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Modelling and Control of a Variable Speed Wind Energy Conversion Turbine driven Synchronous Generator Connected to the Grid

O. HASNAOUI[1], I. B. SALEM[2], M. F. MIMOUNI[3], R. DHIFAOUI[4]
[1]Department of Electrical Engineering, ESSTT, 5 Avenue Taha Hussein 1008, TUNISIA

[3]Department of Electrical Engineering, ENIM, Monastir, TUNISIA

[2,4]Department of Physics and Instrumentation, INSAT, Centre urbain Nord, B.P. N°676, 1080 Tunis Cedex, TUNISIA

Abstract: - This paper presents the modelling and control design for a wind energy conversion scheme using synchronous generator. The wind turbine is coupled to a synchronous generator connected to grid trough a static converter. The objective of the proposed control strategy is to maximize energy captured from the wind turbine. The adapting control law used for extracting maximum power from the wind is based on the utilisation of anemometer sensor. The developed maximum wind power extraction algorithm has the capability of searching the maximum wind turbine power at variable wind speed, constructing an intelligent system to control the inverter for maximum power extraction, with the need and knowledge of wind characteristics and the measurements of mechanical variables such as wind speed and turbine rotor speed. First, the dynamic modelling and control design for $800\,kW$ horizontal axis wind turbine synchronous generator is presented. Second, the control of the proposed structure is achieved using proportional integrator controllers which are based on the linear model and tested under large electrical disturbances of wind speed. The system has been validated by numerical simulation using data from a wind farm turbine situated in the north of Tunisia (SIDI DAOUED). The simulation results have shown good performances of the system and a better grid integration of the wind energy with the proposed converter control strategy.

Key-Words: - Variable Speed Wind Energy Conversion System (VSWECS), Synchronous Generator, Wind Power, Power transferred, Grid, Performance Coefficient.

1 Introduction

Actually, the installed wind power in the world has been increasing at more than 30% per year over the past decade [1]. In this sense, Tunisia is one of the interested countries on the word to use wind power. Prospects for 2010 year point to $300\,MW$ installed power wind energy, which will represent a significant percentage (10%) of the total capacity in the Tunisia electrical system. One raison for the wind energy development is due to the technological maturity, the deregulation cost of electricity markets throughout the world, and government incentives. Also, the recent developments in wind power generation have provided an economically competitive and technically sound solution to reduce greenhouse gas and emissions. In this context, most of actual wind turbine in Tunisia is variable-speed units that use power electronics converters. Most of them include induction and synchronous generators. Compared with a constant speed operation, variable speed operation of wind turbines can offer a number of important advantages such as an increase of energy capture 10 to 15% higher energy output, reduction of fatigue damage on rotor blades and drive train, reduction of aerodynamic acoustic noise level and improvement in operational flexibility [2-4]. Furthermore, the main advantages are that variable speed implies a conversion steep from mechanical energy at variable speed to electrical energy of constant frequency [5, 6]. This conversion is usually realised by power electronics converters. Most adjustable speed drives employ voltage-source inverters. The goal of the control system is to maintain the output voltage (dc-link voltage), at the required level, while currents drawn from the power system should be sinusoidal and in phase with respective phase voltage to satisfy the unity-power factor condition.

In this paper, a variable speed wind energy conversion system (VSWECS) for the synchronous machine is proposed employing a control strategy for a static converter to ensure both controls simultaneously of the active and reactive power. In this context, this paper deals with a simple approach for the analysis of a VSWECS synchronous generator. The control of the synchronous generator was done via a PWM current source, and a speed controller was utilised to maintain optimum power transfer conditions. The adapting control strategy used for extracting maximum power from the wind is based on the utilisation of anemometer sensor and turbine rotor speed.

2 Description of VSWECS

The proposed power generation system of the wind turbine $AE-52$ is shown in Fig.1. The system consists of a synchronous generator, with the shaft connected to the wind turbine and the field rotor winding connected to the exciter; a brushless exciter with field on the stator and armature windings on the rotor; a two static converters respectively of AC/DC type and DC/AC, and a transformer adapting the voltage of converter DC/AC to the voltage of the network.

