Physics of semiconductor devices & renewable energies journal

Vol. 02 n. 01 (2025); ISSN 2992-040X
Journal homepage: www.psdrej.net



Comparative Study of DPC and Backstepping Controllers in a Doubly Fed Induction Generator-Based Wind Energy Conversion System

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Abstract

This paper makes a comparison of two applied control strategies on wind energy conversion systems based on doubly fed induction generator technology: non-linear backstepping and direct power control. Much more effective in managing disturbances and uncertainties is the backstepping, with its nonlinear strategy and robustness. On the other hand, DPC is simple with very quick responses, but it is subject to the constraints of oscillation in the control variables and variable switching frequency. This paper makes a comparative study in assessing the robustness and performance of each method within the different operating regimes of the DFIG, based on simulation results. It is concluded that backstepping is a better solution for a long-time-performance problem, while DPC presents an effective approach for applications that require a faster response and easier method of implementation.

Keywords: *wind energy conversion systems (WECS), Wind Energy(WT); Doubly fed induction generator (DFIG); Backstepping; Direct Power Control (DPC).*

1. Introduction

Renewable energies, therefore, have been at the center of the world's quest for a decarbonized planet and are now moving on toward energy systems with sustainability [1]. Most importantly, in the sector of energy, wind energy is one of the sources with huge potential, which flows from available and renewable resources, as opposed to the rather finite and already well-known environmental worries concerning fossil fuels [2]. Wind energy conversion systems using doubly fed induction generators have found significant adoption in the electricity generation

industry to tap wind resources in the best way, especially during variable wind conditions [3]. It seriously depends on the strategies used to control the energy production and grid integration. All these have acknowledged the simple design and quick response of the power regulation aspect in conventional control strategies like direct power control(DPC) [4]. However, DPC also has several drawbacks, namely: oscillations in the control variables, the undesirability of many applications, and a variable switching frequency, which can lead to instability and the degradation of power quality [5]. Control of such complex problems appears to be promising with the application of the backstepping methodology, which is particularly well known for the robust treatment of problems related to a highly complex system's nonlinearity and uncertainty—much better performance with regard to both stability and dynamic response, particularly in a variable operational environment [6]. Therefore this paper uses a comparison of these two command strategies applied to a DFIG in the energy conversion context from wind. The comparative research is done based on the simulation investigations of the robustness, stability, and performance of every strategy within different operating conditions to reach the most effective strategy that meets the increasing requirement of reliability and performance in modern wind turbine systems.

2. Mdescription of a WCES

The wind energy conversion system relies on a doubly-fed induction generator (DFIG), widely used for its efficiency in modern wind power systems [7]. This system is composed of several interconnected subsystems, including the wind turbine, gearbox, and the DFIG itself. In this setup, the stator of the DFIG is directly connected to the electrical grid, while the rotor is linked via a bidirectional converter, as shown in Fig. 1. This configuration allows for variable speed energy production, maximizing the use of wind resources. Additionally, it provides enhanced control over active and reactive power, ensuring grid stability even under fluctuating wind conditions.

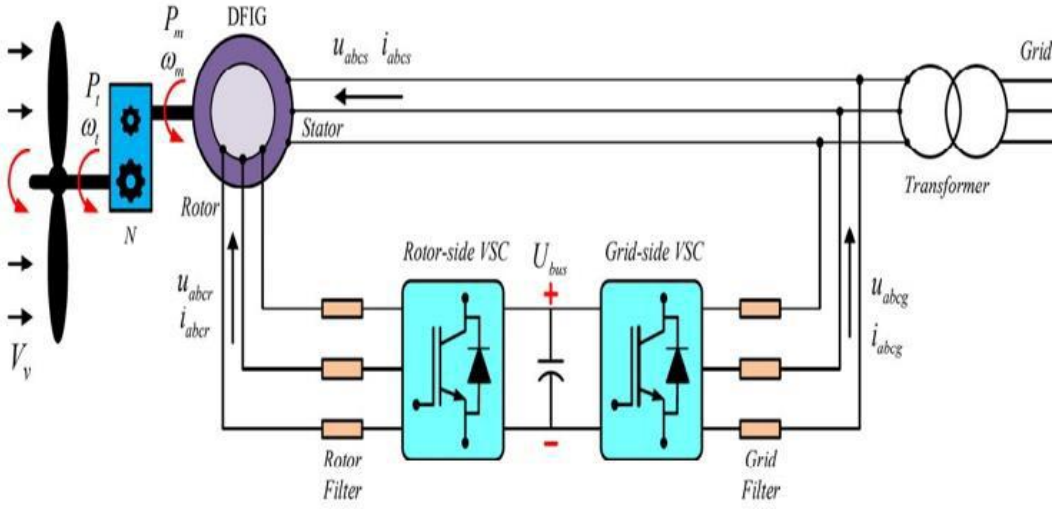


Figure 1: Wind energy conversion system chain with DFIG.

