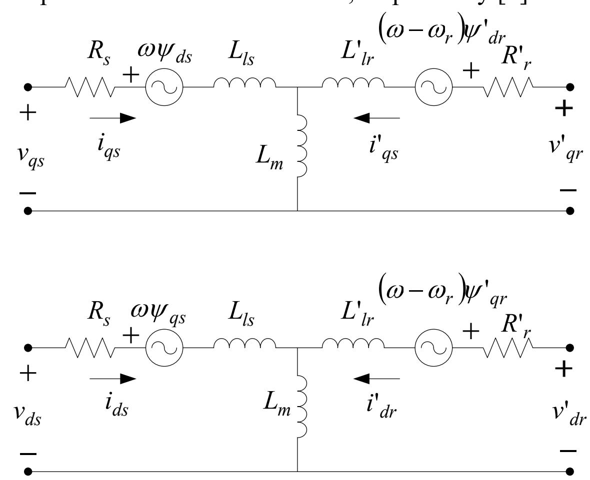
Constants	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
Constant Speed	0.44	125	0.00	0.000	0.00	6.94	16.5	0.00	-0.002
Variable Speed	0.73	151	0.58	0.002	2.14	13.20	18.4	0.02	-0.003
Heier turbine	0.5	116	0.40	0.000		5.00	21.0	0.08	0.035

C. Squirrel Cage Induction Generator

In this paper we use the voltage equations of a squirrel cage induction generator in dq reference frame to model the generator. The complete set of equations can be found in the literature, and as follows [1], [8], [9]:

$$
\begin{aligned}
v_{qs} &= R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega \psi_{ds} \\
v_{ds} &= R_s i_{ds} + \frac{d\psi_{ds}}{dt} + \omega \psi_{qs} \\
v'_{qr} &= 0 = R'_r i_{qr} + \frac{d\psi_{qr}}{dt} + (\omega - \omega_r)\psi'_{ds} \\
v'_{dr} &= 0 = R'_r i'_{dr} + \frac{d\psi'_{dr}}{dt} + (\omega - \omega_r)\psi'_{qs}
\end{aligned}
\tag{9}
$$

where v is voltage, i is the current, R is the resistance and ψ is the flux. All quantities are in per unit. Subscripts d and q stand for direct and quadrature component, respectively, and the subscript r and s for rotor and stator, respectively [1].



d Axis

Fig. 3. dq frame induction generator model

The electrical torque (T_e) is given by:

$$
T_e = \frac{3}{2} p (\psi_{ds} i_{qs} - \psi_{qs} i_{ds})
\tag{10}
$$

And the equation of motion of the generator is:

$$
\begin{aligned}
\frac{d\omega_m}{dt} &= \frac{1}{2H}(T_e - F\omega_m - T_m) \\
\frac{d\theta_m}{dt} &= \omega_m
\end{aligned}
\tag{11}
$$

D. Double Feed Induction Generator

A model of a doubly fed induction generator is similar to that of a squirrel cage induction generator. The first difference is that the rotor windings are not shorted, thus the rotor voltage does not equal zero. The voltage equations of a wound rotor synchronous machine on *dq* frame are:

$$
\begin{aligned}
u_{ds} &= -R_s i_{ds} - \omega_s \psi_{qs} + \frac{d\psi_{ds}}{dt} \\
u_{qs} &= -R_s i_{qs} + \omega_s \psi_{ds} + \frac{d\psi_{qs}}{dt} \\
u_{dr} &= -R_r i_{dr} - s\omega_s \psi_{qr} + \frac{d\psi_{dr}}{dt} \\
u_{qr} &= -R_r i_{qr} + s\omega_s \psi_{dr} + \frac{d\psi_{qr}}{dt}
\end{aligned} \quad (12)
$$

The flux linkage equations of a doubly fed induction generator are identical to that of the squirrel cage induction generator (Section C). Note that it is assumed that the sum of the rotor currents of the doubly fed induction generator is equal to zero. The electro-magnetic torque is given by:

$$T_e = \psi_{ds} i_{qs} - \psi_{qs} i_{ds} \quad (13)$$

Finally we use the same equation of motion as single cage induction generator (11).

E. Speed controller

In double fed induction generator with variable speed wind turbine the speed controller is used to control the electro mechanical torque. The reason for not controlling the power, but the torque, is that the torque is directly dependent on the quadrature component of the rotor current, when stator resistance is neglected [6]. The following relation between torque and i_{qr}, holds, in which u_t is the terminal voltage

$$T_e = -\frac{L_m u_t i_{qr}}{\omega_s (L_{s\sigma} + L_m)} \quad (15)$$

An extensive discussion of this controller can be found on [1], [2].

