Nonlinear Control of a Grid-Connected Double Fed Induction Generator Based Vertical Axis Wind Turbine: A Residential Application

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Abstract—This paper proposes a robust nonlinear feedback control approach of a residential Savonuis Vertical Axis Wind Turbine (VAWT) based on Double Fed Induction Generator (DFIG) and connected to a powerful grid. However, as the studied system is non linear, it is difficult to be controlled using such traditional methods. Thus, in order to achieve an instantaneous control of both stator active and reactive powers flow, the aim of this approach is to control the Rotor Side Converter (RSC) using a robust non-linear feedback control scheme, in which, a robust control law based on Lyapunov theory associated with a sliding mode controller is used to handle the issue of parameters uncertainty and to guarantee a global asymptotic stability of the system. The proposed approach has been evaluated by simulation results using MATLAB/Simulink.

Index Terms—doubly-fed induction generator, Lyapunov function, vertical axis wind turbine, MPPT, sliding mode

I. INTRODUCTION

With the fast increasing of wind energy installed capacity over the last two decades, it is playing a vital role in world's energy markets at the present. It is expected that global total wind power generation will supply around 12% of the total world electricity generation at the end of 2020 [1], [2]. Among the different alternatives to obtain variable speed wind turbines, the Doubly Fed Induction Machine (DFIM) has become the most preferred configuration in wind energy industry [2], [3].

However, to take advantage of the DFIM in energy generation, a control strategy should be achieved taking into account the grid code requirements, the complexity of the WECS-based DFIG, and hence the quality of energy [4]. However, several designs and arrangements have been implemented to cope with problems related to grid integration of WECS-based DFIG, such as the power factor decrease and harmonic pollutions [5]. The prefered configuration in Wind industry using DFIG (Fig. 1), is described as the stator is connected directly to the grid and the three phase rotor windings are supplied via slip rings from a back-to-back Voltage Source Converter (VSC), the Rotor Side Converter (RSC) & Grid Side Converter (GSC) sharing a DC bus [5], [6]. If the converters control is carried, certainly a decoupled control of the stator side active and reactive power is resulted [7], [4].

A lot of researches have been conducted over the past few years to design a robust control to achieve the maximization of the power capture facing to a varying wind conditions [8], [9]. In this paper, a robust control based on the Lyapunov theory is presented in order to regulate the stator active and reactive power flow. Wind power, even though is an abundant source of energy, the power that can be obtained from it changes throughout the day as wind speed changes continually. The maximum power which a wind turbine can deliver at a certain wind speed depends upon certain optimum value of speed at which the rotor rotates. Extracting maximum possible power from the available wind power is of utmost importance, therefore, MPPT control is an active research area. In order to have maximum possible power, the wind turbine should always operate at optimum tip speed ratio. This is possible by operating the turbine at the optimal rotation speed where the tip speed ratio is optimum [10].



Figure 1. Topology of the DFIG-based WECS

II. WIND AND WIND TURBINE MODELING

The geographical site choice and the characteristics of the wind, where the primary factors determine the quantity of the power energy which will be extracted. To know the properties of the site, wind velocity measurement as well as its direction, over a great period of time, are necessary.

To achieve this work, the wind speed is modeled in deterministic form by a sum of several harmonics as the following form [8]:

$$V(t) = 6 + 0.2\sin(0.1047t) + 0.2\sin(0.2665t) + \sin(1.2930t) + 0.2\sin(3.6645t)$$
(1)

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The wind power available on the turbine shaft, extracted from the power of the wind is given by:

$$P_{mec} = \frac{1}{2} C_p \rho \pi R^2 v^3 \tag{2}$$

 ρ and R are the air density and the radius of the vertical axis wind turbine propeller, respectively.

The power coefficient can be described as the portion of mechanical power extracted directly from the available wind power and represents the aerofoil of the wind turbine.

