

Real Time Assessment of Robust Power Control based DFIG-WT: Power Quality Enhancement Delivered to the AC Balanced Load using dSPACE-1103

Fayssal Amrane^{*†}, Azeddine Chaiba^{**}, Habib Benboughenni^{***}, Bruno Francois^{****},
Oussama Gherouat^{*****}, Hichem Itouchene^{*****}

* LAS Research Laboratory, LEPCI Research Laboratory, Department of Electrotechnic, Faculty of Technology, Ferhat ABBAS Setif-1 University, 19000 Setif, Algeria

** Department of Electrical Engineering, Faculty of Technology, University of Batna-2, Algeria

*** Department of Electrical Engineering, Faculty of Technology, Hassiba Benbouali University of Chlef, Chlef, Algeria

**** Univ. Lille, Arts et Métiers Institute of Technology, Centrale Lille, Junia, ULR 2697 - L2EP, F-59000 Lille, France

***** LEPCI Research Laboratory, Department of Automatic, Faculty of Electrical Engineering, University of Sciences and Technology Houari Boumediene, Algeria

***** Université de Bejaia, Faculté de Technologie, Lab de Techn Ind et de l'Information (LTII), 06000 Bejaia, Algeria

(amrane_fayssal@univ-setif.dz, azeddine.chaiba@univ-batna2.dz, habib0264@gmail.com, bruno.francois@centralelille.fr, oussama.gherouat@usthb.edu.dz, hichem.itouchene@univ-bejaia.dz)

[†]Corresponding Author; Fayssal Amrane, Campus El-Maabouda, Université Sétif-1, route de Bejaia, Setif 19000,
Tel: +213 658 26 75 65, amrane_fayssal@univ-setif.dz amranefayssal@gmail.com

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Abstract- The increasing demand for reliable and efficient renewable energy systems has intensified the need for advanced control strategies in Variable Speed Wind Energy Conversion Systems (VSWECS), particularly when operating in stand-alone mode. Doubly Fed Induction Generators (DFIGs) require precise and robust power control to maintain stable operation under varying wind and load conditions. Addressing this challenge, this paper presents the hardware implementation of a Vector Power Control (VPC) strategy for DFIGs operating in stand-alone mode within VSWECS. The proposed VPC approach employs robust Integral-Proportional (IP) controllers to regulate the Rotor Side Converter (RSC) through the d-q components of the rotor current (I_{rd}^* and I_{rq}^*) using an AC-DC-AC converter. The control scheme is experimentally implemented on a dSPACE dS1103 platform and evaluated during both under-synchronous and over-synchronous operation (below and above the 1500 rpm synchronous speed). Experimental results demonstrate that the IP-based control significantly improves dynamic performance, ensures high system stability, and achieves effective decoupled power control of the DFIG-driven wind turbine.

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The system exhibits accurate reference tracking, fast response, and minimal power error, even under abrupt changes in wind speed and rotor current references.

Keywords Vector power control (VPC), doubly fed induction generator (DFIG), integral-proportional (IP), wind energy conversion system (WECS), dSPACE dS1103

1. Introduction

Wind power is a highly favoured and commonly utilized renewable energy source for generating electricity [1-3]. It is accessible year-round, cost-free, and environmentally friendly, as it does not emit harmful gases during energy generation. Turbines play a vital role in converting wind energy into mechanical energy, and there have been notable advancements in wind turbine technology in recent years [4-9].

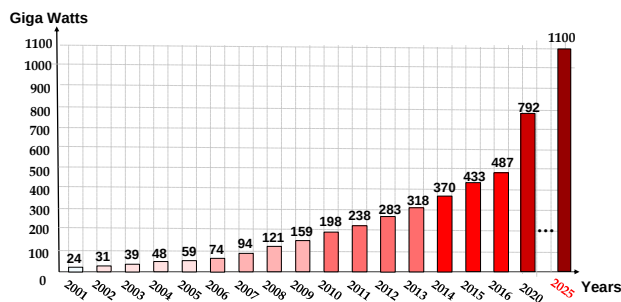


Fig. 1. On-shore cumulative wind power capacity (Giga Watts) from 2001 to 2025.

These advantages include the ability to operate at variable speeds for optimal power capture, decoupled control of active and reactive power, lower converter costs, and reduced overall power losses [10-13]. Figure 1 depicts the global evolution of installed wind power capacity between 2001 and 2020. Over this period, wind energy experienced steady and continuous growth, increasing from just 24 GW in 2001 to more than 1,100 GW in 2020. The figure highlights a gradual rise during the early 2000s, followed by a sharper acceleration after 2010 as wind technology became more cost-effective and widely adopted. In particular, the years after 2015 show significant expansion, with installations reaching 732 GW by 2019 before surpassing the terawatt threshold in 2020. Overall, the figure demonstrates the rapid global shift toward large-scale deployment of wind energy, driven by technological advancements, supportive policies, and increasing demand for clean and sustainable power sources.

The traditional vector power control (VPC) of Doubly Fed Induction Generator (DFIG) based wind turbines has several limitations. First, its performance heavily depends on accurate machine parameters, such as stator and rotor inductances, which can vary with operating conditions, leading to control inaccuracies [14-16]. Second, it relies on precise rotor position measurements, making it sensitive to encoder faults or misalignments [17-18]. Third, the use of proportional-integral (PI) controllers introduces challenges in tuning gains for optimal dynamic response under varying wind speeds [19]. Additionally, the decoupled control of

active and reactive power is often imperfect due to cross-coupling effects, especially during grid disturbances. The method also lacks robustness against grid voltage imbalances and harmonics, which can degrade power quality [20-21].

The Integral-Proportional (IP) controller offers superior performance over traditional PI controllers in DFIG power control due to its enhanced dynamic response and stability [22-23]. Unlike PI controllers, which introduce phase lag and require careful tuning to avoid overshoot, the IP structure provides faster transient response by placing the integral action in the feedback path, reducing oscillations in active and reactive power. This design minimizes steady-state error while improving robustness against parameter variations, such as changes in wind speed or grid disturbances [24-25]. Additionally, IP controllers simplify implementation in stand-alone mode by eliminating the need for decoupling terms, as they inherently handle cross-coupling effects between d- and q-axis currents. In grid-connected operation, IP-based direct power control (DPC) achieves lower harmonic distortion and smoother power tracking compared to PI-based vector control, enhancing power quality [26-27]. The IP controller's adaptability to nonlinearities, such as unbalanced grid voltages, further ensures reliable performance under fault conditions, making it ideal for both isolated and grid-tied DFIG systems [28-30].

In this paper, robust IP controller is proposed instead the traditional PI controller in order to control independently the stator active P_s (W) and reactive powers Q_s (Var) along d-q axes for stand-alone operating mode under RL-balanced load. MPPT strategy is proposed to maintain the maximum power regardless wind speed variation, by keeping the unity power factor close to the unity means the DFIG exchange the active power to the grid.