F. Pitch angle controller

This controller, together with the rotor speed controller the pitch angle controller controls the rotor speed. However, the latter is only active during high wind speeds. To prevent the rotor speed from becoming too high, which would result in mechanical damage, the blade pitch angle is adjusted in order to limit the aerodynamic efficiency of the rotor.

The optimal pitch angle is approximately zero below the nominal wind speed and from the nominal wind speed on; it increases steadily with the wind speed.

In this paper we are use the same pitch angle controller presented in [2]. We adjust the rate of change of pitch angle to be quite low due to the size of the rotor blades (3 a 10 deg/s). Because the blade pitch angle can only change slowly, the pitch angle controller works with a sample frequency fps which is in the order of 1 to 3 Hz.

In Fig. 4 the pitch angle controller is depicted.

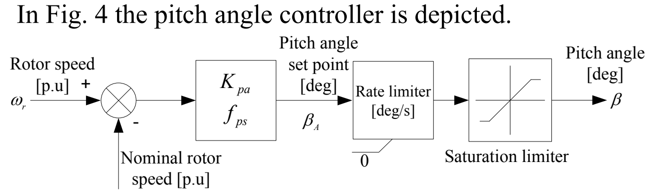


Fig. 4. Pitch angle controller model.

G. Terminal voltage controller

In this paper we a considered a variable speed wind turbine with a doubly fed induction generator able to vary its reactive power output and thus to take part in terminal voltage control.

When stator resistance is neglected, the reactive power generated by the wind turbine is directly dependent on i_{dr} [6] resulting in:

$$Q_s = -\frac{L_m u_t i_{dr}}{L_{s\sigma} + L_m} - \frac{u_t^2}{\omega_s (L_{s\sigma} + L_m)} \quad (16)$$

A terminal voltage controller for a doubly fed induction generator is depicted in Fig. 5.

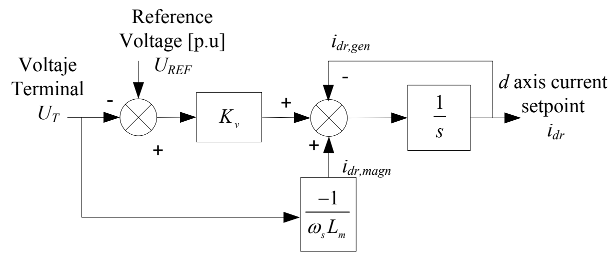


Fig. 5. Model of terminal voltage controller for variable speed wind turbine with doubly fed induction generator

When the value of K_v is changed to zero, a controller keeping the power factor equal to one results. This is the dominating mode of operation nowadays.

III. Simulations and Results

In this section, models were implemented on Matlab® Simulink™. Fig. 6 show test systems were implemented.

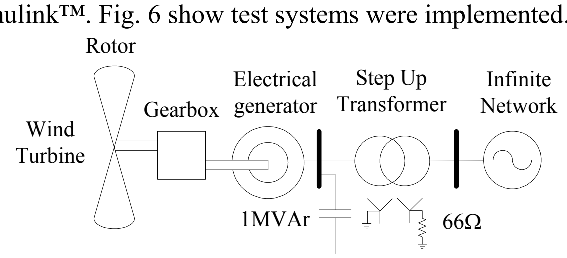


Fig. 6. Test system

All values except wind speed are in per unit and their values are not given. A typical 2MVA, 575 V, induction generator was considered and data is shown on appendix. Coefficient in Table I was used to simulate constant speed with Hier model and variable-speed; both turbines with pitch angle controller. Capacitor for local power factor correction was included with 1MVAr, 575V. A step up transformer, 575V/25kV, X = 0.25 p.u, X/R = 30 was included to connect the wind turbine to a 25 kV infinite bus.

Over this tests system, simulation was developed for several wind speed sequences.

A. Short term wind speed variation

Initially short term variations on wind speed are evaluated for constant and variable-speed wind turbines. The turbulence intensity in the neutral atmosphere clearly depends on the surface roughness. To characterize the landscape type around the turbine, as it reflects the impact of the structure of the wind turbine surroundings on the turbulence intensity; 2 MW turbines was considered with hub height of 80 m, length roughness similar to open sea or sand (z_0 = 0.01) and l is the turbulence

Wind speed time series was developed including the effect of turbulence using Kiamal power spectral density. Fig. 7 and 8 show the results of simulation over test system of constant and variable-speed wind turbine for two different time series of 60 s. Main variables was plotted on constant and variable-speed wind turbines considering the effect of high and low turbulences including IEC 61400-1 model.

