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Research paper

Robust Control of DFIG Wind Turbines in Sub/Super-Synchronous Operation Using Integral Backstepping Controller

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ABSTRACT

This paper presents a robust control strategy for Doubly Fed Induction Generator (DFIG) wind turbines in Sup/Super Synchronous operation using an integral backstepping controller (INT-BCS-Control) based on the Lyapunov function. The objective of this work is to decouple the active and reactive power of the DFIG with high robustness and enhance the performance and reliability of DFIG wind turbines operating in the Sup/Super Synchronous mode within grid-connected systems. The effectiveness of the control strategy is validated through simulations conducted using MATLAB Simulink.

1. INTRODUCTION

As the world industrializes and people consume more electricity, the electricity demand is growing. Fossil fuels are the main source of electricity production, but they are a major contributor to climate change and other environmental problems [1]. Governments are investing in renewable energy sources to ensure sustainable development [2]. The renewable energy sector is becoming more competitive, and wind energy is growing the fastest in the world [3,4].

This work evaluates the impact of integral backstepping control on a wind energy conversion system (WECS) based on a doubly-fed induction generator (DFIG). The DFIG was chosen because it offers several advantages, including improved output power, increased efficiency, grid support capability, variable speed operation, cost-effectiveness, and reduced mechanical stress on the wind turbine [5,6].

Backstepping control is a nonlinear control strategy that decomposes complex systems into simpler subsystems and stabilizes a desired system behavior using a Lyapunov function [6,7]. It was developed

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by Kokotovic in the 1990s [6] and has become a widely studied and used approach for controlling nonlinear systems [8].

This study aims to assess the impact of backstepping control on a DFIG-based WECS, especially under parameter variations. The grid-side converter (GSC) is directly connected to the grid, while the rotor-side converter (RSC) is connected to the grid through a series of converters and transformers [9], as shown in *Figure 1*.

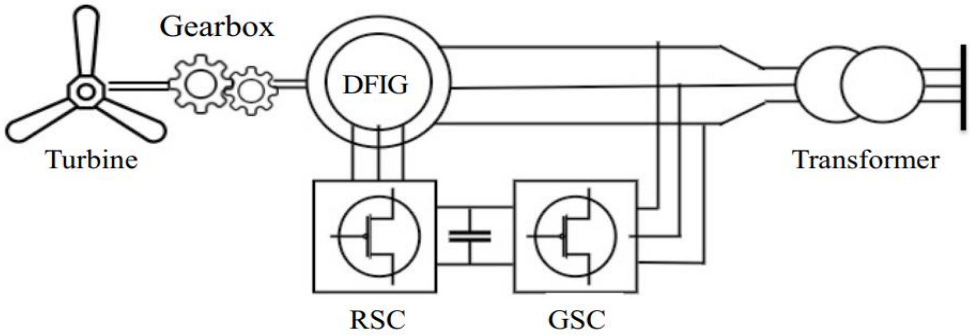

Figure 1. Architecture of wind turbine system (WTS) [10].

This paper is organized as follows: Sections 1 and 2 cover the modeling of the wind turbine and DFIG, while Section 3 presents the modeling of the proposed control (INT-BCS-Control). The effectiveness of this control is confirmed in Section 4 through the presentation of simulation results. Finally, Section 5 wraps up the paper by summarizing and discussing the work that has been presented.

2. WIND TURBINE MODEL

The turbine blades capture wind energy and transfer it through the shaft to the rotor, causing it to rotate. The rotating rotor creates a magnetic field inside the stator, which in turn generates electricity (refer to *Figure 2*).

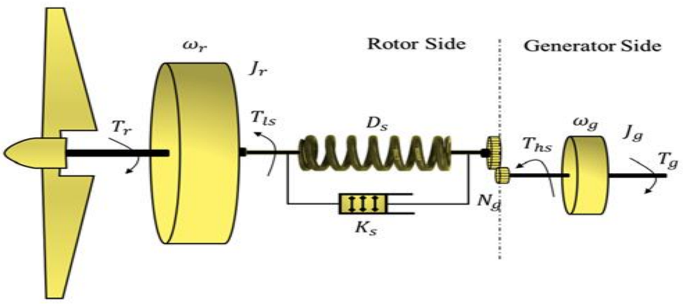

Figure 2. The structure of a wind turbine [7].