a. *WT modeling*

The power generated by wind under undisturbed conditions can be expressed by the following equation [8]:

$$p_t = p_m cp = \frac{1}{2}\rho\pi {R_t}^2 V^3 Cp(\lambda,\beta) \quad (1)$$

The efficiency of energy conversion, represented by the power coefficient Cp, is influenced by both the aerodynamic characteristics of the wind turbine and its operating conditions . For a fixed pitch angle β, the power coefficient is primarily a function of the tip speed ratio λ. However, with variable pitch control, CP depends on both λ and β, as shown in the following expression [4]:

$$Cp(\lambda,\beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{\frac{-21}{\lambda_i}} + 0.0068\lambda \quad (2)$$

The aerodynamic torque experienced by the turbine can be defined as:

$$T_t := \frac{p_t}{\omega_t} = \frac{1}{2}Cp(\lambda,\beta)\rho\pi {R_t}^2 V^3 \frac{1}{\omega_t} \quad (3)$$

To ensure compatibility between the rotational speed of the turbine and the generator, a gearbox is employed. Despite the presence of energy losses due to friction, flexibility, and other mechanical factors, these are often disregarded in simplified models [9].

$$T_{mec} = \frac{T_i}{G} \quad (4)$$

$$\Omega_t = \frac{\Omega_m}{G} \quad (5)$$

As a result, the fundamental dynamic equation governing the system is expressed as [10]:

$$T_t - T_{em} = \Omega_{mec} f + J_{tot}\frac{d\Omega_{mec}}{dt} \quad (6)$$

b. DFIG modeling

The electrical equations that describe the behavior of the Doubly-Fed Induction Generator (DFIG) in the synchronous reference frame can be expressed as follows [11] :

$$\begin{cases} V_{ds} = R_s i_{ds} + \frac{d\varphi_{ds}}{dt} - \omega_s \varphi_{qs} \\ V_{qs} = R_s i_{qs} + \frac{d\varphi_{qs}}{dt} + \omega_s \varphi_{ds} \\ V_{dr} = R_r i_{dr} + \frac{d\varphi_{dr}}{dt} - \omega_r \varphi_{qr} \\ V_{qr} = R_r i_{qr} + \frac{d\varphi_{qr}}{dt} + \omega - \varphi_{dr} \end{cases} \quad (7)$$

The parameters Rs and Rr correspond to the stator and rotor phase resistances, respectively. The electrical angular velocity, denoted by ω =p·Ω, represents the product of P, the number of pole pairs, and Ω, the mechanical angular velocity.

$$\begin{cases} \varphi_{ds} = l_s i_{ds} + M i_{dr} \\ \varphi_{qs} = l_s i_{qs} + M l_r i_{qr} \\ \varphi_{dr} = l_r i_{dr} + M i_{ds} \\ \varphi_{qr} = l_r i_{qr} + M i_{qs} \end{cases} \quad (8)$$

In this formulation, l_s and l_r denote the stator and rotor inductances, respectively, while M refers to the magnetizing inductance, which represents the mutual coupling between the stator and rotor windings. The currents i_{ds} and i_{qs} are the direct and quadrature components of the stator current, respectively, whereas$idr$and i_{qr} are the direct and quadrature components of the rotor current.

The following are the stator's active and reactive powers [3]:

$$\begin{cases} P_s = \frac{3}{2}\left(V_{ds} i_{ds} + V_{qs} i_{qs}\right) \\ Q_s = \frac{3}{2}\left(V_{qs} i_{ds} + V_{ds} i_{qs}\right) \end{cases} \quad (9)$$

Using the stator flux orientation technique, By choosing a reference frame linked to the stator flux ($\varphi = \varphi_{ds} = \varphi_s$

and $\varphi_{qs} = 0$). Our options are [5]:

$$\begin{cases} \varphi_s = l_s i_{ds} + M i_{dr} \\ 0 = l_s i_{qs} + M l_r i_{qr} \end{cases} \quad (10)$$