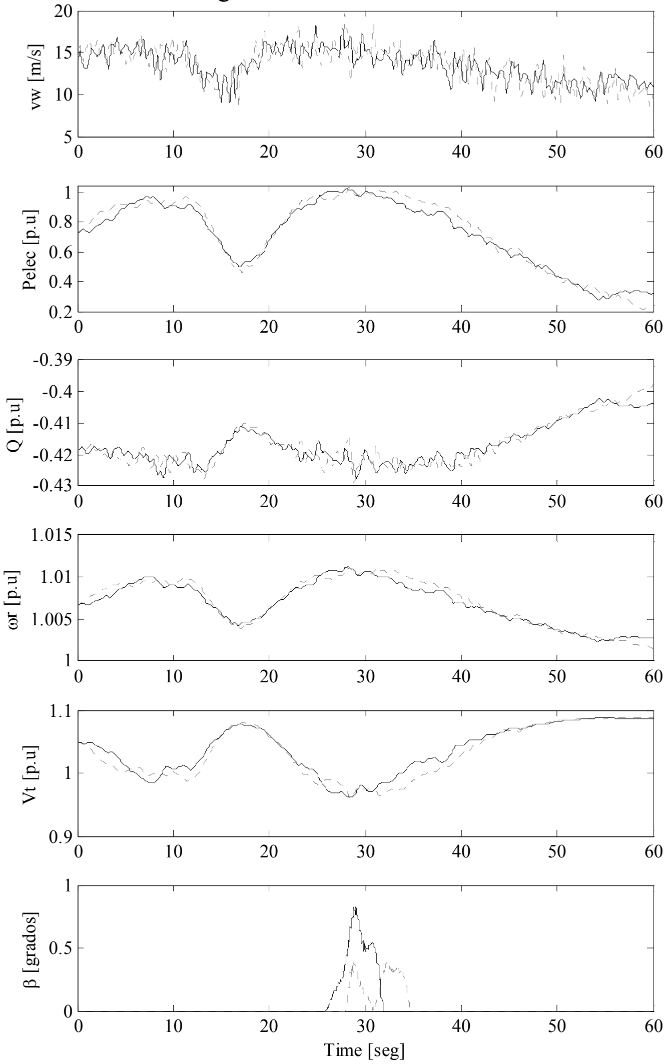


Fig. 7. Constant-speed wind turbine behavior to short term wind speed variations (High turbulence: dotted line, Low turbulence: solid line)

Results of constant-speed wind turbines exhibit a high dependence of wind speed in all parameters (Fig. 7). Reactive power output and terminal voltage in squirrel cage induction generator have a high variability due a great exclusion of wind speed. Though in this paper we include a pitch angle controller, this work just over 15 m/s wind speed; below this wind speed the variations on wind speed influence de dynamic behavior of all electrical and mechanical variables.

High turbulence wind speed series produce high active power output on constant speed wind turbines with low voltage profile that go out regulation (< 0.95 p.u) in twice. Reactive power consumption is a problem in squirrel cage induction generator and high dependence on wind speed is evident in high or low turbulence.

Wind speed series with low turbulence produce a higher rotor speed than low turbulence. Excellent speed regulations are observed in all cases (< 0.5%). On high wind speeds the pitch controller work to adjust the output power of wind turbine. High turbulence produces lower action on pitch angle controller.

The good skills of the controllers in the constant-speed wind turbine are evident in the results showed in Fig. 8.