The mechanical power of a wind turbine (WT) is proportional to the cube of the wind speed, while the torque is proportional to the square of the wind speed. This means that the mechanical power and torque of a wind turbine increase rapidly with increasing wind speed [1]. The relationship between the mechanical power and torque of a WT can be written by the following formula: [10,11]

$$P_{aero} = \frac{1}{2}.\rho.\pi.R^2.v^3.C_p(\lambda;\beta) \tag{1}$$

$$T_{aero} = \frac{C_p(\lambda;\beta).\rho.\pi.R^2.v^3}{2 \cdot \Omega_{turbine}} \quad (2)$$

With the relative speed λ provided by this equation: $\lambda = \frac{\Omega_t.R}{V}$

Cp can be thought of as the percentage of wind energy that is converted into mechanical energy by the turbine. A higher Cp value indicates a more efficient turbine. The power coefficient Cp is described as follows:

$$C_p(\beta,\lambda) = \left(0.5 - 0.0167.(\beta - 2)\right).\sin\left[\frac{\pi.(\lambda + 0.1)}{18.5 - 0.3.(\beta - 2)}\right] - 0.00184.(\lambda - 3) \quad (3)$$

$$(\beta - 2)$$

Figure 3 shows how the power coefficient changes as the speed ratio (λ) and pitch angle (β) change. The figure shows that the optimal speed ratio for maximum power point tracking (MPPT) mode with β= 0° is λ_{opt} = 8.1, which gives a maximum power coefficient of $C_{p\text{-}max}$= 0.48.[11]

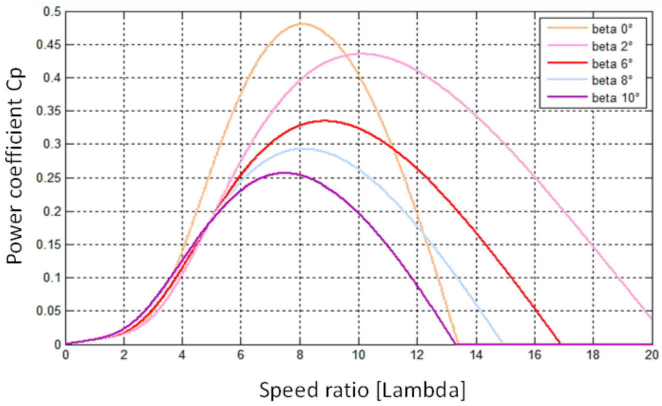

Figure 3. Cp Vs λ

3. DFIG MODEL

The DFIG's electrical equations describe how the voltage and current at the stator and rotor terminals depend on the slip and the speed of the rotor. These equations can be used to model the electrical behavior of the DFIG and to calculate its power output and torque [10-12].

$$\begin{cases} V_{sd} = R_s\, I_{sd} + \frac{d\,\emptyset_{sd}}{dt} - \omega_s\, \emptyset_{sq} \\ V_{sq} = R_s\, I_{sq} + \frac{d\,\emptyset_{sq}}{dt} + \omega_s\, \emptyset_{sd} \\ V_{rd} = R_r\, I_{rd} + \frac{d\,\emptyset_{rd}}{dt} - \omega_r\, \emptyset_{rq} \\ V_{rq} = R_r\, I_{rq} + \frac{d\,\emptyset_{rq}}{dt} + \omega_r\, \emptyset_{rd} \end{cases} \quad (4)$$

With:

$$\begin{cases} \emptyset_{sd} = L_s\, I_{sd} + M\, I_{rd} \\ \emptyset_{sq} = L_s\, I_{sq} + M\, I_{rq} \\ \emptyset_{rd} = L_r\, I_{rd} + M\, I_{sd} \\ \emptyset_{rq} = L_r\, I_{rq} + M\, I_{sq} \end{cases} \tag{5}$$