Thus the following expression can be used to represent the electromagnetic torque:

$$T_{em} = -\frac{3}{2} p \frac{M}{l_s} (\varphi_s i_{qr}) \quad (11)$$

It is reasonable to assume that the stator resistance R_s can be neglected and that the stator flux φ can be kept constant when the stator is steadily connected to the grid, following the logic of the control design. Therefore, the d and q components of the stator voltages from equation (12) can be rewritten

$$as: \begin{cases} v_{ds} = 0 \\ v_{qs} = v_s = \omega_s \varphi_s \end{cases} \quad (12)$$

Therefore, it is possible to rewrite the relationships between stator current and rotor current as

$$\begin{cases} i_{ds} = \frac{\varphi_s}{l_s} - \frac{l_m}{l_s} i_{dr} \\ i_{qs} = -\frac{l_m}{l_s} i_{qr} \end{cases} \quad (13)$$

Moreover, the stator voltages and currents could indicate the stator's active and reactive powers in the following ways: written as

$$\begin{cases} P_s = -V_s \frac{M}{l_s} i_{qr} \\ Q_s = -V_s \frac{M}{l_s} i_{dr} + \frac{{V_s}^2}{l_s \omega_s} \end{cases} \quad (14)$$

3. DPC technique

In WECS equipped with a (DFIG), the objective of Direct Power Control (DPC) is to regulate the stator's active and reactive powers. This approach is based on principles similar to those of Direct Torque Control (DTC). While DTC directly controls the rotor flux and electromagnetic torque, DPC focuses on the direct regulation of the stator's active and reactive powers [5].

Traditional DPC, designed to optimize the management of active and reactive powers in DFIG systems, has become a key method for enhancing the performance of wind energy conversion systems. The technical specifics and the foundations of this control strategy are detailed in [12].

4. Back stepping technique

Backstepping is a relatively new technique for controlling nonlinear systems. It enables the systematic and sequential selection of a Lyapunov function and the derivation of the system's control law. The core idea is to treat certain state variables as virtual controls and develop intermediate control laws for them, which are then used to constructively derive the overall control law for the nonlinear system [13].

The expression for the rotor voltage is now:

$$\begin{cases} V_{dr} = R_r i_{dr} + \sigma l_r \omega_r i_{qr} \\ V_{qr} = R_r i_{qr} + \sigma l_r \frac{dI_{qr}}{dt} + \sigma l_r \omega_r i_{dr} + \omega_r \frac{M}{Ls} \varphi_s \end{cases} \quad (15)$$

Where:

$$\sigma = 1 - \frac{M^2}{i_r Ls} \quad (16)$$

The expressions for the derivatives of the rotor currents are given by[14]:

$$\begin{cases} i_{rd} = -\frac{1}{\sigma T_r} i_{rd} + g w_s i_{rq} + \frac{1}{\sigma L_r} V_{rd} \\ i_{rq} = -\frac{1}{\sigma}\left(\frac{1}{T_r} + \frac{M^2}{L_s T_s L_r}\right) i_{rq} - g w_s i_{rd} + \frac{1}{\sigma L_r} V_{rq} \end{cases} \quad (17)$$

The expressions for the derivatives of the power are as follows:

$$\frac{dP_s}{dt} = -V_s \frac{M}{L_s} I_{rq} \quad (18)$$

$$\frac{dQ_s}{dt} = -V_s \frac{M}{L_s} I_{rd} \quad (19)$$

a. *First, the active controller*

The active power error is:

$$\begin{cases} e_1 = P_{s_ref} - P_S \\ \dot{e}_1 = \dot{P}_{s_ref} - \dot{P}_S \end{cases} \quad (20)$$

V_1 is described as:

$$V_1 = \frac{1}{2} e_1^2 \quad (21)$$

Then

$$\dot{V}_1 = e_1 \dot{e}_1 = e_1 \left(\dot{P}_{s_ref} + V_s \frac{M}{L_s} \dot{I}_{rq}\right) \quad (22)$$

By substituting the I_{rq} expression in equation (22):

$$\dot{V}_1 = e_1 \left[\dot{P}_{s_ref} + \frac{V_s M}{L_s L_r \sigma} V_{rq} - \frac{V_s M}{L_s L_r \sigma} R_r I_{rq} - \frac{V_s M}{L_s} g w_s I_{rd} - \left(\frac{V_s M}{L_s}\right)^2 . \frac{g}{L_r \sigma}\right] \quad (23)$$