The main contributions of this paper are illustrated as follow:

- Improved Dynamic Response – The IP controller reduces overshoot and settling time by placing the integral action in the feedback path, enabling faster and smoother power tracking compared to PI controllers.
- Reduced Steady-State Error – The IP structure inherently minimizes power deviations, ensuring more precise regulation of $P_s(W)$ and $Q_s(var)$ under varying operating conditions.
- Elimination of Decoupling Requirements – Unlike PI-based vector control, which needs additional decoupling terms for d-q axis currents, the IP controller naturally mitigates cross-coupling effects, simplifying implementation.
- Simplified Tuning Process – IP controllers require fewer tuning adjustments than PI controllers, as their structure inherently reduces dependency on exact gain matching for optimal performance.
- Lower Harmonic Distortion – When applied in DPC schemes, IP controllers reduce current THD by minimizing

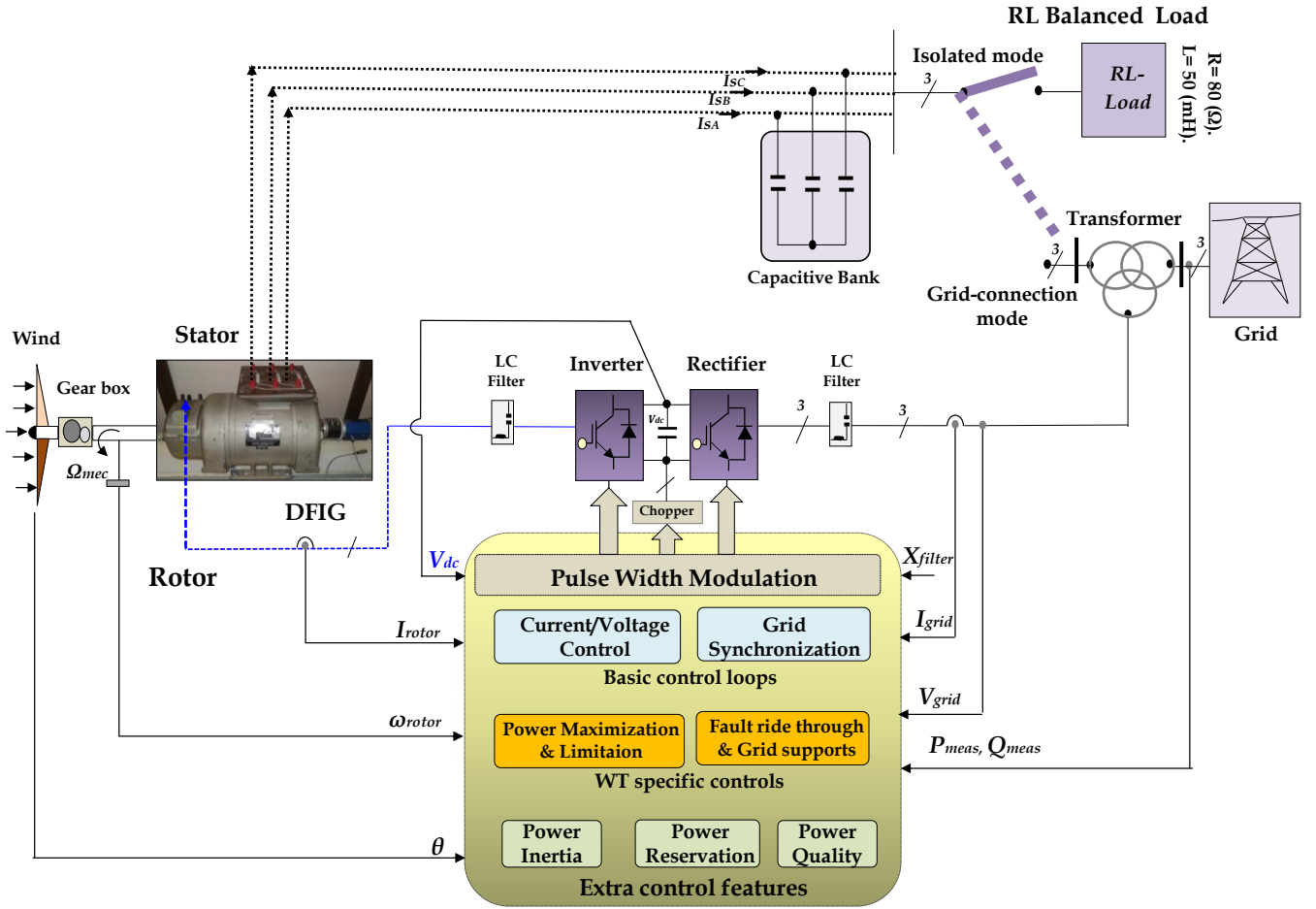


Fig. 2. The power control scheme based on DFIG variable speed Wind turbine for both operating modes: “grid-connection and stand-alone”.

power oscillations, enhancing power quality.

➤ Unified Control for Stand-Alone and Grid-Tied Modes – The IP structure ensures consistent performance in both modes, eliminating the need for control reconfiguration when switching between isolated and grid-connected operations.

This paper is organized as follows; firstly, the modeling of Wind turbine (WT) and DFIG are presented respectively in sections (2 and 3). In Section-4 Vector power control is applied using advanced controllers. In Section 5 power flow characteristics across speed ranges is illustrated and explained. In Section-6, the proposed Integral-Proportional (IP) regulators applied in DFIG-Vector power control is presented. In Section-7, experimental results are shown and discussed. Finally, the reported work is concluded.

Figure 2 presents the DFIG power control scheme for both grid-connection and stand-alone operating modes.

2. Mathematical Model of Wind Turbine (WT)

The input power of a WT can be expressed as mention in Equation (1) [31-36] :

$$P_v = \frac{1}{2} \cdot \rho \cdot S_w \cdot v^3 \quad (1)$$

Where: S_w is the WT blade swept area; ρ is the air density; v is the wind speed. The mechanical power generated by the WT can be expressed as mentioned in Equation (2):

$$P_m = C_p \cdot P_v = \frac{1}{2} \cdot C_p \cdot \rho \cdot S_w \cdot v^3 \quad (2)$$

Where the power coefficient (C_p) represents the WT's power conversion efficiency. C_p is a nonlinear function of the Tip Speed Ratio (TSR or λ) and the blade pitch angle β° (in degrees $^\circ$). λ is defined as the ratio of the turbine blades' tip speed to the wind speed. TSR is given in Equation (3):

$$\lambda = \frac{R \Omega_t}{v} \quad (3)$$

Where: Ω_t is the angular speed of the turbine, and R is the blade radius.