This power coefficient "Cp" is generally defined as a function of the tip-speed-ratio (λ) as following:

$$C_{p}(\lambda) = -0.12992R\lambda^{3} + 0.11681\lambda^{2} + 0.45406\lambda \quad (3)$$

where, $\lambda = \frac{\omega R}{v}$

 ω corresponds to the speed of the wind turbine.

From Fig. 2 it can be seen that the maximum power extracted from a wind turbine is given by driven the wind turbine at any optimal wind speed.

III. THE DOUBLE FED INDUCTION MACHINE MODEL

It is expressed, in the synchronous reference frame, by the following equations:

Voltage equations:

$$\overline{u}_{s} = R_{s} \cdot \overline{i}_{s} + \frac{d\overline{\Psi}_{s}}{dt} + j \cdot \omega_{s} \cdot \overline{\psi}_{s}$$

$$\overline{u}_{r} = R_{r} \cdot \overline{i}_{r} + \frac{d\overline{\Psi}_{r}}{dt} + j \cdot \omega_{r} \cdot \overline{\psi}_{r}$$
(4)

Current-Flux equations:

$$\begin{cases} \overline{i}_{S} = \gamma \overline{\psi}_{S} + \lambda \overline{\psi}_{r} \\ \overline{i}_{r} = \chi \overline{\psi}_{r} + \lambda \overline{\psi}_{S} \end{cases}$$
(5)

where $\gamma = \frac{1}{\sigma L_s}$, $\lambda = -\frac{1}{\sigma L_s L_r}$, $\chi = \frac{1}{\sigma L_s}$.

From (4) and (5), the all flux state model is given like:

$$\begin{cases} \overline{u}_{s} = \frac{1}{\sigma . T_{s}} \overline{\phi}_{s} - \frac{M}{\sigma . T_{s} . L_{r}} \overline{\phi}_{r} + \frac{d}{dt} \overline{\phi}_{s} + j\omega_{s} \overline{\phi}_{s} \\ \overline{u}_{r} = -\frac{M}{\sigma . T_{r}} L_{s} \overline{\phi}_{s} + \frac{1}{\sigma . T_{r}} \overline{\phi}_{r} + \frac{d}{dt} \overline{\phi}_{r} + j\omega_{r} \overline{\phi}_{r} \end{cases}$$
(6)

The stator power expressions are:

$$\begin{cases} P_{S} = Re\left\{\overline{u}_{S} \cdot \overline{i}_{S}^{*}\right\} \\ Q_{S} = Im\left\{\overline{u}_{S} \cdot \overline{i}_{S}^{*}\right\} \end{cases}$$
(7)

Replacing (5) in (7) with equalization of the real and imaginary parts, the following equation is obtained:

$$\begin{cases} P_{s} = \gamma U_{sd} \cdot \varphi_{sd} + \lambda U_{sd} \cdot \varphi_{rd} + \gamma U_{sq} \cdot \varphi_{sq} + \lambda U_{sq} \cdot \varphi_{rq} \\ Q_{s} = \gamma U_{sq} \cdot \varphi_{sd} + \lambda U_{sq} \cdot \varphi_{rd} - \gamma U_{sd} \cdot \varphi_{sq} - \lambda U_{sd} \cdot \varphi_{rq} \end{cases}$$
(8)

The equalization of the Real parts and Imaginary parts of (6) gives the following [6]:

$$\begin{cases} u_{sd} = \gamma_1 \cdot \varphi_{sd} - \gamma_2 \cdot \varphi_{rd} + \frac{d}{dt} \varphi_{sd} - \omega_s \cdot \varphi_{sq} = -f_1 + \frac{d}{dt} \varphi_{sd} \\ u_{sq} = \gamma_1 \cdot \varphi_{sq} - \gamma_2 \cdot \varphi_{rq} + \frac{d}{dt} \varphi_{sq} + \omega_s \cdot \varphi_{sd} = -f_2 + \frac{d}{dt} \varphi_{sq} \\ u_{rd} = -\gamma_3 \cdot \varphi_{sd} + \gamma_4 \cdot \varphi_{rd} + \frac{d}{dt} \varphi_{rd} - \omega_r \cdot \varphi_{rq} = -f_3 + \frac{d}{dt} \varphi_{rd} \\ u_{rq} = -\gamma_3 \cdot \varphi_{sq} + \gamma_4 \cdot \varphi_{rq} + \frac{d}{dt} \varphi_{rq} + \omega_r \cdot \varphi_{rd} = -f_4 + \frac{d}{dt} \varphi_{rq} \end{cases}$$
(9)
With: $\gamma_1 = \frac{1}{\sigma \cdot T_s}, \gamma_2 = \frac{M}{\sigma \cdot T_s \cdot L_r}, \quad \gamma_3 = \frac{1}{\sigma \cdot T_r \cdot L_s}, \gamma_4 = \frac{1}{\sigma \cdot T_r}$ And,
$$\begin{cases} -f_1 = \gamma_1 \cdot \varphi_{sd} - \gamma_2 \cdot \varphi_{rd} - \omega_s \cdot \varphi_{sq} \\ -f_2 = \gamma_1 \cdot \varphi_{sq} - \gamma_2 \cdot \varphi_{rq} + \omega_s \cdot \varphi_{sd} \\ -f_3 = -\gamma_3 \cdot \varphi_{sd} + \gamma_4 \cdot \varphi_{rd} - \omega_r \cdot \varphi_{rq} \\ -f_4 = -\gamma_3 \cdot \varphi_{sq} + \gamma_4 \cdot \varphi_{rq} + \omega_r \cdot \varphi_{rd} \end{cases}$$
(10)

The rewrite of (9) gives:

$$\begin{cases} \frac{d}{dt}\varphi_{sd} = f_1 + u_{sd} \\ \frac{d}{dt}\varphi_{sq} = f_2 + u_{sq} \\ \frac{d}{dt}\varphi_{rd} = f_3 + u_{rd} \\ \frac{d}{dt}\varphi_{rq} = f_4 + u_{rq} \end{cases}$$
(11)

IV. VECTOR CONTROL STRATEGY OF DFIG

Vector control strategy is based on the following consideration, where the stator voltages are constrained in dq-axis as following [11], [12]:

$$\begin{cases} u_{sd} = 0\\ u_{sq} = u_s \end{cases}$$
(12)

Replacing (12) in (8) the power expressions become:

$$\begin{cases} P_{S} = u_{S}(\lambda . \varphi_{rq} + \gamma . \varphi_{Sq}) \\ Q_{S} = u_{S}(\lambda . \varphi_{rd} + \gamma . \varphi_{Sd}) \end{cases}$$
(13)

Then a Lyapunov function can be defined as following:

$$V_1 = \frac{1}{2}(P_s - P_{sref})^2 + \frac{1}{2}(Q_s - Q_{sref})^2 > 0$$
 (14)

Its derivative is:

$$V_{1} = (P_{s} - P_{sref})(P_{s} - P_{sref}) + (Q_{s} - Q_{sref})(Q_{s} - Q_{sref})$$
(15)

Substitutes (11) and (13) in (15), it results:

$$V_{1} = (P_{s} - P_{sref})(\alpha_{1} + \lambda u_{s} u_{rq} - P_{sref}) +$$

$$(16)$$

$$(Q_{s} - Q_{sref})(\alpha_{2} + \lambda u_{s} u_{rd} - Q_{sref})$$

With: $\alpha_1 = \lambda . u_s . f_4 + \gamma . (f_2 + u_s), \alpha_2 = \lambda . u_s . f_3 + \gamma . f_1$

Then, (16) can be definite negatively if we define the following control law:

$$\begin{cases} u_{rd} = \frac{1}{\lambda . u_s} (-\alpha_2 + \dot{Q}_{sref} - K_2 (Q_s - Q_{sref})) \\ u_{rq} = \frac{1}{\lambda . u_s} (-\alpha_1 + \dot{P}_{sref} - K_1 (P_s - P_{sref})) \end{cases}$$
(17)