Mechanical equation:

$$T_{em} = T_r + J\frac{d\Omega_r}{dt} \tag{6}$$

The state model can then be written as:

$$[\dot{X}] = [A].[X] + [B].[U] \tag{7}$$

With:

$$\begin{cases} [X] = [I_{sd}\ I_{sq}\ I_{rd}\ I_{rq}\ ]^t \\ [U] = [V_{sd}\ V_{sq}\ V_{rd}\ V_{rq}\ ]^t \end{cases} \tag{8}$$

Where:

$$[A] = \begin{bmatrix} -a_1 & \mathrm{a}\omega + \omega_s & a_3 & a_5\omega \\ -\mathrm{a}\omega - \omega_s & -a_1 & -a_5\omega & a_3 \\ a_4 & -a_6\omega & -a_2 & -\frac{\omega}{\sigma} + \omega_s \\ a_6\omega & a_4 & \frac{\omega}{\sigma} - \omega_s & -a_2 \end{bmatrix}, [\mathrm{B}] = \begin{bmatrix} b_1 & 0 & -b_3 & 0 \\ 0 & b_1 & 0 & -b_3 \\ -b_3 & 0 & b_2 & 0 \\ 0 & -b_3 & 0 & b_2 \end{bmatrix}$$

$$\alpha = \frac{1-\sigma}{\sigma};\ a_1 = \frac{R_s}{\sigma\, L_s};\ a_2 = \frac{R_r}{\sigma\, L_r};\ a_3 = \frac{R_r\, M}{\sigma\, L_s\, L_r};\ a_4 = \frac{R_s\, M}{\sigma\, L_s\, L_r};\ a_5 = \frac{M}{\sigma\, L_s};\ a_6 = \frac{M}{\sigma\, L_r}$$

Based on the last equations, the DFIG model in Matlab/Simulink can be simplified as shown in the following figure.

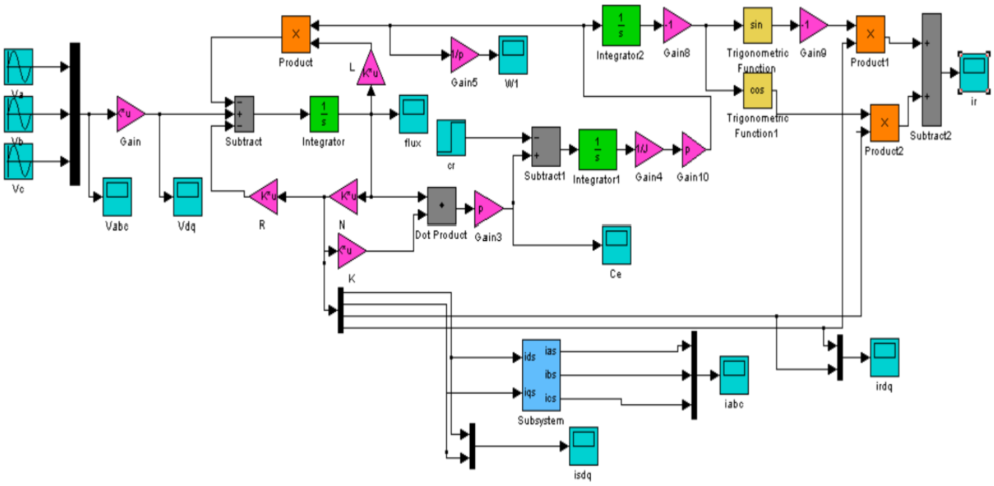

Figure 4. DFIG Module in Matlab/Simulink.