The expression for $C_p(\lambda, \beta)$ can be represented as mentioned in Equation (4): [31-36] :

$$C_p(\lambda, \beta) = (0.5 - 0.0167 \cdot (\beta - 2)) \cdot \sin\left[\frac{\pi(\lambda + 0.1)}{18.5 - 0.3(\beta - 2)}\right] - 0.00184 \cdot (\lambda - 3) \cdot (\beta - 2) \quad (4)$$

In this paper, the sensorless MPPT strategy is applied for variable speed DFIG based on stand-alone mode.

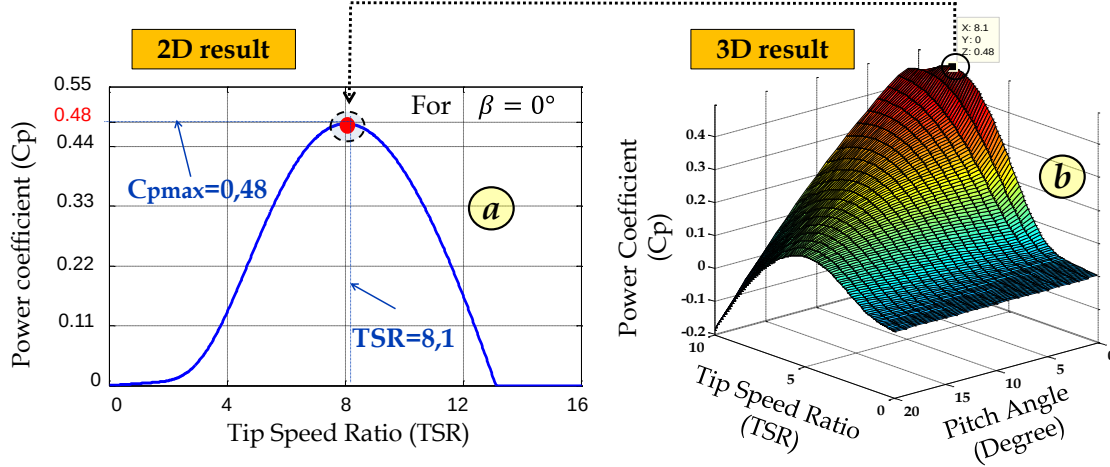


Fig. 3. MPPT simulation results; a: 2D power coefficient versus TSR based on zero pitch angle, and b: 3D power coefficient C_p versus TSR based for different pitch angle β° .

This algorithm calculates the stator power reference as P_s^* by the product of the MPPT's output (the mechanical speed Ω_{mec}) by the electromagnetic torque T_{em}^* , which yields to $P_s^* = \Omega_{mec} \cdot T_{em}^*$. Figure 3a the C_p presents the maximum $C_p=0.48$, is achieved at a pitch angle of zero ($\beta^\circ=0^\circ$), corresponding to the optimal TSR ($\lambda=8.1$). Figure 3b illustrates the three-dimension (3D) characteristic of C_p as a function of the TSR and pitch angles (β°), we can see how the variations of the step angles (β°) influence the C_p result, in this case study, and the relationship in these factors is inversely proportional.

3. Mathematical Model of DFIG

The general electrical state model using Park transformation [31-36]:

Stator and rotor voltages are shown in Equation (5) to Equation (8) :

$$V_{sd} = R_s \cdot I_{sd} + \frac{d}{dt} \Phi_{sd} - \omega_s \cdot \Phi_{sq} \quad (5)$$

$$V_{sq} = R_s \cdot I_{sq} + \frac{d}{dt} \Phi_{sq} + \omega_s \cdot \Phi_{sd} \quad (6)$$

$$V_{rd} = R_r \cdot I_{rd} + \frac{d}{dt} \Phi_{rd} - (\omega_s - \omega_r) \cdot \Phi_{rq} \quad (7)$$

$$V_{rq} = R_r \cdot I_{rq} + \frac{d}{dt} \Phi_{rq} + (\omega_s - \omega_r) \cdot \Phi_{rd} \quad (8)$$

Stator and rotor fluxes are shown in Equation (9) to Equation (12) :

$$\Phi_{sd} = L_s \cdot I_{sd} + L_m \cdot I_{rd} \quad (9)$$

$$\Phi_{sq} = L_s \cdot I_{sq} + L_m \cdot I_{rq} \quad (10)$$

$$\Phi_{rd} = L_r \cdot I_{rd} + L_m \cdot I_{sd} \quad (11)$$

$$\Phi_{rq} = L_r \cdot I_{rq} + L_m \cdot I_{sq} \quad (12)$$

The electromagnetic torque is given in Eq. (13):

$$T_{em} = P \cdot L_m \cdot (I_{rd} \cdot I_{sq} - I_{rq} \cdot I_{sd}) \quad (13)$$

And its associated motion equation are given in Equation (14) to Equation (16)):

$$T_{vis} = f \cdot \Omega_{mec} \quad (14)$$

$$T_{em} - T_r = J \cdot \frac{d}{dt} \Omega_{mec} + T_{vis} \quad (15)$$

$$J = \frac{J_{turbine}}{G^2} + J_g \quad (16)$$

Where; R_s , R_r , L_r , and L_s : are respectively the resistances and the inductances of the stator of the rotor circuit and L_m is the mutual inductance, σ : is the leakage factor $\sigma = 1 - \frac{L_m^2}{L_s \cdot L_r}$.

V_{sd} , V_{sq} , V_{rd} , V_{rq} , I_{sd} , I_{sq} , I_{rd} , I_{rq} , Φ_{sd} , Φ_{sq} , Φ_{rd} and Φ_{rq} : illustrate respectively the components along the d and q axis of the stator and rotor voltages, currents and flux. T_{em} , T_r , and T_{vis} : are the electromagnetic, load, and viscous torques. J_g , $J_{turbine}$ and J : are respectively the generator, turbine and total inertia, Ω_{mec} : is the mechanical speed, and G : is the gain of gearbox. P : is the number of pole pairs, ω_s is the stator pulsation, ω_r : is the rotor pulsation, ω_{slip} : is the slip pulsation and f : is the friction coefficient. Knowing that: $\omega_{slip} = (\omega_s - \omega_r)$.

Figure.4 shows a descriptive diagram of the three-phase stator and rotor windings.

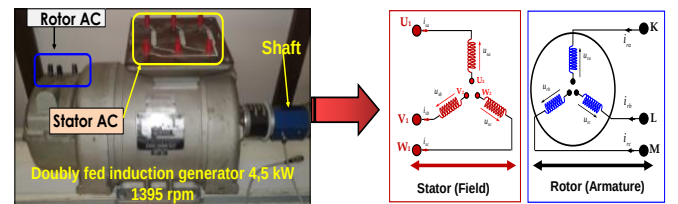


Fig. 4. The DFIG' stator and rotor windings.