Then

$$\dot{V}_1 = -Z_1 e_1^2 < 0 \quad (24)$$

V_1 has to be negative, for example:

$$\dot{V}_1 = e_1 \left[\dot{P}_{s_ref} + \frac{V_s M}{L_s L_r \sigma} V_{rq} - \frac{V_s M}{L_s L_r \sigma} R_r I_{rq} - \frac{V_s M}{L_s} g w_s I_{rd} - \left(\frac{V_s M}{L_s}\right)^2 . \frac{g}{L_r \sigma}\right] = -Z_1 e_1^2 \quad (25)$$

$V_{rq}, namely$:

$$V_{rq} = -\frac{L_s L_r \sigma}{V_s M}\left(\dot{P}_{sref} + Z_1 e_1\right) + R_r I_{rq} + L_r \sigma g w_s I_{rd} + g \frac{M V_s}{L_s} \quad (26)$$

b. Secend, the reactive controller

The tracking error for reactive power is:

$$\begin{cases} e_2 = Q_{s_ref} - Q_S \\ \dot{e}_2 = \dot{Q}_{s_ref} - \dot{Q}_S \end{cases} \quad (27)$$

Then

$$V_2 = \frac{1}{2} e_2^2 \quad (28)$$

The derivation of the Lyapunov candidate is:

$$\dot{V}_2 = e_2 \dot{e}_2 = e_2 \left(\dot{Q}_{s_ref} + V_s \frac{M}{L_s} \dot{I}_{rq}\right) \quad (29)$$

Equation (21) can be modified by substituting the current derivative I_{rd} expression.

$$\dot{V}_2 = e_2 \left[\dot{Q}_{sref} + \frac{V_s M}{L_s L_r \sigma} V_{rd} - \frac{V_s M}{L_s L_r \sigma} R_r I_{rd} + \frac{V_s M}{L_s} g w_s I_{rq}\right] \quad (30)$$

$$\dot{V}_2 = -Z_2 e_2^2 < 0 \quad (31)$$

To ensure a steady decrease in the derivative of V2 , which requires a negative value, the following references can

be synthesized using variable virtual control:

$$\dot{V}_2 = e_2\left[\dot{Q}_{sref} + \frac{V_s M}{L_s L_r \sigma} V_{rd} - \frac{V_s M}{L_s L_r \sigma} R_r I_{rd} + \frac{V_s M}{L_s} g w_s I_{rq}\right] == -Z_2 e_2^2 \quad (32)$$

$V_{rd}, namely$:

$$V_{rd} = -\frac{L_s L_r \sigma}{V_s M}\left(\dot{Q}_{sref} + Z_2 e_2\right) + R_r I_{rq} - L_r \sigma g w_s I_{rq} \quad (33)$$

5. Simulation results

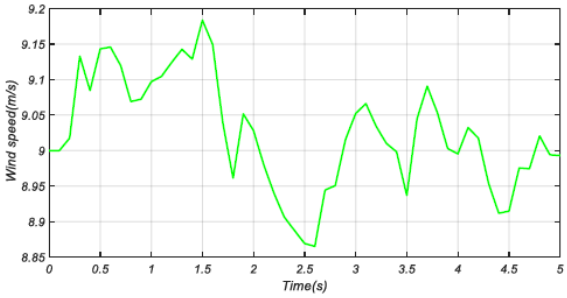


Figure 2: Wind speed.

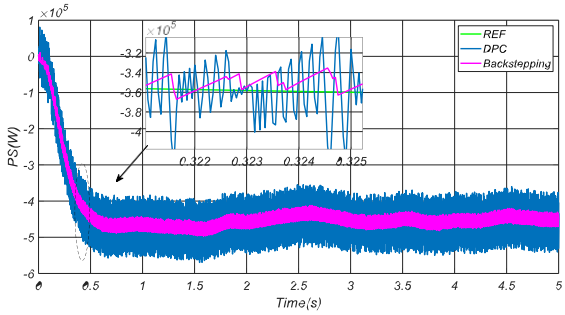


Figure 3: Active power.

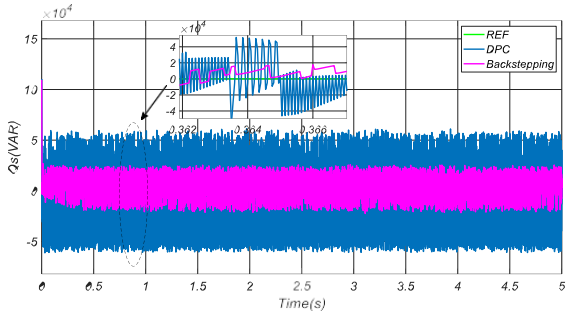


Figure 4: Reactive power .