The synchronous machine is a named alternator 1FQ2 and made by Siemens SEM Drazov [4] in Czechoslovakia. The excitation of the machine is assured by an excitatory in tip of tree; the current is controlled by a DC supply $49V, 3A$. The constructor's technical document provides two characteristics; serving to the clarification of the voltage regulator. These characteristics link the frequency f of the machine, its unloaded electromotive force (emf) E_v and the current of excitation of the excitatory I_{ex}.

The synchronous generator supplies power via a diode rectifier chosen for its simplicity, low cost and low losses. The use of the diode rectifier is possible since the voltage control of the DC link is achieved through automatic voltage regulator by the control of the duty cycle ratio of the DC/DC converter. The inverter DC/AC controls the active and reactive power supplied to the grid.

The transformer permits to adapt the voltage of the inverter that is adjusted to $1000V$ between phases to the network $30kV$ of which the terminal voltage is situated about $40km$ of the site of Wind Park. The transformer is modelled by a classical circuit composed by a back emf and impedance $\overline{Z}_r$. Where $\overline{Z}_r$ represents the equivalent impedance of the transformer $\overline{Z}_T$ and the transmission line $\overline{Z}_L$.

$$\overline{Z}_r = \overline{Z}_T + \overline{Z}_L = 0.0330 + j0.2277 \ pu \qquad (1)$$

3 Mathematical modelling of system components

To simulate the WECS used in this work, it is necessary to develop a mathematical model that can represent as well as possible all elements of WECS. The WECS considered in this work consists of a wound rotor synchronous generator driven by a fixed pitch wind turbine, a diode rectifier, a brushless exciter and a current control pulse width modulated (PWM) inverter connected to the grid. A brief description of each elements of the control system is given below.

3.1 Wind Turbine model

The aerodynamic transfer at the rotor is modeled as a steady state nonlinear process characterized by the mechanical characteristics of a wind turbine described by the following equations:

$$\omega_T \frac{d\,\omega_T}{d\,t} = \frac{1}{J}\left[P_w - P_{load} \right] \qquad (2)$$

For all wind energy models, the wind power is expressed as follows:

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

Where P_w is a wind turbine mechanical power, P_{load} is load power, v_w is wind speed, A_r is sweeping area of the turbine rotor, $C_p(\lambda)$ is the turbine performance coefficient, J is the inertia constant and λ, define by the following equation, is the tip speed ratio.

$$\lambda = \frac{v_t}{v_w} = \eta_{GB} \frac{2r\,\omega_r}{pv_w} = \frac{R\,\omega_r}{v_w} \qquad (4)$$

The tip ratio λ is written as follows where r holds for the length of the blade, η_{GB} is the gear box ratio and p the number of poles of the synchronous generator.

The general model of the performance coefficient or the power coefficient $C_p(\lambda)$ for variable speed wind turbine is approximate by the following equation with constant parameters, [18].

$$C_p(\lambda) = k_1(k_2 y - k_3 - k_7\beta)e^{-k_4 y} = k_1 f_1 f_2 \qquad (5)$$

Variable y is translated by equation (6).

$$y = \frac{1}{\lambda + k_8\beta} - \frac{k_9}{1+\beta^3} \qquad (6)$$

Fig.2 shows a wind turbine $C_p(v_w)$ curve obtained for the pitch angle $\beta = 0$. Where the constant parameters are: $k_1 = 0.22$, $k_2 = 116$, $k_3 = 5$, $k_4 = 12.5$, $k_7 = 0.4$, $k_8 = 0.08$ and $k_9 = 0.035$.