4. Vector Power Control based on Advanced Controller

From Equation (18), it is evident that the torque can be controlled by manipulating the rotor quadrature current component (I_{rq}) of the DFIG. Similarly, the direct rotor current component (I_{rd}) is employed to manage the generated reactive power (Equation (17)):

$$Q_s^* = \frac{V_s^2}{\omega_s \cdot L_s} - V_s \frac{L_m}{L_s} \cdot I_{rd}^* \quad (17)$$

$$I_{rq}^* = \frac{L_s}{P \cdot L_m \cdot \Phi_s} \cdot T_{em}^* \quad (18)$$

$$I_{rd}^* = \frac{\Phi_s}{L_m} - \frac{L_s}{V_s \cdot L_m} \cdot Q_s^* \quad (19)$$

$$I_{rq}^* = \frac{L_s}{V_s \cdot L_m} \cdot P_s^* \quad (20)$$

Figure 5 shows the fundamental mechanical characteristic torque as a function of the speed of the DFIG. We note the different operating quadrants of the DFIM, in our case study we will be exclusively interested in the generator operating mode (negative electromagnetic torque $T_{em} < 0$). The ideal operating zone of the DFIG is the stable zone (or so-called nominal or rated), this zone represents +/- 30% of the rotation speed of the rotor shaft, we can see that the torque/speed characteristic behaves like a linear straight line, beyond this zone the characteristic becomes non-linear.

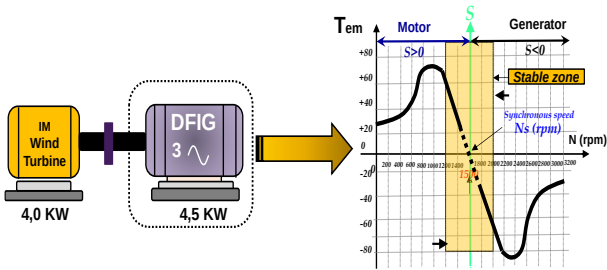


Fig. 5. The DFIG mechanical characteristic torque versus speed of the DFIG.

5. Power flow characteristics across speed ranges

Figure 6 clearly demonstrates the relationship between rotor speed and power flow direction. The system exhibits two distinct operational modes [31-36]:

5.1 Sub-synchronous Operation ($n < 1500 \text{ rpm}$):

The rotor absorbs power from the grid through the back-to-back converter, which corresponds to positive slip conditions.

5.2 Super-synchronous Operation ($n > 1500 \text{ rpm}$):

The rotor delivers power to the grid via the back-to-back converter, which corresponds to negative slip conditions.

5.3 The synchronous speed ($n = n_s = 1500 \text{ rpm}$):

This speed zone represents the critical transition point between operational modes. As illustrated in Figure 6, the back-to-back converter enables seamless bidirectional power

transfer across this threshold, effectively managing the transition between sub- and super-synchronous states.

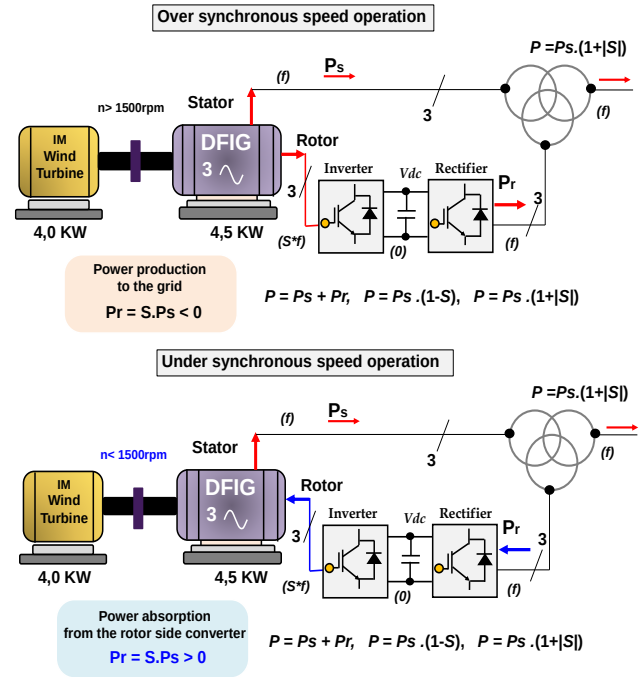


Fig. 6. Rotor power flow when the rotor speed changes (Over synchronous and Under-synchronous operating modes).

Figure 7 represents simulation results of generated power from the DFIG when the rotation speed changes. From this figures, there are three operating zone: starting zone, MPPT (maximum power point tracking) zone and blade orientation zone. The MPPT zone is ideal one, in this case the rotation speed is near the synchronous speed which means the stable zone (linear function: Torque versus Speed, the slip is very small (close to 5%) and the rotor power flow depends on the sign of the slip (+: production the power and -: injection the power).

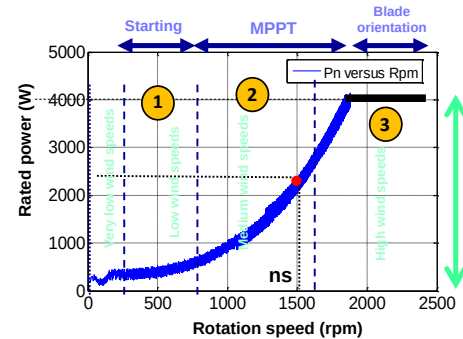


Fig. 7. Power curve versus rotation speed: under three operating zones.

6. The proposed integral-proportional (IP) regulators applied in vector power control

For compensation implementation, the open-loop transfer function (OLTF) is formulated with a time constant fixed at 10ms, which ensures satisfactory dynamic response suitable for the slow wind speed variations and large mechanical time constants involved [22].