4. INTEGRAL BACKSTEPPING CONTROL

Integral Backstepping (INT-BCS-Control) is a variation of Backstepping control that adds integral action. This makes it more robust to perturbations and can help to eliminate steady-state errors. The error variable is defined as the difference between the actual and desired states of the system. The specific definition of the error variable will depend on the application and system dynamics [11,12].

$$\begin{cases} \dot{e_{01}} = e_{r1} = P_s^* - P_s \\ \dot{e_{02}} = e_{r2} = Q_s^* - Q_s \end{cases} \tag{9}$$

$$\begin{cases} e_{01} = \gamma * \int_0^t e_{r1}(t).dt\,, \qquad \gamma > 0 \\ e_{02} = \gamma * \int_0^t e_{r2}(t).dt\,, \qquad \gamma > 0 \end{cases} \tag{10}$$

Lyapunov function:

$$\begin{cases} V(e_{r1}) = \frac{1}{2}.e_{r1}^2 + \frac{1}{2}.e_{01}^2 \\ V(e_{r2}) = \frac{1}{2}.e_{r2}^2 + \frac{1}{2}.e_{02}^2 \end{cases}$$

Derivative of Lyapunov function:

$$\begin{cases} \dot{V}(e_{r1}) = e_{r1}\,\dot{e_{r1}} + \gamma e_{r1}\,e_{01} \\ \dot{V}(e_{r2}) = e_{r2}\,\dot{e_{r2}} + \gamma e_{r2}\,e_{02} \\ \dot{V}(e_{r1}) = e_{r1}\,(\dot{e_{r1}} + e_{01}) \\ \dot{V}(e_{r2}) = e_{r2}\,(\dot{e_{r2}} + e_{02}) \end{cases} \tag{11}$$

The expression of the Backstepping stabilizer with integral action (INT-BCS-Control) is typically taken as follows:

$$\begin{cases} v_{rd} = -\frac{2}{3}\frac{Y}{X}\dot{Q}_s^* + R_r i_{rd} - g w_s Y i_{rq} - \frac{2}{3}\frac{Y}{X}\,(k_2\,e_{r2} + e_{02}) \\ v_{rq} = -\frac{2}{3}\frac{Y}{X}.\dot{P}_s^* + Y g w_s i_{rd} + R_r i_{rq} + gX - \frac{2}{3}\frac{Y}{X}\,(k_1\,e_{r1} + e_{01}) \end{cases} \tag{12}$$

Where: $\mathrm{X} = \frac{\mathrm{V_s\,L_m}}{\mathrm{L_s}}$, $\mathrm{Y} = \sigma.\mathrm{L_r}$

$$\begin{cases} \dot{V}(e_1) = -k_1\,e_{r1}^2 \\ \dot{V}(e_{r1}, e_{r2}) = -k_1\,e_{r1}^2 - k_2\,e_2^2 \end{cases} \tag{13}$$

With: K_1 and K_2 being positive.

5. SIMULATION RESULTS

The DFIG used in this work is a DFIG that is connected to the grid. The nominal parameters of the DFIG and the turbine parameters are given in Appendix. The INT-BCS-Control will be tested through simulation using MATLAB/SIMULINK software. The following tests will be conducted:

- References tracking and transient response.
- Robustness to perturbations.

5.1 References Tracking and Transient Response

In this case, the wind turbine operates under variable wind speeds, with an average value of 10 m/s, as shown in Figure 5A. Figure 5 represents the simulation results for the INT-BCS-Control of DFIG. The objective of this test is to evaluate the performance of an Integral Backstepping control system in terms of its ability to accurately track specified references.