The power, expressed by relation (2), becomes:

$$P_w = k_6 f_1 f_2 v_w^3 \quad (7)$$

Where $k_6 = \frac{\rho}{2} A_r k_1$, $f_1 = k_2 y - k_3 - k_7 \beta$ and $f_2 = e^{-k_4 y}$,

The sensitivities of P_w , to respect successively ω_r , v_w *and* β , are expressed by the following equations:

$$\frac{\partial P_w}{\partial \omega_r} = -k_6 v_w^3 f_2 f_3 f_4 \quad (8)$$

$$\frac{\partial P_w}{\partial v_w} = -k_6 v_w^3 f_2 (3 f_1 + \frac{\lambda f_3 f_4}{R}) \quad (9)$$

$$\frac{\partial P_w}{\partial \beta} = -k_6 v_w^3 f_2 (f_3 f_5 - k_7) \quad (10)$$

Where the functions f_3, f_4 and f_5 are expressed respectively by: $f_3 = k_2 - k_4 f_1$, $f_4 = \frac{R}{(\lambda + k_8 \beta)^2}$ and $f_5 = \frac{3 k_9 \beta}{(1+\beta^3)^2} - \frac{k_8}{R} f_4$.

The wind turbine model focuses on the energy transfer characteristics within a wind speed. Fig.2 shows a wind turbine $C_p(\lambda)$ curve. This curve can be integrated in the model to entire wind power generation system along with other components.

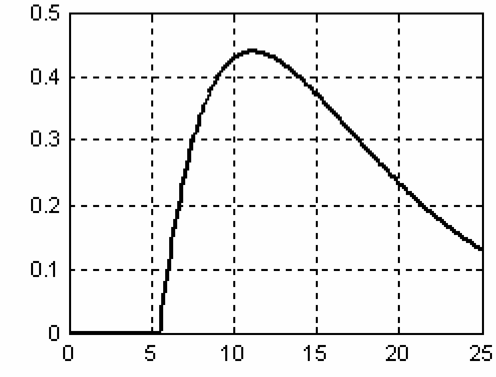

Fig.2: Performance coefficient $C_p(v_w)$

3.2 Synchronous Generator Dynamics

Many theoretical models for generator producing power from a wind turbine have been developed in the literature [8-10]. The synchronous generator under investigation is assumed to have three phase windings, one field winding, and without damper windings.

Let us first define the following quantities to normalise machine variables. So, generally speaking, per unit variables are used. The set of differential equations dynamics are expressed in the synchronous reference frame linked to the rotor flux in terms of voltage, flux and current by:

$$\begin{cases} V_d = X_{fd} I_f - R I_d + X_d I_q - \dfrac{d\Phi_d}{\omega_b dt} \\ V_q = -R I_q - X_q I_d - \dfrac{d\Phi_q}{\omega_b dt} \\ V_f = R_f I_f + \dfrac{d\Phi_f}{\omega_b dt} \end{cases} \quad (11)$$

$$\begin{cases} \Phi_d = X_q I_d + X_{fd} I_f \\ \Phi_q = X_d I_q \\ \Phi_f = X_f I_f + X_{fd} I_d \end{cases} \quad (12)$$

Where R_s, R_r are respectively the stator and rotor resistance, X_d, Xq are the stator reactance; X_{fd} is the mutual reactance; V_d, V_q are the two-axis machine voltages, I_d, I_q are the two-axis stator currents and I_f the rotor current. Φ_d, Φ_q are the two-axis machine flux, and Φ_f is the magnitude of the rotor flux established by the effect of the rotor current and the direct stator current.

The expression of electromagnetic torque delivered by the machine is written as:

$$C_e = X_{fd} I_f I_q - (X_d - X_q) I_d I_q \quad (13)$$

Furthermore, the wind turbine is coupled to the synchronous generator through a gear box characterized by the ratio η_{GB}, the relation between the angular velocity of the rotor (ω_m) and the mechanical angular velocity of the wind turbine (ω_T) is given by:

$$\omega_m = \eta_{GB}\, \omega_T \quad (14)$$

3.3 Uncontrolled rectifier, DC/DC converter and current controlled inverter

Usually, the wind speed in not constant and so the synchronous machine generator produces variable voltage and variable frequency output. A three phase diode rectifier is used to convert the output to dc voltage. The rectifier output voltage (V_h) is expressed in terms of the peak phase voltage (fundamental component) of the generator as follows [11]:

$$V_h = \frac{3\sqrt{3}}{\pi} E_v \quad (15)$$

Therefore for the maximum utilization efficiency of the structure, all subsystem must be matched together so that the equilibrium operating point coincides with the maximum power point. In order to ensure this performance, the use of a DC/DC converter is indispensable. It serves as interface between synchronous generator and PWM inverter to maintain the input voltage of the inverter at the reference value, by controlling its switching duty cycle. The control of the duty cycle of the DC/DC converter is achieved by comparing the instantaneous DC voltage with its reference.

Actually, the DC power available at the DC/DC converter output is converted to the AC power using a PWM current controlled inverter. Then the current controlled inverter is capable of operating on a wide rage of Dc voltages. In order to enable the inverter to track the maximum power output from the wind turbine generator, the output of the wind turbine generator must be controlled by adjusting the rotor speed of the machine, the rotor current field, and the duty cycle ratio of the DC/DC converter.

4. The control strategy on maximum wind power extraction algorithm

4.1 Supervisory control system

The purpose of supervisory control system is to control the active and reactive power injected by the wind farm in the grid [12-13]. First, we can specify the reference DC voltage magnitude and the active power P_{ref} used in the control. For our study, the voltage V_{cref} is constant and equal to the nominal voltage which is used to determine the nominal AC grid voltage. The power P_{ref} is specified in order to extract the maximum power from the available wind energy for wind speed below rated. Here, the adapting control strategy used for extracting maximum power from the wind is based on the utilisation of anemometer sensor. The anemometer provides the wind power reference, and this reference is used to determine the rotor speed reference of the synchronous generator. This reference is compared with the real speed and by using a proportional integrator controller (PI). The input DC voltage can be derived. Also, this signal is used into the duty-cycle ratio controller to provide the instantaneous driving signal for the DC/DC converter.

4.2 Conventional control loops design

To provide effective controls to wind power generation systems under variable wind conditions, direct and quadrature currents demand control applies the recorded research results from the desired regime to inverter controls [14-17]. To ensure this result, the proposed control system objectives are summarized in the structure shown in fig.3. In the proposed structure, four control loops are suggested:

- A speed controller, that acts on a set of essentially mechanical variables, such as the pith angle of the blades and the mechanical power reference. This regulator generates the reference of speed N_{ref}, the current reference I_{exref} of excitation of the excitatory, and the reference of electrical power P_{ref} provided to the network. His inputs are essentially the measure of the speed N of the machine, the measure of the wind speed V_w and the measure of the power really transferred to the network,
- A controller of excitation that acts on the current of excitation of the excitatory that acts on the current of excitation of the field of the synchronous machine and therefore on the fem E_v. The inputs of this regulator are essentially on the one hand the measures of the current of excitation I_{ex} and the speed N and of the associated references N_{ref} and I_{exref} on the other hand; generated variables from the speed regulator,
- A controller of the duty cyclic ratio of the DC/DC converter, it controls the voltage of the DC link bus of the inverter to the reference value. This controller command the clock of sends signals of the switches of the DC/DC converter. One could consider that the cyclic ratio is quickly feasible and that it useless to integrate it. Actually, the cyclic ratio is linked to a set of very necessary measures to assure a good dynamics of the voltage of the DC bus of the inverter. To take into account the possible delays of these measures, the implication of a regulator of the cyclic ratio is recommended,
- A controller of energy transferred to the network; that permits to inject in the network the totality of the power available to the frequency $50\,Hz$ and under a factor of unit power. From the values of the reference power to transfer P_{ref}, of the voltage V_c of the capacitor and measures from the network, this controller calculates in a first time the amplitude and the phase is of a reference current is of a reference voltage to assure by the inverter. The controller determines in a second time the state of the keys of the inverter.