Replace (17) in (16) we get:

$$V_1 = -K_1 (P_s - P_{sref})^2 - K_2 (Q_s - Q_{sref})^2 < 0$$
 (18)

So (18) is stable if Ki (i=1, 2) were of course all positives [6], and hence:

$$\begin{cases} \lim_{t \to +\infty} Q_s - Q_{sref} = 0\\ \lim_{t \to +\infty} P_s - P_{sref} = 0 \end{cases}$$
(19)

V. ROBUST NON LINEAR FEEDBACK CONTROL

A large model uncertainty due to parameter variations, noises, and measurement errors is the main problem faces the good control behavior [11]. In this end we propose a novel robust control scheme to deal with this problem. In the kind of feedback control, the model uncertainties are more globally related to the nonlinear function, fi (i=1, 2, 3, 4), than to the parameter drifts. In practice, these nonlinear feedback functions can be strongly affected by the conventional effect of Induction Machine (IM) such as temperature, saturation and skin associated to the different no linearly caused by harmonic pollution and the noise measurements. Globally we can write:

$$\begin{cases} f_i = \hat{f}_i + \Delta f_i \\ \alpha_i = \hat{\alpha}_i + \Delta \alpha_i \end{cases}$$
(20)

NLFF: nonlinear feedback function.

 f_i : NLFF effective;

 Δf_i : NLFF variation around of \hat{f}_i .

 \hat{f}_i : is the true nonlinear feedback function.

The Δf_i can be generated from all parameters and variables as indicated above. We assume that all of the Δf_i are bounded as follows: $|\Delta f_i| < \beta_i$, where β_i is a known bound. Knowledge of the β_i is not difficult to obtain, since one we use a sufficiently large number to satisfy the constraint $|\Delta f_i| < \beta_i$.

Replacing (20) in (11), we obtain:

$$\begin{cases}
\frac{d}{dt}\varphi_{sd} = f_1 + \Delta f_1 + u_{sd} \\
\frac{d}{dt}\varphi_{sq} = f_2 + \Delta f_2 + u_{sq} \\
\frac{d}{dt}\varphi_{rd} = f_3 + \Delta f_3 + u_{rd} \\
\frac{d}{dt}\varphi_{rq} = f_4 + \Delta f_3 + u_{rq}
\end{cases}$$
(21)

Taking into account the Δf_i , the new law control can be chosen as follows:

$$\begin{cases} u_{rd} = \frac{1}{\lambda . u_s} (-\alpha_2 + \dot{Q}_{sref} - K_2 (Q_s - Q_{sref}) - K_{22} sign(Q_s - Q_{sref})) \\ u_{rq} = \frac{1}{\lambda . u_s} (-\alpha_1 + \dot{P}_{sref} - K_1 (P_s - P_{sref}) - K_{11} sign(P_s - P_{sref})) \end{cases}$$
(22)

where, $K_{ii} \ge \beta_i$, $K_i > 0$ and i=1, 2.

Then the analogue derivate Lyapunov function established from (16) using (21) and (22) becomes as follows:

$$V_{2} = (P_{s} - P_{sref})(\Delta \alpha_{1} - K_{11} \operatorname{sgn}(P_{s} - P_{sref})) + (Q_{s} - Q_{sref})(\Delta \alpha_{2} - K_{22} \operatorname{sgn}(Q_{s} - Q_{sref})) + \dot{V}_{1} < 0$$
(23)

Hence the \hat{f}_i variations can be absorbed when the system stability is increased if we choose:

$$K_{11} = |\Delta \alpha_1|$$

$$K_{22} = |\Delta \alpha_2|$$
(24)

Finely we can write:

$$\dot{V}_2 < \dot{V}_1 < 0$$
 (25)

We can conclude that the control law giving by (22) to end at the convergent process stability for any $\hat{\alpha}_i$.

VI. MAXIMUM POWER POINT TRACKING STRATEGY

Several techniques can be used to obtain an MPPT operation of the WECS, such as gradient method, P&O, fuzzy logic...etc.