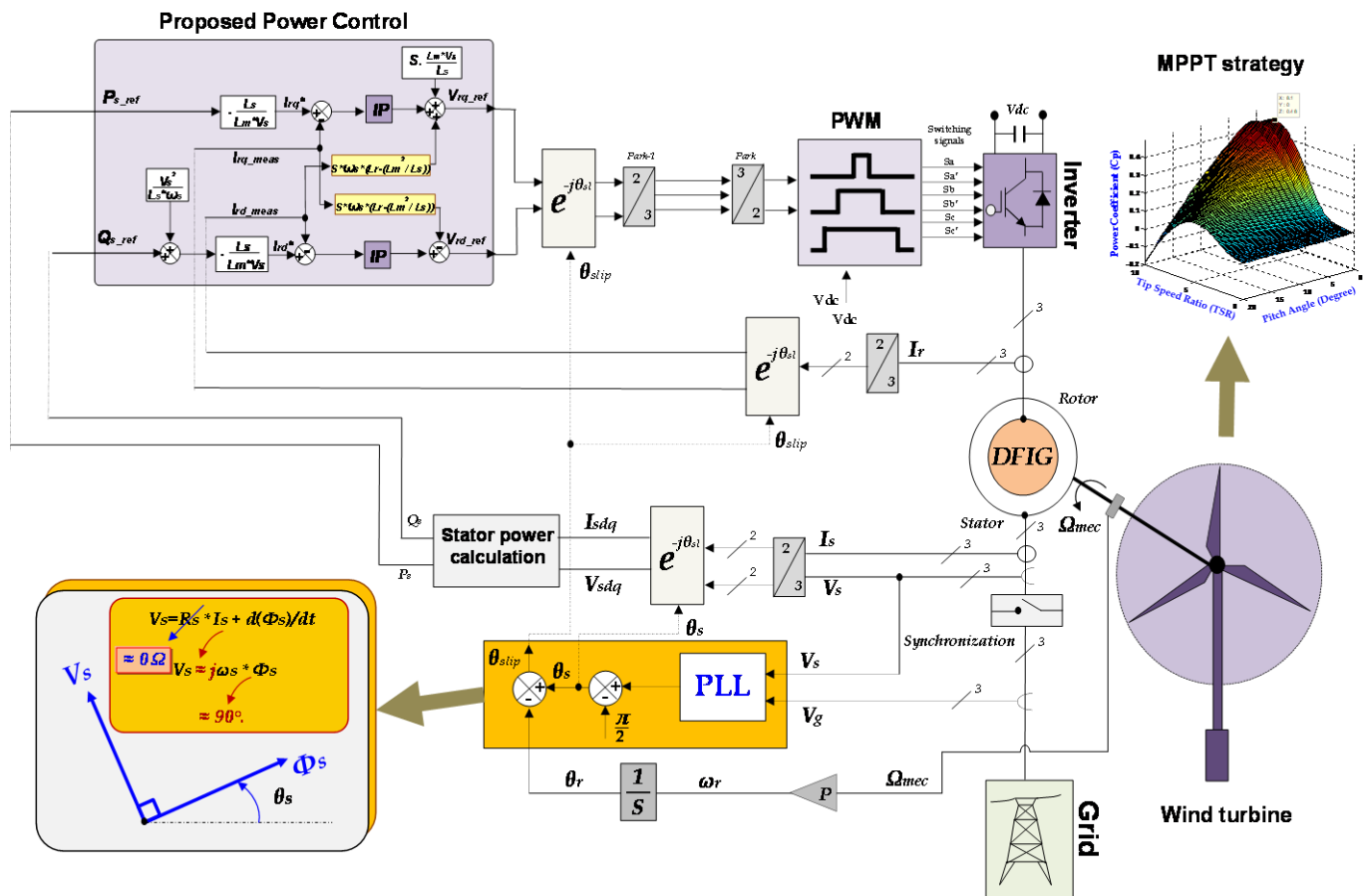


Fig. 8. Block Diagram of a WECS based on DFIG with proposed power control.

The control design process begins by simplifying the system to a single-variable model. The closed-loop transfer function (CLTF) incorporating the PI controller is then derived, where "S" denotes the Laplace variable. Through identification with a standard second-order system transfer function, the controller gains are expressed in terms of the machine parameters. Substituting the expressions for parameters A and B yields the final controller design equations.

The initial control strategy involves reducing the complex system to a manageable single-variable representation. The resulting CLTF with IP control action is formulated as shown below, with "S" representing the complex frequency variable in the Laplace domain (as mentioned in Equation (21)).

$$CLTF = \frac{Output}{Input\_ref} = \frac{K_{ip} \cdot Kp_{ip} \cdot A}{S^2 + (Kp_{ip} \cdot A + B)S + K_{ip} \cdot Kp_{ip} \cdot A}$$

Such as:
$$\begin{cases} A = \frac{L_m \cdot V_s}{L_s \cdot L_r - L_m^2} \\ B = \frac{L_s \cdot R_r}{L_s \cdot L_r - L_m^2} \end{cases} \quad (21)$$

Using the identification process with a 2nd-order transfer function (TF) system [22] as mentioned in Equation (22):

$$CLTF = \frac{V_{rdq}}{I_{rda}} = \frac{k \cdot \omega_n^2}{S^2 + (2 \cdot \xi \cdot \omega_n) \cdot S + \omega_n^2} \quad (22)$$

The correctors' gains will be calculated as a function of the machine parameters, as shown in Equation (23):

$$\left\{ \begin{array}{l} Ki_{ip} = \frac{\omega_n^2}{Kp_{ip} \cdot A} \\ Kp_{ip} = \frac{2 \cdot \xi \cdot \omega_n - B}{A} \end{array} \right. \quad (23)$$

Upon substitution of A and B with their respective expressions, as mentioned in Equation (24):

$$\left\{ \begin{array}{l} Ki_{ip} = \frac{\omega_n^2 \cdot (L_s \cdot L_r - L_m^2)}{Kp_{ip} \cdot L_m \cdot V_s} \\ Kp_{ip} = \frac{2 \cdot \xi \cdot \omega_n \cdot (L_s \cdot L_r - L_m^2) - L_s \cdot R_r}{L_m \cdot V_s} \end{array} \right. \quad (24)$$

The damping coefficient ξ governs the system's behavior at its natural frequency, determining whether the response

will be attenuated or exhibit resonance. To achieve the desired performance specification of less than 5% overshoot, a damping ratio exceeding 0.7 is required.

The system's dynamic response varies significantly with different ξ values. For critically damped and over damped conditions ($\xi \geq 1$), both rise time and settling time deteriorate. In the under damped region ($\xi < 1$), the response time increases as damping decreases due to amplified oscillations and extended transient periods.

An optimal compromise between adequate damping and fast response is attained at approximately $\xi = 0.7$. This value maintains the overshoot below the 5% threshold while providing minimal response time. The theoretically optimal damping ratio is $\xi = 1/\sqrt{2} \approx 0.707$, which represents the ideal balance between these competing requirements. During simulation, the natural frequency will be tuned to achieve this optimal performance characteristic

Figure 8 presents a detailed diagram of the proposed power algorithm based on IP regulators, in order to control independently the stator active and reactive powers $P_s(W)$ and $Q_s(Var)$ of the DFIG along the two d-q axes.

7. Experimental Assessment under dSPACE1103

Experimental tests were performed on a 4.5 kW laboratory-scale setup to assess the performance of the pro-

DFIG and the 4 kW wind turbine emulator and experimental conditions are provided in Appendix (Tables 4, 5 and 7 respectively). Figure 9 displays the experimental setup at the L2EP Laboratory (École Centrale de Lille), highlighting the key components and equipment used in this study.

In this configuration (refer to Figure 10), the stator is connected to an RL balanced load through bank capacitors; the RL-Load parameters are illustrated in Table 6. Experimental results are presented for three operational modes: Under-synchronous, synchronous, and Over-synchronous operation. The hardware tests were conducted using a dSPACE1103 card integrated with MATLAB environment and ControlDesk.

This section investigates the DFIG's operational behavior by analyzing sinusoidal rotor current dynamics. Figure 11 demonstrates the measured rotor current response during speed transitions around 1500 rpm (synchronous zone), capturing both sub-synchronous to super-synchronous transitions and vice versa.

