Backsetepping Controller of Grid Connected Wind Energy Conversion System with Power Factor Correction

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Abstract—**This paper presents modeling and nonlinear control of a grid connected wind energy conversion system based on a wind turbine using a permanent magnet synchronous generator (PMSG). The objective of the control is: assuring a satisfactory power factor correction (PFC) with respect to the power supply net. First, a model of the whole controlled system is developed in the Park's coordinates. Thereafter control strategies PFC is used to inject power into a grid while keeping a very good power factor. A nonlinear controller is synthesized using the backstepping design technique. A formal analysis based on Lyapunov stability is developed to describe the control system performances. The results of various simulations of all the chain of conversion, carried out under MATLAB/Simulink software, made it possible to evaluate the performances of the proposed system.**

Keywords- Nonlinear control systems, Lyapunov stability, backstepping approach, AC/DC/AC converters, Wind power.

I. INTRODUCTION

Energy consumption in the world grew more and more. To meet the energy needs for the future requires years to find and develop new energy sources. In the immediate future, we have inexhaustible renewable energy resources. We are able to operate more easily and clearly. Due to its renewable nature of the energy and environmental problems reduced, wind energy plays an increasingly important in the production of electricity.
Market growth of wind turbines in the world over the past five years has been about 30% per year, most wind turbines operate at a constant speed (with a tolerable deviation 2.1%) [1]. the turbines would adapt well to the specificities of our country, Morocco and so justifying somewhat the choice of this technology for our present study.
The problems of power factor correction are known and very much discussed currently. Large pallets of solutions are proposed to improve the quality of the power delivered by the mains [2], [3].In particular the victor control [4], and Adaptive Resonant Controller for Grid-Connected Converters in Distributed Power Generation Systems [5].

In this paper, the focus is made on the generation system in Figure 1 based on a permanent synchronous generator.
This system converts the kinetic energy of wind into mechanical energy and then into electricity. The rotor blades of wind capture a portion of the energy contained in wind or transfer to the hub which is fixed on the shaft of the turbine. It then transmits the mechanical power to the electric generator which converts mechanical energy into electrical energy. More than synchronous generator like permanent our system also contains two power converters. The machine side power converter controls the active power and reactive power produced by the machine. As the network side converter, it controls the DC bus voltage and power factor network side.
It is necessary to develop solutions to reduce harmonic distortion caused by classic DC-AC converters. These solutions are grouped under the term "Power Factor Correction" and must allow the network to absorb a sinusoidal current as possible with minimal phase shift between the fundamental current and grid voltage.

We study in this work the three-phase DC-AC converters along with the function of power factor correction and we will examine the simulator Matlab / Simulink.

In this paper, we present a technique for network control side converters. The rest of this paper is organized as follows. Section II recalls the mathematical model of system study and the purpose of the order. Then Section III presents the design of backstepping control law. Experimental results are present in the fourth section, and conclusions are drawn in the last section of this article.

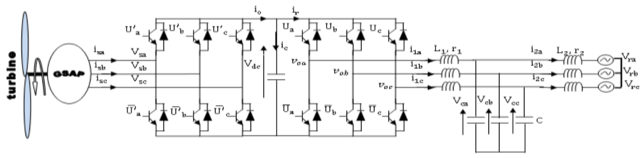

Figure 1. Architecture of AC/DC/AC power converter in wind power system

II. DC/AC CONVERTER MODELING

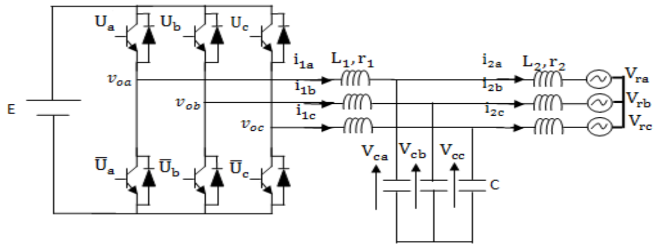

Figure 2. Grid side converter diagram

Applying standard Kirchoff law, one has:

$$L_1 \frac{d\left[i_{1\_abc}\right]}{dt} + -r_1\left[i_{1\_abc}\right] = \left[v_{o\_abc}\right] - \left[v_{c\_abc}\right] \quad (1a)$$

$$L_2 \frac{d\left[i_{2\_abc}\right]}{dt} + -r_2\left[i_{2\_abc}\right] = \left[v_{c\_abc}\right] - \left[v_{r\_abc}\right] \quad (1b)$$

$$C \frac{d\left[v_{c\_abc}\right]}{dt} = \left[i_{1\_abc}\right] - \left[i_{2\_abc}\right] \quad (1c)$$

where

$$\left[i_{1\_abc}\right] = \begin{pmatrix} i_{1a} \\ i_{1b} \\ i_{1c} \end{pmatrix}, \quad \left[i_{2\_abc}\right] = \begin{pmatrix} i_{2a} \\ i_{2b} \\ i_{2c} \end{pmatrix}, \quad \left[v_{c\_abc}\right] = \begin{pmatrix} v_{ca} \\ v_{cb} \\ v_{cc} \end{pmatrix},$$

$$\left[v_{r\_abc}\right] = \begin{pmatrix} i_{ra} \\ i_{rb} \\ i_{rc} \end{pmatrix}, \quad \left[v_{o\_abc}\right] = \begin{pmatrix} i_{oa} \\ i_{ob} \\ i_{oc} \end{pmatrix}$$

(i_{1a}, i_{1b}, i_{1c}), (i_{2a}, i_{2b}, i_{2c})are the triphase abc-components of the current flowing the inductors L_1 and L_2 respectively. (v_{ca}, v_{cb}, v_{cc}), (v_{ra}, v_{rb}, v_{rc}), (v_{oa}, v_{ob}, v_{oc}), are the same components of the voltage across the capacitor, in the grid side and in the output of inverter respectively.

applying well known Park transformation to the model (1) we obtain the following model in dq frame [6].

$$L_1 \frac{di_{1d}}{dt} = -r_1 i_{1d} + v_{od} - v_{cd} + L_1\omega\ i_{1q} \quad (2a)$$

$$L_1 \frac{di_{1q}}{dt} = -r_1 i_{1q} + v_{oq} - v_{cq} - L_1\omega\, i_{1d} \quad (2b)$$

$$L_2 \frac{di_{2d}}{dt} = -r_2 i_{2d} + v_{cd} - v_{rd} + L_2\omega\, i_{2q} \quad (2c)$$

$$L_2 \frac{di_{2q}}{dt} = -r_2 i_{2q} + v_{cq} - v_{rq} - L_2\omega\, i_{2d} \quad (2d)$$

$$C \frac{dv_{cd}}{dt} = i_{1d} - i_{1d} + C\omega\, v_{cq} \quad (2e)$$

$$C \frac{dv_{cq}}{dt} = i_{1q} - i_{1q} - C\omega\, v_{cd} \quad (2f)$$

Where: L_1 and L_2 the self-inductances, r_1 and r_2 are its parasitic resistances, (i_{1d} , i_{1q}), (i_{2d} , i_{2q}) are the dq-components of the current flowing the inductors L_1 and L_2 respectively. (v_{cd} , v_{cq}), (v_{rd} , v_{rq}), (v_{od} , v_{oq}) are the dq-components of the capacitor and grid voltage and in the output of inverter respectively. The inverter is featured by the fact that the grid d- and q-voltage can be controlled independently [7]. In fact, one has:

$$v_{od} = E/2u_d \quad (3a)$$

$$v_{oq} = E/2u_q \quad (3b)$$

where: u_d , u_q represent the average *d*- and *q*-axis (Park's transformation) of the 3 phase duty ratio system (u_a, u_b, u_c). Now, let us introduce the following notation:

$$x_1 = \bar{i}_2,\ x_2 = \bar{v}_c,\ x_3 = \bar{i}_1 \quad (4)$$

where: x represent an averaging value over a cutting period of a real signal $\bar{x}$.