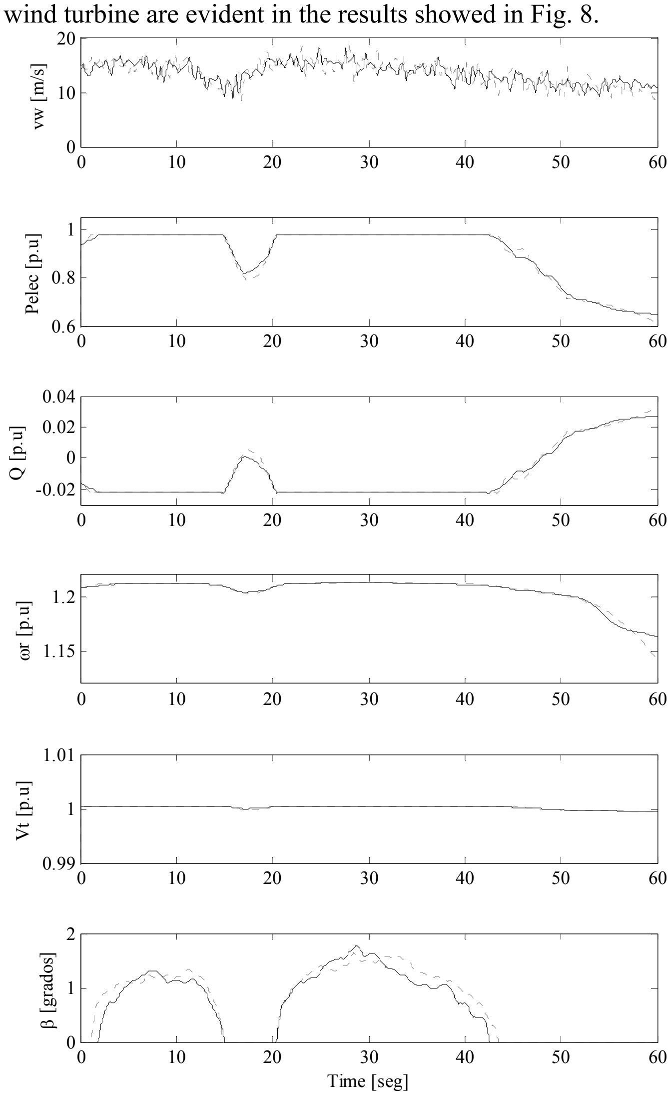


Fig. 8. Variable-speed wind turbine behavior to short term wind speed variations (High turbulence: solid line, Low turbulence: dotted line)

High wind speed (> 15m/s) produce the best performance in all electrical and mechanical variables on variable-speed wind turbines. Active power output is adjusted by pitch angle controller to 1.0 p.u and low turbulence produce the largest power production. Reactive power is sustained on -0.02 p.u on high wind speed but this value is reduced for lower wind speeds. High voltage profile is found in high turbulence an excellent regulation is obtained with a variable-speed wind turbine. The terminal voltage control adjusts fast and effective the value and regulation below a 0.01% is obtained.

On low wind speed (< 15m/s) output power is reduced and the terminal voltage controller try to sustain bus voltage but reduction on wind energy cause a rotor speed reduction with a large reduction on active power production. The best dynamic behavior of all electrical and mechanical variables in variable-speed wind turbines is evident over constant-speed wind turbines based on squirrel cage induction generator. Low turbulence produces the largest output production.

B. Long term wind speed variation

In this paper a 600s (10 min) wind speed time series is applied to constant and variable-speed wind turbine to exanimate de dynamic behavior. Van der Hoven's model is considered to large-band wind speed modeling (slower components). The turbulence component is assumed to be dependent on the medium- and long-term wind speed evolution. It is considered as a non-stationary process.