4.3 Generation of the references of the control structure

4.3.1 References rotor speed and mechanical power

As indicated by the constructor's technical document the convenient sequence of setting in production of the wind turbine begins from a steady speed equal to $750\,rpm$. It allows us to consider that the zero watt of production and the rotation speed $750\,rpm$ is associated to an initial speed of wind of about $3.5\,m/s$ whereas the rated power $800\,kW$ and the rated speed $1500\,rpm$ is associated to a rated wind speed equal to $12\,m/s$. Enters these two boundary-interval of wind speed, the reference of the rotation speed must evolved in a proportional way whereas the reference of mechanical power must correspond to the characteristic indicated by fig.5. When the wind speed exceeds $12\,m/s$, the references of speed and power are saturated to their rated values. We represent this principle in a formal way by the figures 5(a) and 5(b) where V_w, N_{ref} and P_{ref} designate respectively the wind speed, the reference speed of the machine and the level of reference power to convert.

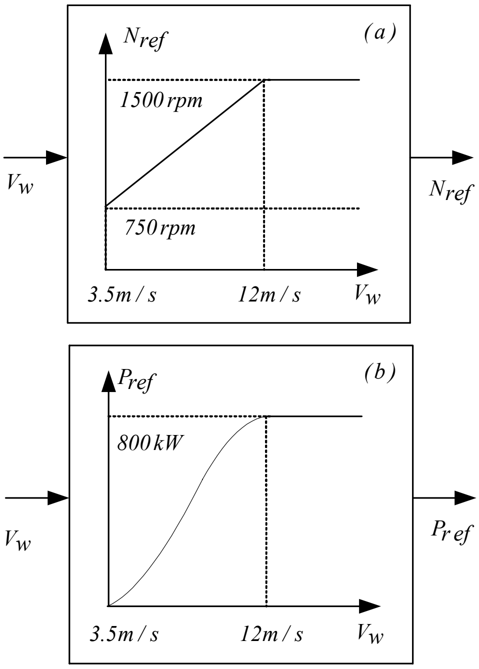

Fig.5: Generation of references rotor speed and mechanical power

4.3.2 References voltage and duty cycle ratio of DC/DC converter

One admits that the role of the voltage controller is to maintain the current of excitation of the field winding of the synchronous generator to a fixed value what permits to guarantee a linear law between the emf of the generator and the rotation speed. For every reference speed N_{ref}, are associated two references; a reference I_{exref} for the field current of the excitatory, and a reference E_{vref} for the emf of the unloaded machine, Fig.6 (a) and (b) depicts the generation references.

In the range of the considered frequency via the characteristic of excitation introduced in the constructor's technical document, we can deduce obtain the following relation between the unloaded emf E_{vref} and the reference speed:

$$E_{vref} = 22.2859 + 0.3645\,N_{ref} \qquad (16)$$

The machine being connected to the DC/DC converter by a rectifier, the reference voltage V_{href} of the supply of this converter corresponds to following voltage straightened average:

$$V_{href} = \frac{3\sqrt{6}}{\pi} E_{vref} = 52.1287 + 0.8526\ N_{ref} \quad (17)$$

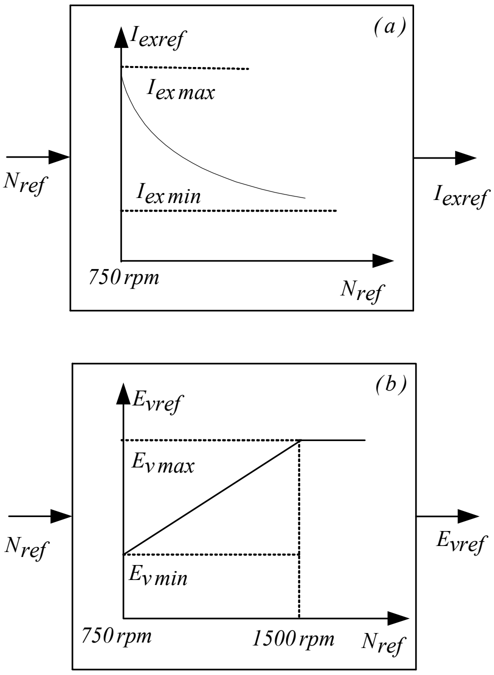

Fig.6: Generation references excitatory current and emf

The reference voltage of the continuous bus of the inverter and the reference voltage of the DC/DC converter define the reference duty-cycle ratio with which the DC/DC converter will be commanded:

$$\alpha_{ref} = 1 - \frac{V_{href}}{V_{cref}} = 1 - \frac{52.1287 + 0.8526\ N_{ref}}{V_{cref}} \qquad (18)$$

4.3.3 Reference current injected in the network

The injected current in the network must be of amplitude and phase allowing the transfer of the reference power P_{ref} with unit power factor. His amplitude is easily determined using the following relation, where I_{chref} is the reference current provided by the continuous bus of the inverter:

$$I_{ref} = \frac{2}{\sqrt{3}} I_{chref} = \frac{2}{\sqrt{3}} \frac{P_{ref}}{V_{cref}} \qquad (19)$$

As representing the network and the transformer by an active receptor formed of a source of amplitude sinusoidal voltage E_r placed behind a resistance R_l and a reactance X_l, the active and the reactive power generated at output of the inverter:

$$\begin{aligned} P &= P_{ref} + R_l\, I_{ref}^2 \\ Q &= -X_l\, I_{ref}^2 \end{aligned} \qquad (20)$$

The phase of the vector current in the reference frame of emf of the network is therefore given by:

$$\gamma_{ref} = a\tan\left(\frac{-Q}{P}\right) \qquad (21)$$

To have the instantaneous wave of the current in the network, it is necessary to have a clock synchronized on the emf of this network to provide the following angle of reference:

$$\begin{aligned} \bar{i}_{ref} &= I_{ref} \exp\left(j\left(\gamma_{ref} + \theta_{ref}\right)\right) \\ \theta_{ref} &= \omega_r\, t \end{aligned} \qquad (22)$$

4.3.4 Estimation of the reference input voltage of the inverter

We have been considered that the dynamics of the DC/DC converter is very fast by comparison to the one of the capacitor. The voltage of the capacitor could be sufficiently estimated by:

$$V_c = \frac{V_h}{1-\alpha} = \frac{3\sqrt{6}}{\pi} \frac{E_v}{1-\alpha} \qquad (23)$$

However, this calculation must take into account the temporal variations of the duty-cycle ratio and the emf of the machine. We admit that the constant of time of the field of the synchronous generator is very weak in front of the one of the excitatory, hypothesis often true for the industrial machines. This hypothesis permits to deduct the unloaded emf directly of the machine according to the current of the excitatory by the characteristic defined by the constrictor. This operation must be achieved with the precaution to take in account the effect of the real value of the rotation speed as:

$$E_v(N, I_{ex}) = \frac{N}{N_b} E_v(N_b, I_{ex}) \qquad (24)$$

While combining the relations (23) and (24), we finally express the dynamics of the voltage of the capacitor at any speed, what current of excitation of the excitatory and what duty-cycle ratio of the DC/DC converter by:

$$V_c(N, I_{ex}, \alpha) = \frac{3\sqrt{6}\,N}{\pi N_b (1-\alpha)} E_v(N_b, I_{ex}) \qquad (25)$$

5. Simulation results

In order to simplify the simulations and in particular to accelerate the time of simulation, we considered controllers described by functions of first-class transfer. The constants of time are worth 0.5 s respectively for the speed regulator, 0.5 sec for the excitation regulator and 0.2 sec for the duty-cycle ratio regulator.

5.1 First case of simulation:

The machine being to the speed $750\,rpm$, one considers a reference wind speed equal to the rated value $12\,m/s$. The power is transferred to the network while controlling the inverter by assuring a unit power factor. This option is well suitable in wind energy application. The current controller is of the type hysteresis.