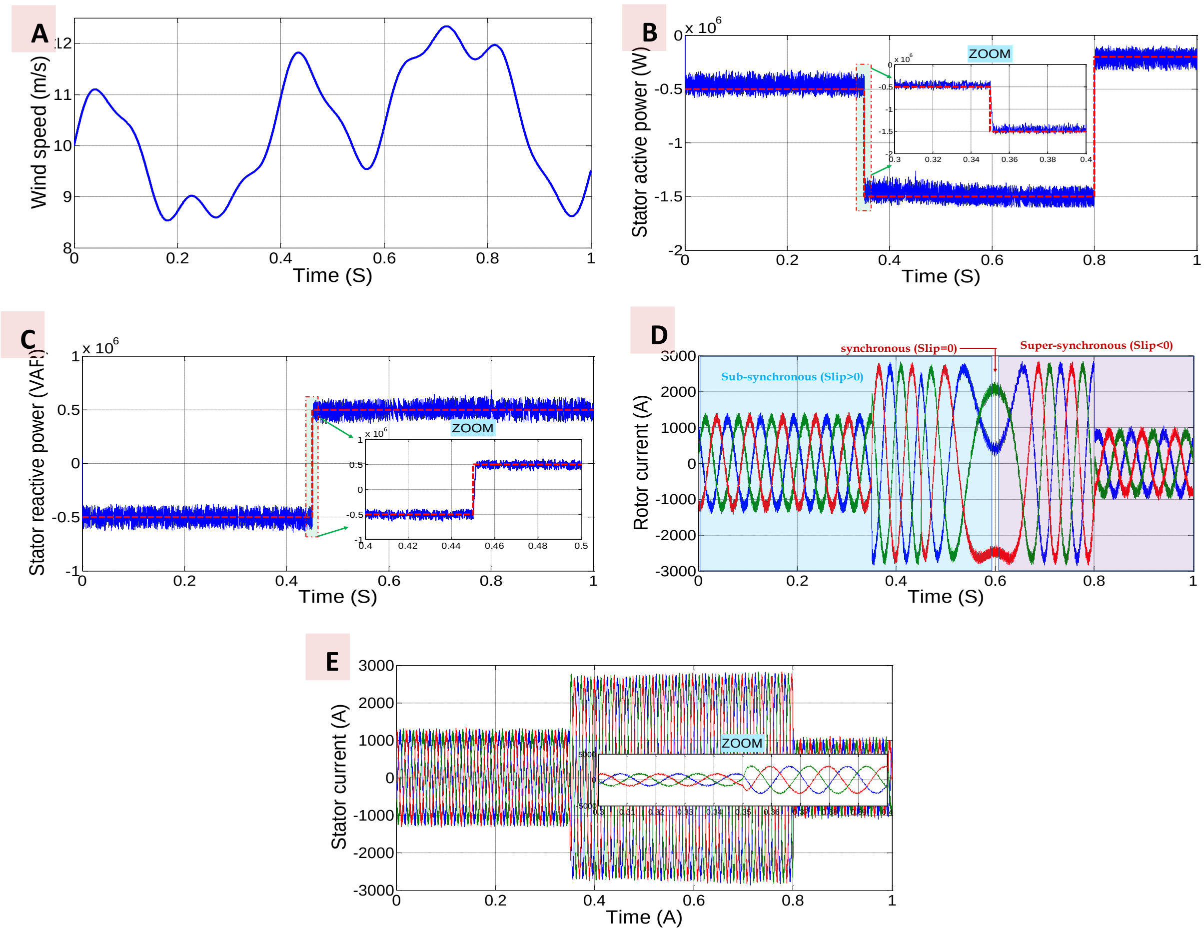

Figure 5. Simulation results of the INT-BCS-Control of WECS-DFIG under random wind speed.

The simulation results show that the INT-BCS-Control is a robust and effective control strategy for DFIG wind turbines. It can accurately track the desired references for both the stator active/reactive power, as evident from the fact that the graphs of the stator active and reactive power closely follow the reference signals. Additionally, the currents, which are proportional to the active power, also exhibit sinusoidal behavior because the INT-BCS-Control is designed to regulate the active/reactive power of the DFIG. The rotor current undergoes a smooth and controlled transition from the Sub-synchronous mode to the Super-synchronous mode of the DFIG at 0.5 seconds because the wind profile applied to the wind turbine changes at this time. The Sub-synchronous mode is the mode in which the rotor speed is less than the synchronous speed of the DFIG, while the Super-synchronous mode is the mode in which the rotor speed is greater than the synchronous speed of the DFIG.

5.2 Robustness to Perturbations

The robustness test was conducted by varying the parameters of the DFIG model. The stator inductance, Ls, and rotor inductance, Lr, were reduced by 10% of their rated values. This was done to analyze the performance of the system. Figure 6 illustrates the simulation results of the INTBCS-Control applied to the DFIG.