Substituting (3-4) in (2), the state space equations obtained up to now are put together to get a state-space model of the whole system including the DC/AC converter connected to the grid through an *LCL* filter . For convenience, the whole model is rewritten here for future reference:

$$L_2\dot{x}_{1d} = -r_2 x_{1d} + x_{2d} - v_{rd} + L_2\omega\, x_{1q} \quad (5a)$$

$$L_2\dot{x}_{1q} = -r_2 x_{1q} + x_{2q} - v_{rq} - L_2\omega\, x_{1d} \quad (5b)$$

$$C\dot{x}_{2d} = x_{3d} - x_{1d} + C\omega\, x_{2q} \quad (5c)$$

$$C\dot{x}_{2q} = x_{3q} - x_{1q} - C\omega\, x_{2d} \quad (5d)$$

$$L_1\dot{x}_{3d} = -r_1 x_{3d} + E/2u_d - x_{2d} + L_1\omega\, x_{3q} \quad (5e)$$

$$L_1\dot{x}_{3q} = -r_1 x_{3q} + E/2u_q - x_{2q} - L_1\omega\, x_{3d} \quad (5f)$$

III. CONTROLLER DESIGN

In the framework of trajectory tracking, the basic idea of the backstepping control is to make the system loop; equivalent subsystems order a waterfall in stable Lyapunov, which gives it the qualities of strength and overall stability of the asymptotic tracking error. For a large class of systems, this technique is a systematic and recursive method for the synthesis of non-linear control laws. Thus at each stage of the process, a virtual command is generated to ensure the convergence of subsystems to order a further characterizing the trajectories towards their equilibrium states (zero errors in the deterministic and continued unperturbed case) [8]. This technique allows the synthesis of robust control law despite a certain lack of knowledge of the system parameters and certain disturbances.

The control objective is to inject power into grid while keeping a very good power factor (PFC). This means that the system of three-phase current (i_2) must be in phase with the system of grid voltage.

A. Step 1: stabilization of subsystem (5a-b)

Let's define the following tracking error on the current:

$$z_{1d} = (x_{1d} - x_{1d}^*) \quad (6a)$$

$$z_{1q} = (x_{1q} - x_{1q}^*) \quad (6b)$$

where x_{1d}^* and x_{1q}^* are the reference signals (assumed bounded and sufficiently differentiable). Their time derivatives are given by:

$$\dot{z}_{1d} = -r_2 x_{1d} + x_{2d} - v_{rd} + L_2\omega\; x_{1q} - L_2\dot{x}_{1d}^* \quad (7a)$$

$$\dot{z}_{1q} = -r_2 x_{1q} + x_{2q} - v_{rq} + L_2\omega\; x_{1d} - L_2\dot{x}_{1q}^* \quad (7b)$$

Let's assume x_{2d} and x_{2q} to be the virtual control inputs used to ensure global asymptotic stability of the current loop and consider the candidate Lyapunov function as follows:

$$V_1 = \frac{1}{2}z_{1d}^2 + \frac{1}{2}z_{1q}^2 \quad (8)$$

Its time derivative is given by the following equation:

$$\dot{V}_1 = z_{1d}\dot{z}_{1d} + z_{1q}\dot{z}_{1q} \quad (9)$$

A judicious choice of x_{2d} and x_{2q} makes $\dot{V}_1$ negative definite and provides stability for the dynamics of $\dot{z}_{1d}$ and $\dot{z}_{1q}$ is $x_{2d} = x_{2d}^*$ and $x_{2q} = x_{2q}^*$ in such way that:

$$\dot{V}_1 = z_{1d}\dot{z}_{1d} + z_{1q}\dot{z}_{1q} = -c_{1d}z_{1d}^2 - c_{1q}z_{1q}^2 \quad (10)$$