The rotor currents (I_{rabc} (A)) follow patterns that correlate with wind speed variations. These measurements, along with shaft speed data, were acquired using an oscilloscope through dSPACE1103 and ControlDesk system. Current regulation is achieved through slip angle control

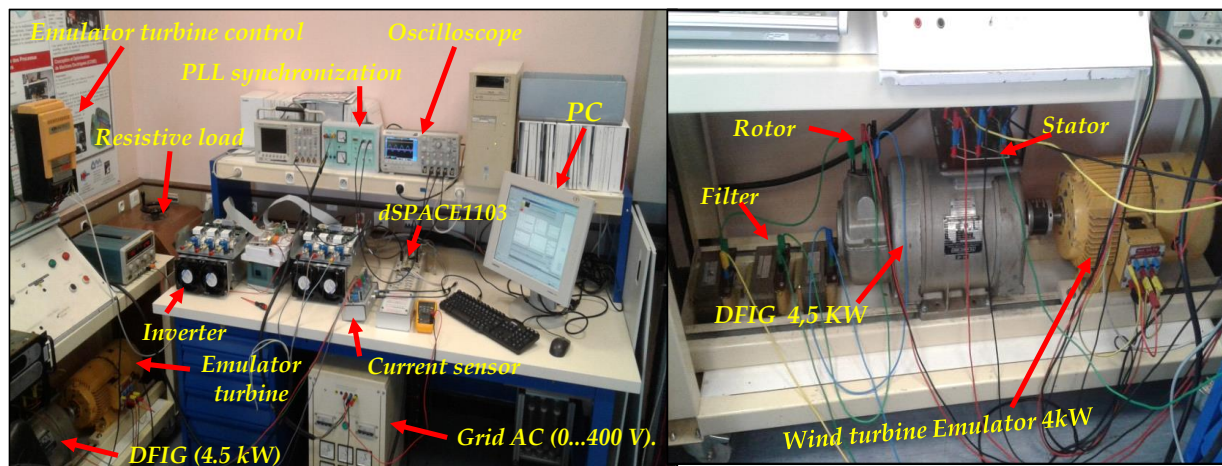


Fig. 9. Hardware test bench based on a 4.5 KW DFIG via dSPACE1103 (L2EP Laboratory, EC-Lille).

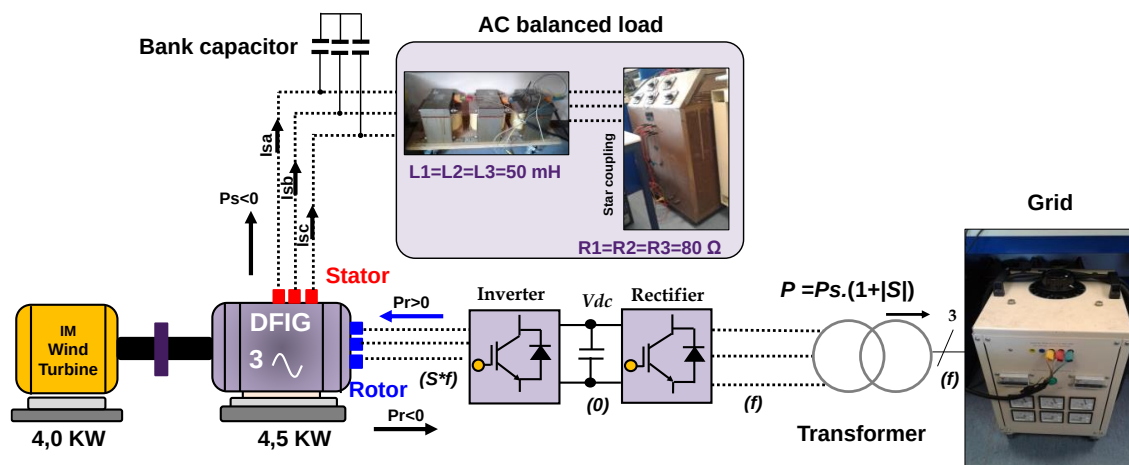


Fig. 10. The proposed experimental DFIG power control scheme.

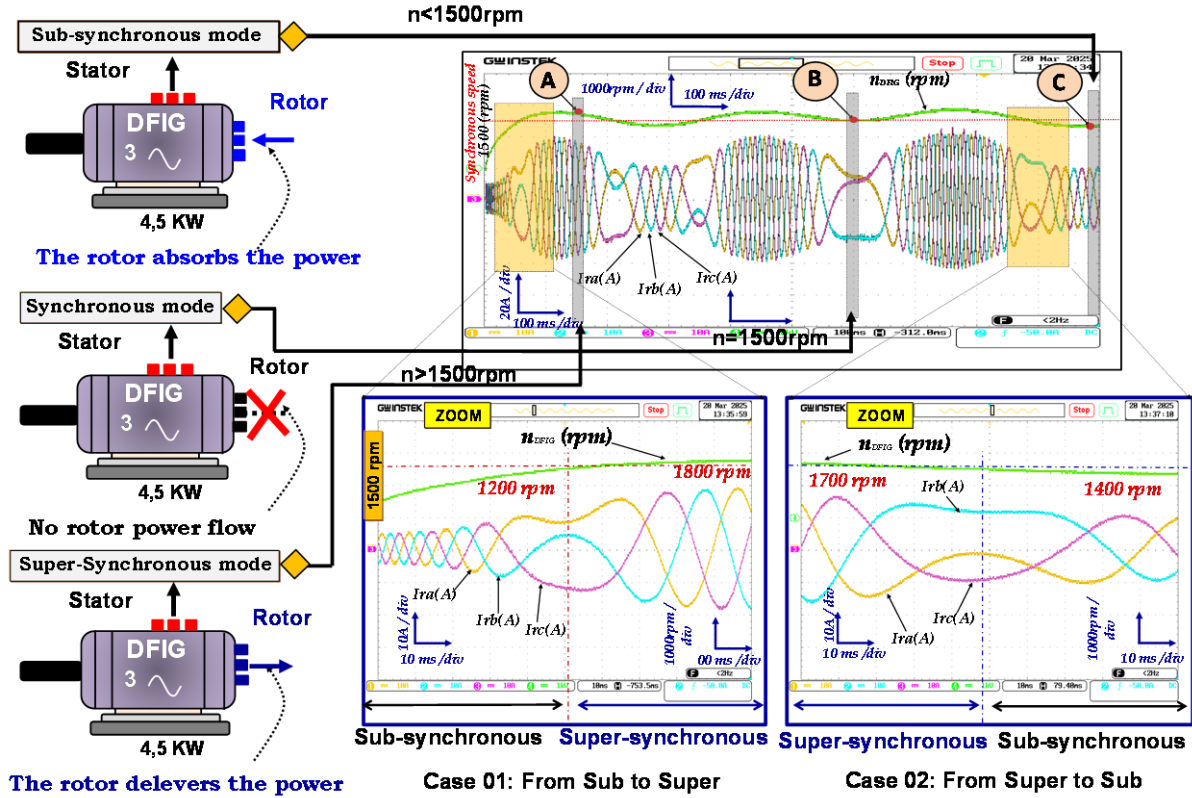


Fig. 11. Experimental results for the various operating modes of the DFIG.