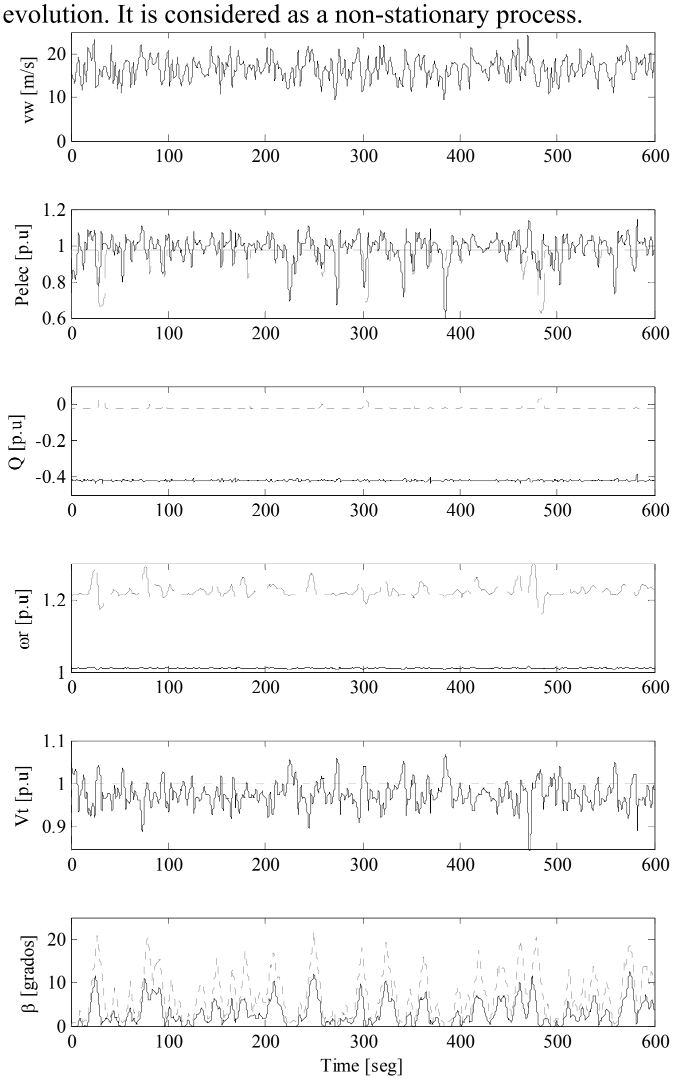


Fig. 9. Variable-speed wind turbine behavior to short term wind speed variations (High turbulence: solid line, Low turbulence: dotted line)

The spectrum of turbulence describes the frequency content of wind-speed variations, we use in this paper the von Karman spectrum gives a good representation of atmospheric turbulence above about 150 m.

Fig. 9 show results dynamic behavior of main variables on constant and variable-speed under a long term wind speed time series based on von Karman model (v_{av} = 16.5 m/s). Excellent behavior of variable-speed is evident. Terminal voltage is perfectly controlled in variable-speed wind turbine but squirrel cage induction generator with constant-speed wind turbine has a uncontrolled reactive power consumption that affect in great way the voltage profile.

Reactive power requirement of constant-speed wind turbines is larger than constant speed but lowest overshoot is evident. Terminal voltage controller in doubly fed induction generator produces larger reactive power exclusion than constant-speed wind turbine. Rotor speed of variable-speed wind turbine is larger than constant-speed and this has a better regulation (<0.01%).

Excellent active power production in variable-speed wind turbine is result of good performance on pitch angle control that act to modify the rotor speed to adjust the real power to set point.

IV. Conclusions

Complete modeling issues of constant-speed wind turbines with squirrel cage induction generator and variable-speed wind turbine with doubly fed induction generator are presented in this paper. Several wind speed time series was generated. Van der Hoven's model was used to short term wind speed variation based with van Kiamal power spectrum and long term variations with Karman spectral density function.

High turbulence short term wind speed variation exhibit a larger output power production than results with low turbulence. The best power quality is reached with variable-speed wind turbines.

Long time wind speed variation simulations show the differences in operating condition between constant-speed and variable speed wind turbines. Because extended averaging periods are used in power performance testing (usually 10 min, 600s) a significant amount of wind energy is contained in the turbulence. Consequently there is more energy in the wind than indicated by the average value of the wind speed.

V. Appendix

TABLE A.1. CHARACTERISTIC OF SIMULATED WIND TURBINE [1], [2]

Wind turbine characteristic	*Value*
Rotor speed (constant speed)	15 RPM
Minimum Rotor Speed (variable speed)	9 RPM
Nominal Rotor Speed (variable speed)	12 RPM
Rotor diameter	75 m
Rotor swept area A_r	4418 m
Nominal power	2 MW
Nominal wind speed (constant speed)	15 m/s
Nominal wind speed (doubly fed)	14 m/s
Gear box ratio (variable speed)	1:100
Gear box ratio (constant speed)	1:89

TABLE A.2. INDUCTION GENERATOR PARAMETERS

Generator characteristic	*Value*
Number pairs of poles	2
Generator speed (constant speed)	1517 RPM
Generator speed (variable speed)	1900 RPM
Nominal Power	2.0 MVA
Nominal Voltage	575.0 V
Mutual inductance	3.0 p.u.
Stator leakage inductance	0.010 p.u.
Rotor leakage inductance	0.080 p.u.
Stator resistance	0.010 p.u.
Rotor resistance	0.010 p.u.
Compensating capacitor	0.500 p.u.
Inertia constant	5.0 s

TABLA A.3
PITCH ANGLE CONTROLLER PARAMETERS

Parameter	*Value*
K_{pa}	175.00
F_{ps}	0.02
Slope	5 deg/s

TABLA A.4
ACTIVE POWER CONTROLER PARAMETERS

Parameter	*Value*
K_{pt}	3.45
K_{it}	0.005

TABLA A.5
VOLTAJE CONTROLLER PARAMETERS

Parameter	*Value*
K_v	50.00
U_{REF}	1.00 p.u

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VII. BIOGRAPHY

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