Using (7-10) one easily gets:

$$-r_2 x_{1d} + x_{2d} - v_{rd} + L_2\omega\; x_{1q} - L_2\dot{x}_{1d}^* = -c_{1d}z_{1d} \quad (11a)$$

$$-r_2 x_{1q} + x_{2q} - v_{rq} + L_2\omega\; x_{1d} - L_2\dot{x}_{1q}^* = -c_{1q}z_{1q} \quad (11b)$$

Solving equations (11) with respect to x_{2d} and x_{2q} yields the following stabilizing functions namely x_{2d}^* and x_{2q}^*.

$$x_{2d}^* = -c_{1d}z_{1d} + r_2 x_{1d} + v_{rd} - L_2\omega\, x_{1q} + L_2\dot{x}_{1d}^* \quad (12a)$$

$$x_{2q}^* = -c_{1q}z_{1q} + r_2 x_{1q} + v_{rq} + L_2\omega\, x_{1d} + L_2\dot{x}_{1q}^* \quad (12b)$$

As x_{2d}^* and x_{2q}^* are not the actual control inputs, then we define a second tracking error between stabilizing functions (x_{2d}^*, x_{2q}^*) and virtual control inputs (x_{2d}, x_{2q}).

$$z_{2d} = (x_{2d} - x_{2d}^*) \quad (13a)$$

$$z_{2q} = (x_{2q} - x_{2q}^*) \quad (13b)$$

Tacking into account equations (13), $\dot{z}_{1d}$, $\dot{z}_{1q}$, $\dot{V}_1$ can be rewritten as :

$$\dot{z}_{1d} = -c_{1d}z_{1d} + 1/C\, z_{2d} \quad (14a)$$

$$\dot{z}_{1q} = -c_{1d}z_{1d} + 1/C\, z_{2d} \quad (14b)$$

$$\dot{V}_1 = -c_{1d}z_{1d}^2 - c_{1q}z_{1q}^2 + 1/C\,(z_{1d}z_{2d} + z_{1q}z_{2q}) \quad (15)$$

B. Step 2: stabilization of subsystem (5c-d)

Using (13), ttime derivatives of z_{2d} and z_{2q} are given by:

$$\dot{z}_{2d} = x_{3d} - x_{1d} + C\omega\, x_{2q} - C\dot{x}_{2d}^* \quad (16a)$$

$$\dot{z}_{2q} = x_{3q} - x_{1q} - C\omega\, x_{2d} - C\dot{x}_{2q}^* \quad (16b)$$

The virtual inputs x_{3d} and x_{3q} are used to ensure stability of the voltage loop. The second Lyapunov function is selected such that:

$$V_2 = V_1 + \frac{1}{2}\left(z_{2d}^2 + z_{2q}^2\right) \quad (17)$$

Its derivative is:

$$\dot{V}_2 = -c_{1d}z_{1d}^2 - c_{1q}z_{1q}^2 + z_{2d}\left(\frac{z_{1d}}{C} + \dot{z}_{2d}\right) + z_{2q}\left(\frac{z_{1q}}{C} + \dot{z}_{2q}\right) \quad (18)$$

It can be easily checked that the time derivative $\dot{V}_2$ is a negative definite function of z_{2d}, z_{2q} if the control input is chosen so that:

$$x_{3d}^* = x_{1d} - C\omega\, x_{2q} + C\, \dot{x}_{2d}^* - (c_{2d}z_{2d} + 1/C\, z_{1d}) \quad (19a)$$

$$x_{3q}^* = x_{1q} - C\omega\, x_{2d} + C\, \dot{x}_{2q}^* - (c_{2q}z_{2q} + 1/C\, z_{1q}) \quad (19b)$$

where $c_{2d} > 0$ and $c_{2q} > 0$ are design parameter.