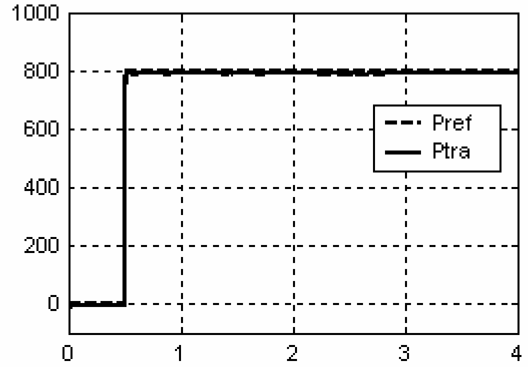

Fig.7: Power wind and power transferred

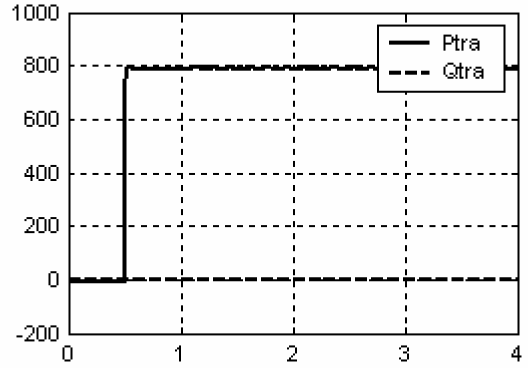

Fig.8: Active and reactive power

Fig.7 depicts the power reference and the power transferred to the grid. Figure 8 shows that effectively the reactive power is null. These characteristics show that all the measured values, such as the powers active and reactive reach their references quickly.

5.2 Second case of simulation:

A scenario of turbulent wind is considered and the structure suggested is simulated. In this simulation, the inverter is controlled in tension also while ensuring a unit power-factor. The goal to change algorithm is to test the controller under large electrical disturbances of wind speed. Fig.9 gives the evolution of the wind turbine.

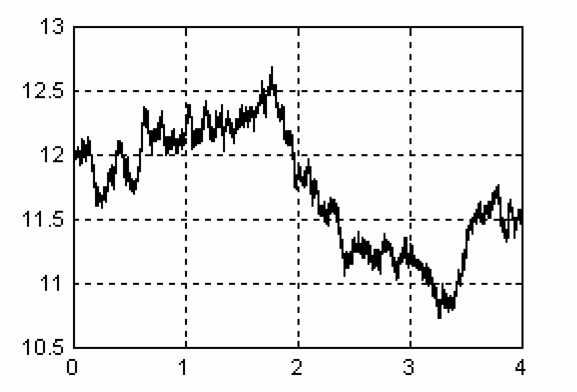

Fig.9: Turbulent wind turbine

Fig.10 represents the power reference generated with a turbulent wind and fig.11 compared the active and reactive power.