$(\theta_{slip} = \int |\omega_{slip}| = (\omega_s - \omega_r) dt + \theta_0$, where: $\omega_s = 2\pi.f$, (stator frequency) and $\omega_r = P \cdot \Omega_{mec}$ (rotor speed). As the rotor speed varies with wind speed (governed by MPPT control), the power flow direction adapts accordingly:

- Sub- to super-synchronous transition: Rotor absorbs grid power.
- Super- to sub-synchronous transition: Rotor injects power into the grid via back-to-back converter.

Table 1 provides a comprehensive summary of DFIG speed values for both operational scenarios.

Table 1. Shaft speed values for DFIG operating modes.

Cases	DFIG operation mode :
Case 01:	Transition from Sub to Super-synchronous speed: $\Rightarrow$ 1200 rpm to 1800 rpm
Case 02:	Transition from Super to sub-synchronous speed: $\Rightarrow$ 1700 rpm to 1400 rpm

According to Figure 11, point "A" corresponds to Super-synchronous operation, meaning that the DFIG injects electrical energy into the grid via B-2-B converters; the amount of energy delivered corresponds exclusively to the value of the slip realized at each instant of operation of the DFIG. In this case study, the slip $S_A = (1500-1750) / 1500 = -0.143$, therefore the rotor power injected into the grid equals $P_r = -0.143 \cdot 4000 = -572W$.

Point "B" corresponds to Synchronous operation, meaning that the DFIG neither injects electrical energy into the grid nor absorbs energy, this is due to the absence of slip ($S_B = 0$), in other words the shaft rotation speed equals the synchronous speed $n = n_s = 1500\text{rpm}$, therefore the rotor power equals $P_r = 0 \cdot 4000 = 0W$.

Point "C" corresponds to Sub-synchronous operation, meaning that the DFIG absorbs energy from the grid via the B-2-B converters. The amount of energy absorbed depends exclusively on the slip value achieved at each instant of DFIG operation. In this case study, the slip $S_C = (1500-1400)/1500 = +0.067$, so the rotor power injected into the grid is equal to $P_r = +0.067 \cdot 4000 = +268W$.

Figure 12 illustrates the behavior of the stator and rotor currents under varying d-q axis rotor currents for three generator speeds: 1000 rpm, 1500 rpm, and 1700 rpm. The results demonstrate that the DFIG operates effectively with high performance across all operating regimes—sub-synchronous, synchronous, and super-synchronous. The current trajectories closely follow their references, exhibiting excellent tracking at both low and high speeds, which highlights the superior stability provided by the proposed IP controller.

The direct and quadrature rotor currents, I_{rd} (A) and I_{rq} (A), were varied between 0 and -10 A, with the negative sign indicating generator mode operation. Notably, the stator and rotor currents (Figure 12-(a, b, and c)) maintain a perfectly sinusoidal waveform, confirming the robustness and efficiency of the IP controller. The system exhibits a fast response time, minimal overshoot (nearly negligible), and a low static power error (less than 3%).

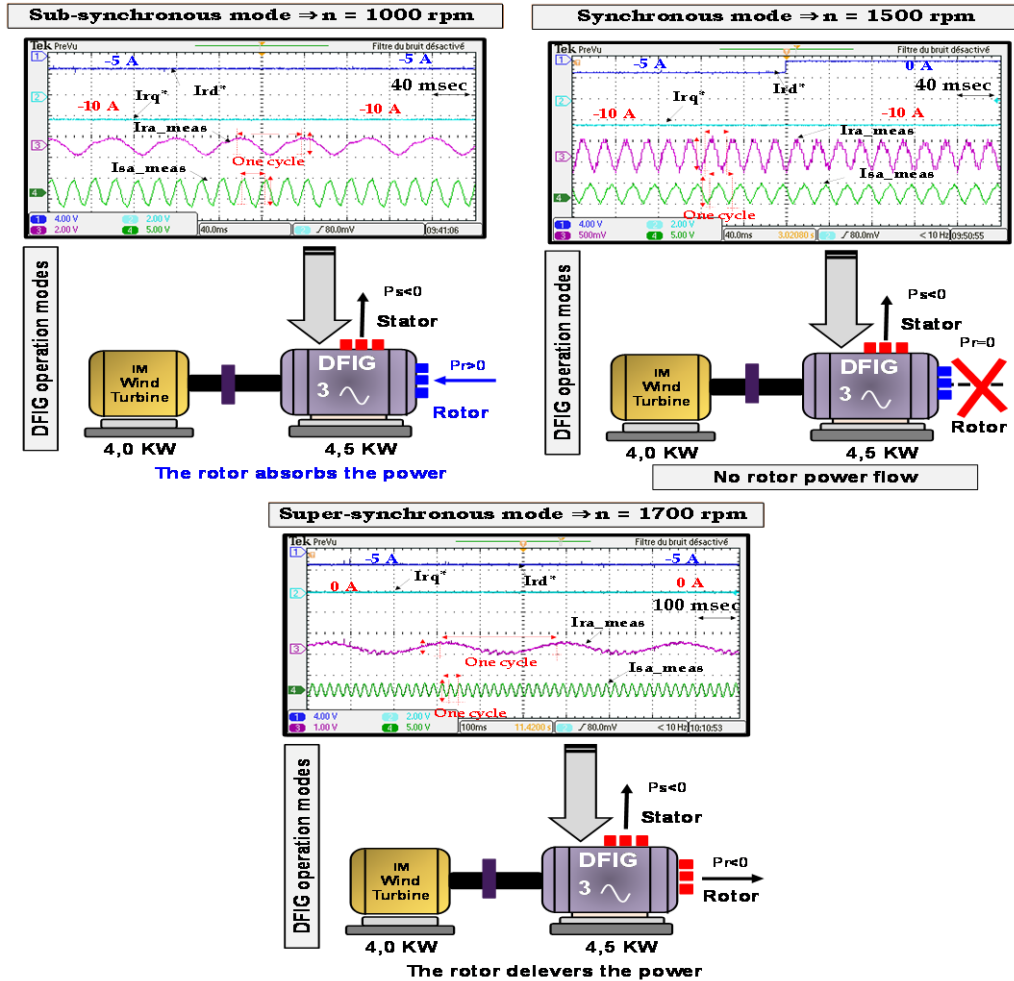


Fig. 12. Experimental analysis of stator and rotor current dynamics across speed regimes (1000, 1500, 1700 rpm) under d-q axis current variation.