As x_{3d}^* and x_{3q}^* are not the actual control inputs, then we define a third tracking error between stabilizing functions (x_{3d}^*, x_{3q}^*) and virtual control inputs (x_{3d}, x_{3q}).

$$z_{3d} = (x_{3d} - x_{3d}^*) \quad (20a)$$

$$z_{3q} = (x_{3q} - x_{3q}^*) \quad (20b)$$

Tacking into account equations (13), $\dot{z}_{2d}$, $\dot{z}_{2q}$, $\dot{V}_2$ can be rewritten as :

$$\dot{z}_{2d} = -1/C\, z_{1d} - c_{2d}z_{2d} + 1/L_1\, z_{3d} \quad (21a)$$

$$\dot{z}_{2q} = -1/C\, z_{1q} - c_{2q}z_{2q} + 1/L_1\, z_{3q} \quad (21b)$$

$$\dot{V}_2 = -c_{1d}z_{1d}^2 - c_{1q}z_{1q}^2 - c_{2d}z_{2d}^2 - c_{2q}z_{2q}^2 + z_{3d}\left(\frac{z_{2d}}{L_1} + \dot{z}_{3d}\right) + z_{3q}\left(\frac{z_{2q}}{L_1} + \dot{z}_{3q}\right) \quad (22)$$

C. Step 3: stabilization of subsystem (5e-f)

The second design step consists in choosing the actual control signals, u_d and u_q, so that all errors (z_3, z_4, z_5, z_6) converge to zero. To this end, we should make how these errors depend on the actual control signals (u_d, u_q). We start focusing on z_{3d}, z_{3q}; it follows from (20) that:

$$\dot{z}_{3d} = -r_1 x_{3d} + E/2\, u_d - x_{2d} + L_1\omega\, x_{3q} - L_1 \dot{x}_{3d}^* \quad (23a)$$

$$\dot{z}_{3q} = -r_1 x_{3q} + E/2\, u_q - x_{2q} - L_1\omega\, x_{3d} - L_1 \dot{x}_{3q}^* \quad (23b)$$

To analyze the error system, composed of equations (14),(21) let us consider the following augmented Lyapunov function candidate:

$$V_3 = V_2 + \frac{1}{2}z_{3d}^2 + \frac{1}{2}z_{3q}^2) \quad (24)$$

Its time-derivative along the trajectory of the state vector (z_{1d}, z_{1q}, z_{2d}, z_{2q}, z_{3d}, z_{3q}) is:

$$\dot{V}_2 = -c_{1d}z_{1d}^2 - c_{1q}z_{1q}^2 - c_{2d}z_{2d}^2 - c_{2q}z_{2q}^2 + z_{3d}\left(\frac{z_{2d}}{L_1} + \dot{z}_{3d}\right) + z_{3q}\left(\frac{z_{2d}}{L_1} + \dot{z}_{3q}\right) \quad (25)$$

Using (23-25) the control law for the system is given by:

$$u_d^* = 2/E(-c_{3d}z_{3d} - 1/L_1\, z_{2d} + r_1 x_{3d} + x_{2d} - L_1\omega\, x_{3q} + L_2 \dot{x}_{3d}^* \quad (26a)$$

$$u_q^* = 2/E(-c_{3q}z_{3q} - 1/L_1\, z_{2q} + r_1 x_{3q} + x_{2q} + L_1\omega\, x_{3d} + L_2 \dot{x}_{3q}^* \quad (26b)$$

where c_{3d} and c_{3q} are new arbitrary positive real design parameters. Or u_d^* and u_q^* are the actual inputs, then: $u_d^* = u_d$ and $u_q^* = u_q$. Finally, $\dot{z}_{1d}$, $\dot{z}_{1q}$, $\dot{V}_1$ can be rewritten as :

$$\dot{z}_{3d} = -1/L_1\, z_{2d} - c_{3d}z_{3d} \quad (27a)$$

$$\dot{z}_{3q} = -1/L_1\, z_{2q} - c_{3q}z_{3q} \quad (27b)$$

$$\dot{V}_3 = -c_{1d}z_{1d}^2 - c_{1q}z_{1q}^2 - c_{2d}z_{2d}^2 - c_{2q}z_{2q}^2 - c_{3d}z_{3d}^2 - c_{3q}z_{3q}^2 \quad (28)$$