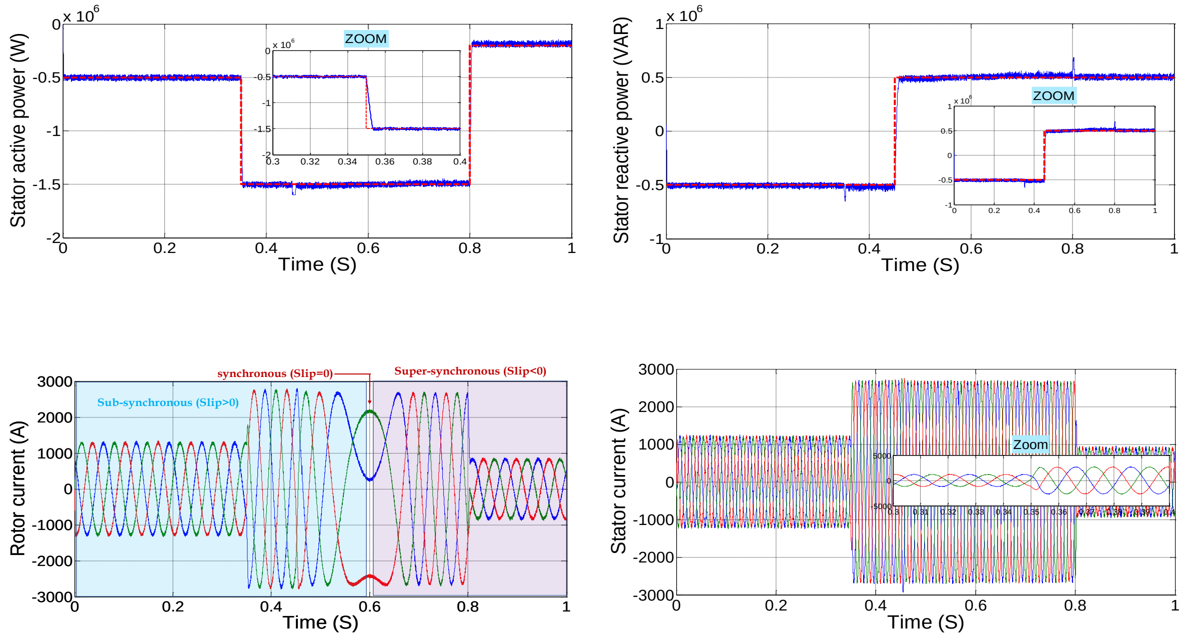

Figure 6. Simulation results of the INT-BCS-Control of WECS-DFIG under parameter variations

The INT-BCS-Control, exhibits good dynamic and static performance, despite variations in the DFIG parameters. This is evident in the curve shown in Figure 6. The response time of the active/reactive powers is fast and impressive, with INT-BCS-Control demonstrating a response time of 0.0007 seconds. However, it is important to note that the last nonlinear method does exhibit high-frequency oscillations, particularly in the rotor currents. This could potentially lead to problems with the power converter or the DFIG itself.

6. CONCLUSION

In this paper, a robust nonlinear control strategy, namely INT-BCS-Control, has been presented. These strategies enable independent control of the active and reactive stator powers of the DFIG, which is driven by a variable-speed wind turbine. The results obtained from robustness tests using MATLAB/Simulink have demonstrated that the INT-BCS-Control strategy is a simple and robust control technique. This strategy has the advantage of being easily implemented in real-time and effectively eliminates static errors while reducing the gap between measurement and reference. Through a comprehensive study of the proposed control method in this paper and based on the simulation results using MATLAB Simulink, we can say that the INT-BCS-Control technique excels in the following aspects:

- References tracking and transient response.
- Good dynamic and static performance.
- Accurately tracks desired reference signals.
- Effective for systems with nonlinear dynamics.
- Robust against uncertainties and disturbances.
- Utilizes Lyapunov stability theory for stability analysis.
- Relatively complex to design and implement.

APPENDIX

The parameters of the DFIG and Wind turbine, in SI units are:

P_n= 1.5Mw, P= 2, R_s= 0.012Ω, R_r= 0.021 Ω, L_s= 0.0137 Ω, L_r= 0.0136 Ω, L_m= 0.0135 Ω, V_{dc}= 1200 volt,
Np= 3, R= 35.25m, G= 90, f_v= 0.0024, J= 1000Kg.m^2

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