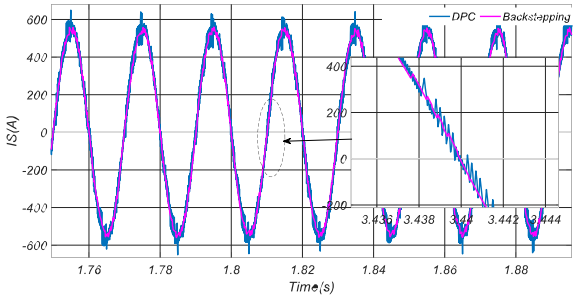
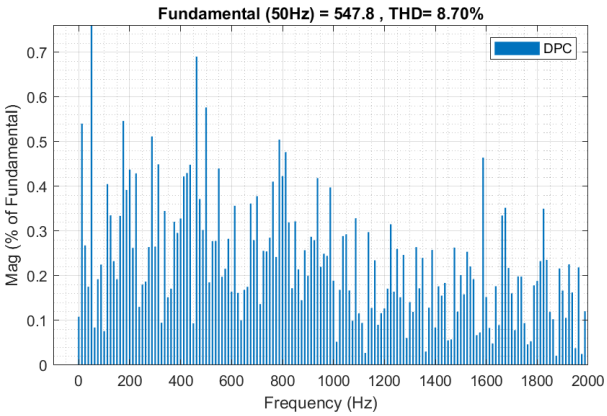


Figure 5: stator current IS.



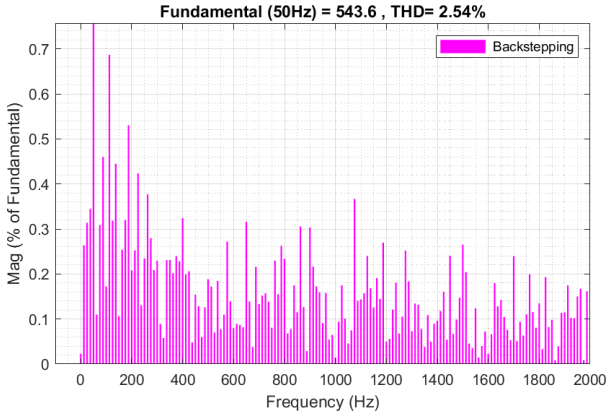


Figure 6: Stator current FFT analysis, (a)DPC, (b) Backstepping

The results presented provide a detailed comparison between the Direct Power Control (DPC) strategy and the Backstepping method, focusing on active power (Ps), reactive power (Qs), and stator current (ISa). Figures 3 and 4 show that DPC leads to significant fluctuations in the regulation of active and reactive power, especially during the initial phases. In contrast, the Backstepping method significantly reduces these fluctuations, leading to faster

energy stabilization and improving the system's response to load variations. Regarding stator current (ISa), Figure 5 reveals that DPC generates more pronounced oscillations, resulting in energy losses and less stable regulation. On the other hand, Backstepping provides a smoother response, reducing oscillations and improving system regulation. Concerning total harmonic distortion (THD), Figures 6(A) and 6(B) demonstrate the superiority of Backstepping, with a THD of 2.54% compared to 8.70% for DPC, significantly improving the quality of the electrical signal and reducing losses. Overall, the Backstepping method outperforms DPC, particularly in terms of power regulation, minimizing oscillations, and reducing harmonic distortions, making it more effective for systems requiring a fast response and higher signal quality

6. Conclusion

In this study, we propose an advanced control method based on the Backstepping technique for the precise regulation of active and reactive power in (DFIGs). The performance of this innovative approach has been thoroughly analyzed and benchmarked against the commonly used (DPC) method.

Simulations conducted in Matlab/Simulink confirm the effectiveness of the DPC approach in DFIG-based WECS. However, DPC exhibits notable limitations, particularly its increased sensitivity to system parameter variations and its implementation complexity. In contrast, the results demonstrate that the Backstepping strategy offers significant advantages, not only by enhancing the stability and quality of electrical power but also by significantly reducing the total harmonic distortion (THD) of the current and minimizing associated energy losses.

Moreover, the Backstepping strategy stands out for its exceptional robustness against external disturbances and parameter variations, making it a highly efficient and reliable solution for complex industrial environments. These findings illustrate that the Backstepping method significantly outperforms DPC under real operating conditions, while offering greater flexibility and reliability for DFIG-based wind energy systems.

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