Proposition 1. Consider the system under study, described by its averaging model (1) and assume that the references signals x_{1d}^* and x_{1q}^* are differentiable up to order 3 and bounded, then , in the (z_{1d}, z_{2d}, z_{3d}, z_{1q}, z_{2q}, z_{3q})-coordinate the closed loop system is exponentially stable and is described by:

$$\begin{pmatrix} \dot{z}_d \\ \dot{z}_q \end{pmatrix} = A \begin{pmatrix} z_d \\ z_q \end{pmatrix}$$

where

$$\dot{z}_d = \begin{pmatrix} \dot{z}_{1d} \\ \dot{z}_{2d} \\ \dot{z}_{3d} \end{pmatrix}, \dot{z}_q = \begin{pmatrix} \dot{z}_{1q} \\ \dot{z}_{2q} \\ \dot{z}_{3q} \end{pmatrix}, z_d = \begin{pmatrix} z_{1d} \\ z_{2d} \\ z_{3d} \end{pmatrix}, z_q = \begin{pmatrix} z_{1q} \\ z_{2q} \\ z_{3q} \end{pmatrix}$$

$$A = \begin{pmatrix} A_1 & O_{(3,3)} \\ O_{(3,3)} & A_2 \end{pmatrix}.$$

with:

$$A_1 = \begin{pmatrix} -c_{1d} & 1/C & 0 \\ -1/C & -c_{2d} & 1/L_1 \\ 0 & -1/L_1 & -c_{3d} \end{pmatrix}, A_2 = \begin{pmatrix} -c_{1q} & 1/C & 0 \\ -1/C & -c_{2q} & 1/L_1 \\ 0 & -1/L_1 & -c_{3q} \end{pmatrix}$$

IV. SIMULATIONS

The experimental setup, described by Fig. 3, has been simulated in Matlab/Simulink environment. The involved elements have the following characteristics:

$E = 1000V$, $E_r = 220 * sqrt(2)\ Volt$ $fr = 50Hz$, $\omega = 2 * pi * fr$, $L_1 = 5mH$, $L_2 = 5mH$, $r_1 = 50m\Omega$, $r_2 = 50m\Omega$, $C = 500\mu F$, $i_{2d}^* = 0A$, $i_{2q}^* = -50A$.

The following values of the controller design parameters proved to be suitable: $c_{1d} = 1000$, $c_{1q} = 1000$, $c_{2d} = 750$, $c_{2q} = 750$, $c_{3d} = 750$, $c_{3q} = 750$.

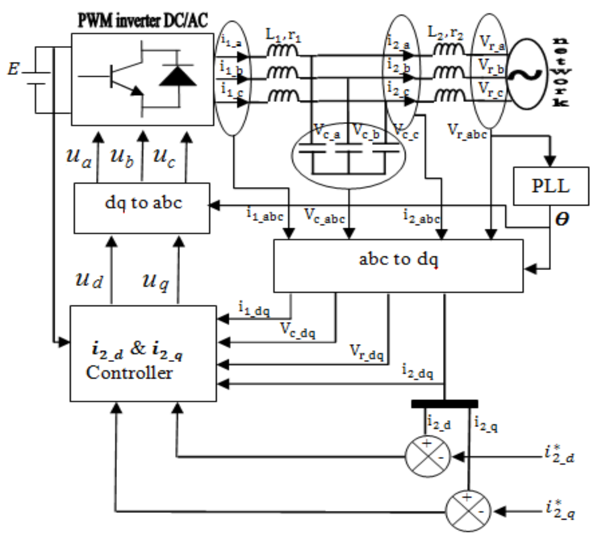

Figure 3. *Control block diagram for double PWM converter with synchronous generator.*

In the followings, it will be presented the simulation results for the operation mode of the converter. A simulation time was considered with fixed step size and ode1 (Euler).

The performance of the controller is shown in Figures 4 which show that the quality monitoring of the proposed controller is quite satisfactory for all controlled variables i_{2d} , i_{2q} .

Fig 5 shows that a unitary power factor is actually achieved. We observe that the estimation results are very satisfactory in terms of robustness, indeed Figure 6 show that from errors of estimation are low.