In this paper, an extracting the maximum wind power through the Savonuis wind turbine needs: Operating at variable speed plus a well-known of the Savonuis wind turbine aerofoil as it is shown in the control scheme (Fig. 2).



Figure 2. Block diagram of DFIG control scheme.

VII. SIMULATION RESULTS

A. Tracking Performance

The DFIG parameters and the vertical axis wind turbine data are given in the appendix below. In order to validate our approach, a digital simulation has been realized using the general block-diagram depicted in Fig. 2. Assume to have a wind speed illustrated by the basic profile defined in Fig. 3. Hence, the obtained results are organized according to the following specifications: the Fig. 4 and Fig. 5 respectively show the active and reactive power injected to the grid, whereas, the active power reference is generated by the MPPT bloc and the reactive power is fixed at 0 VAR, the Fig. 6 shows the Tip speed ratio versus time which is almost maintained to the maximum Tip speed ratio in which the Power Coefficient of the vertical axis wind turbine is maintained to its maximum value as it is shown in the Fig. 7, finally the stator power factor is shown in the Fig. 8 which is also maintained to the unity at all the operation modes, that reflects the good quality of electrical energy injected to the grid.



Figure 5. Stator reactive power response



B. Robustness Performance

The robustness of the structure should be checked against the incertitude of parameters. So the following step is taken to check the robustness against the resistance stator and rotor changing.

It is well-known that the problem in the electrical machines is the changing of their electrical parameters due to the changing of the temperature; these changes may cause some problems. Therefore, in order to know the control structure behavior under these critical conditions, an attempt was made to check it by test of robustness, when the stator and rotor resistances are changed as shown in Fig. 9.

The simulation test was made without the MPPT bloc in order to show clearly the control performance, thus the stator powers references have been chosen as fixed setpoints as it is shown in Fig. 10. The obtained results show the robustness (Fig. 11) of the scheme against a 100% changing of the rotor and stator resistances; although a small disturbances can be observed, they do not have any notable effect on the stator active and reactive powers (figures zoom respectively).



Figure 11. Ps and Qs zooms

3.6

3.8

4

4.2

3.4

VIII. CONCLUSION

Recently the residential WECS's are considered as an important solution of the electrification issue whether in stand alone or grid integration operation. The DFIM double accessibility is an important advantage; it induces a good control of the power flow between the machine and the grid and hence permits to inject the power such that the grid power factor is closed to unity. In this paper, a robust vector control intended for Doubly Fed Induction Generator (DFIG) has been investigated. The stability of the robust control has been guaranteed using the second Lyapunov approach with a sliding mode controller. The test of performance is realized in two ways; first; in order to check the tracking performance from a fluctuated power reference and then the robustness performance against parameters uncertainty is checked by testing the control scheme under a changing of the rotor and stator resistances. The obtained results have demonstrated the efficiency of the proposed control when a good reference tracking has been shown without any recorded effects, and a good robustness against the parameters uncertainty is noted. As a conclusion this proposed control can be considered as an interesting solution in residential wind conversion system.

APPENDIX

The DFIG parameters and the vertical axis wind turbine data are given in the following table:

TABLE. WECS DATA

DFIG data		
Output power	Pn=7.5 KW	
Stator resistance	Rs=0.455 Ω	
Rotor resistance	Rr=0.62 Ω	
Stator inductance	Ls=0.084 H	
Rotor inductance	Lr=0.081 H	
Mutual inductance	Msr= 0.078 H	
Number of poles	4	
Inertia moment	j=0.3125 Nms ²	
Rubbing factor	f=6.73e ⁻³	
Vertical Axis Wind Turbine Data (Savonuis)		
Rated power KW		7
Density of air (ρ) kg/m ³		1.2
Area swept (Diameter × height) m ²		40
Rotor diameter m		4
Tip speed ratio		2.19
Optimal coefficient C _{pmax}		0.19
Gearbox ratio		40

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3.2

3

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