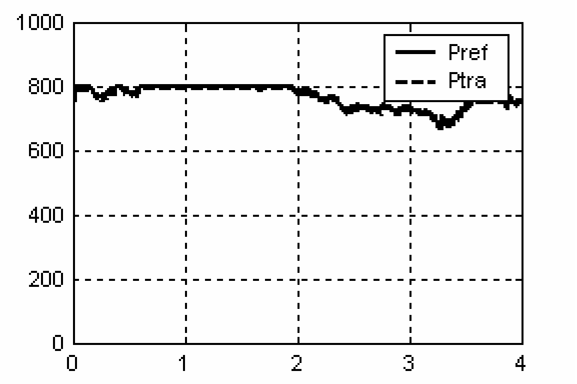

Fig.10: Power wind and power transferred

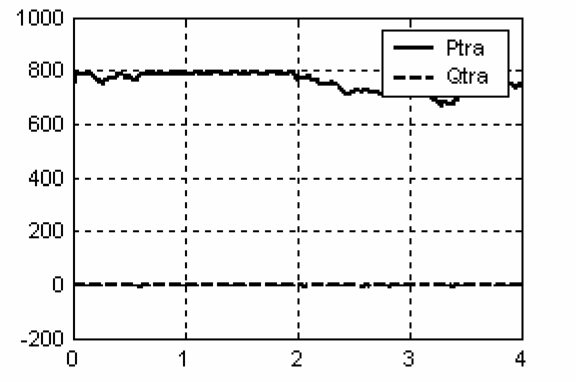

Fig.11: Active and reactive power transferred

6 Conclusion

In this paper, we have developed and simulate a control algorithm which performed a VWECS connected to the network. The considered algorithm is based on the use static converter supply the electrical energy into the grid. The proposed scheme ensures perfect tracking of maximum captured power and improves good dynamics of four control loops. Although, the conception of the suggested controllers does not require the knowledge of the parameters of the machine, and the implementation of the suggested method is simple and does not affect significantly the cost and the complexity of the VWECS drive. It has been shown by simulations that the proposed algorithm gives a good performance for the maximum power tracking.

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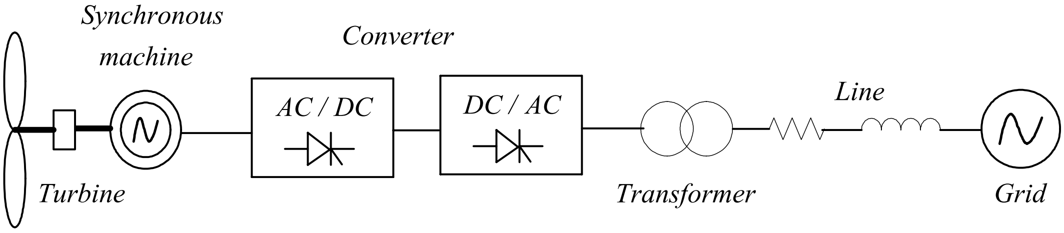

Fig.1: System configuration of the proposed variable-speed power generation system

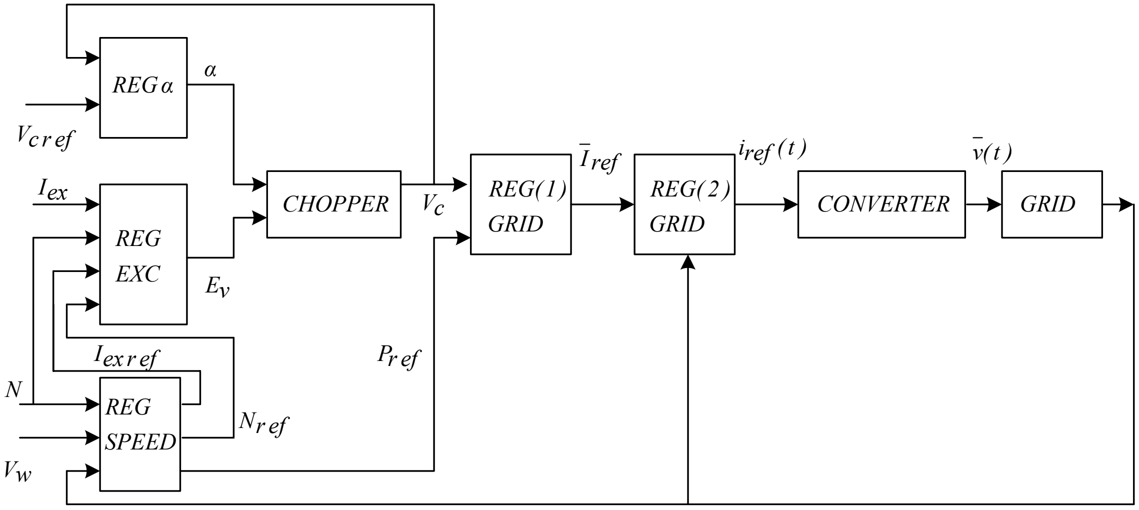

Fig.3: General structure of the control algorithm proposed