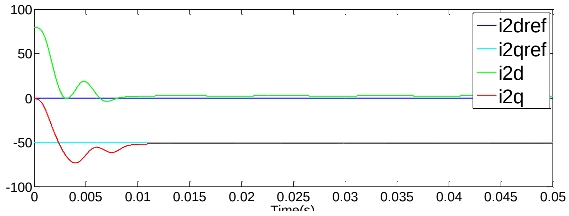

Figure 4. dq-axis current *idq*(A)

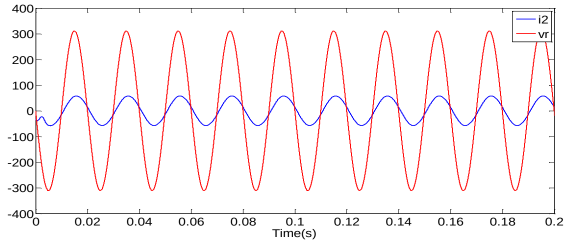

Figure 5. *Current inject* i_2 *A*, Grid *voltage* v_r *V*

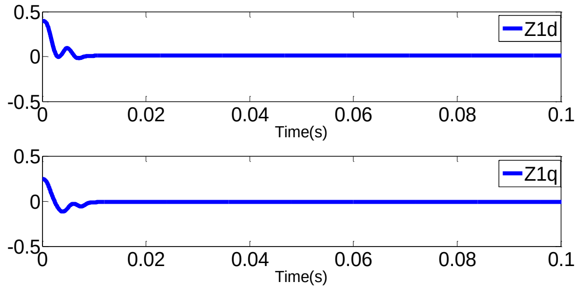

Figure 6. *the tracking error*

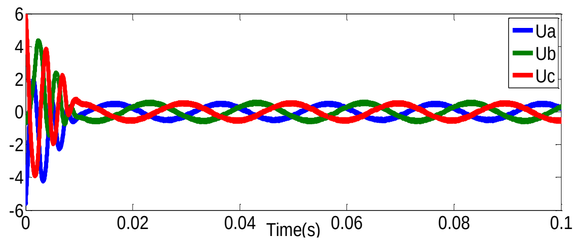

Figure 7. The control signals *abc*-axis

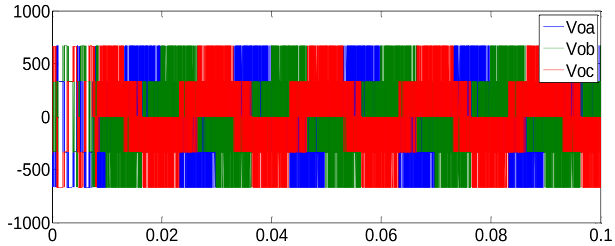

Figure 8. The voltage across the capacitor

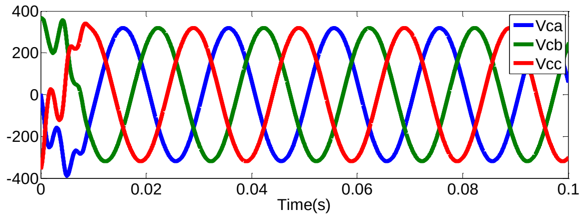

Figure 9. The voltage output of inverter

V. CONCLUSION

In this paper we have considered the problem of controlling the wind turbine synchronous generator connected to the power network through power electronic AC/DC/AC converters. The system dynamics have been described by the averaged 6th order nonlinear state-space model (5a-f). Based on such a model, the Lyaponuv stability and averaging theory are used to design nonlinear controller defined by equations (26a-b). the later guarantees quite interesting average performances: The (average) dq-axis current i_{2d} , i_{2q} track perfectly its reference i_{2d}^{*} , i_{2q}^{*} and consequently the PFC requirement, at the AC network, is satisfied. It is formally established that the control objectives are actually achieved in average with a quite satisfactory accuracy. The formal results are confirmed by several simulations.

in the next study we will generalize the network control for overall system (fig1) synchronous generator / Converters /grid

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