Figure 13 presents a comparative study based on three important criteria (THD of the stator current, overshoot and static error in steady state) for the two configurations presented in this work, namely: power control based on a classic PI regulator and power control based on a robust IP regulator.

We clearly notice a remarkable superiority of the proposed IP controller compared to that of the classic regulator; whose energy quality is improved THD $I_s = 1.5\%$ for power control via IP against 3.8% for control via PI, the tracking is almost perfect using the power control based on IP (overshoot equal to 1% against 12% for power control via PI. All these indices clearly show the whatever the wind variation and the RL load change; and finally the static error in the permanent regime is negligible equals to 5% for power control via IP against 12% improvement offered by the proposed power algorithm the nominal values displayed in the nameplates in the Appendix below (Table.4 and 5).

This analysis (refer to Table.2) evaluates the static performance of proposed Integral-Proportional (IP) and conventional Proportional-Integral (PI) controllers in controlling active and reactive power in DFIG-based wind turbines. To further highlight the effectiveness of the proposed DPC-IP strategy, a comparative analysis with

previously reported control methods from the literature is conducted.

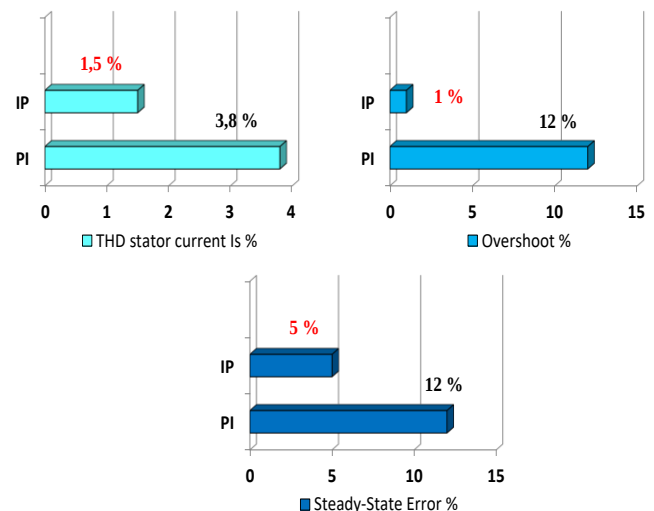


Fig. 13. The DFIG- wind turbine performance metrics for proposed and traditional power control algorithms.

Table 3 summarizes key performance indicators, including overshoot, response time, THD, ripples, and robustness, for different control approaches applied to DFIG-

Table 2. The performance recapitulation of the conventional and proposed algorithm control

Citerions	IP Controller	PI Controller
Steady-State Error	5–8%	8–12%
Total Harmonic Distorsion THD	1.5–2%	5–6%
Robustness	High (compensates parameter variations)	Low (sensitive to parameter drift)
Overshoot	<2%	> 12%
Power error	+/- 80 W_Var≈ 2%	+/- 150 W_Var≈ 3.75 %
Power tracking	Excellent	Good
Dynamic response	Very Fast (12.5* ms)	Fast (167 ms)
Stability	Moderate (nominal conditions)	High (adaptive to disturbances)
Grid compliance	Requires external compensators	Autonomous LVRT capability
Tuning complexity	Moderate (fixed gains)	High (adaptive laws)
Computational Load	Low	Moderate to High
Hardware Cost	Low (simple structure)	Low (simple structure)

Table 3. A comparative analysis of different control strategies applied to DFIG-based wind turbines

Ref	Year	Control Method	Overshoot (%)	Power Rated	THD Is (%)	Response time (ms)	Ripples (%)	Robustness
[37]	2023	TOSMC	Neglected	DFIG (10kW)	1.45	0.65	32.79	High
[38]	2024	FBC	7.41	PMSG (2MW)	1.78	84	16.66	High
[39]	2024	Adaptive FL	11.86	PMSG	0.76	60	80	----
[40]	2022	PD-(1+PI)	Neglected	DFAG (1.5MW)	0.62	Fast (-)	56.66	High
[41]	2025	DPC	99.81	AG (1.5kW)	0.69	0.706	Low	High
[42]	2023	BC-SSMC-MRAS	0	IM (1.5kW)	0.56	370	82	High
[43]	2025	DPC-PDPI	70.31	IG (1.5MW)	0.60	0.31	60	High
[44]	2023	DTC-FOSOCSCMC	1.5	DFIG (1.5 MW)	0.12	Fast (-)	---	High
[45]	2023	FOC-PII	8.95	IM (1.5kW)	1.86	Low (-)	75.16	----
[46]	2023	FOC-FOSTA	7.23	AG (1.5MW)	0.01	0.02075	53.56	---
[47]	2023	DPC-SPI-GA	----	AG (1.5MW)	0.54	Fast (-)	22.95	High
[48]	2023	BC-TOSMC	---	AM (1.5kW)	1.09	----	57.14	High
[49]	2023	ANN-DPC	---	DFIG (1.5kW)	2.22	----	---	High
[50]	2024	DPC-FPI	37.93	DFIG (1.5MW)	0.13	1.7	58.60	---
[51]	2023	DPC-FOSC	85	AG (1.5MW)	0.13	6.58	72.5	---
[52]	2024	DPC-NSTSMC	32.20	DFIG (1.5kW)	0.83	0.0054	10	High
[53]	2024	DFOC-FOSC-FOPI-PSO	67.77	AG (1.5MW)	0.02	5	99.67	High
[54]	2024	DPC-NSTA	65.35	DFIG (1.5MW)	0.18	0.0087	73.54	High
[55]	2025	BC	0	SEIG	0.53	---	---	High
[56]	2024	DPD-DSTSMC	---	DFIG (1.5MW)	0.19	---	83.33	---
[57]	2024	IFOC-PDI	57.79	DFIG (1.5MW)	2.25	8.2	46.24	Medium
[58]	2020	DFC-PI	< 7%	DFIG (3 kW)	---	Meduim	---	High
[59]	2011	VOC-PR3	---	DFIG (2.2 kW)	< 5	Good	---	Good
[60]	2014	PDPC-PI	< 10%	DFIG (20 kW)	5.98	Good	---	Medium
[61]	2025	DFC-SVM PI	≈ 2%	DFIG (3.0 kW)	< 5	Medium	---	High
[62]	2010	FOC PI-R	< 6%	DFIG (2.2 kW)	< 5	Excellent	---	Good
[63]	2025	DVC FOFL	None	DFIG (3.0 kW)	< 4	Excellent	---	High
[64]	2025	VPC-T2-FLC	Neglected	DFIG (4.0 kW)	0.60	Excellent	---	---
[65]	2024	STA-SMC	Neglected	DFIG (1.5 MW)	1.85	5.6873	---	---
Proposed	---	DPC-IP	2	DFIG (4.5kW)	1.5	12.5	15.5	High

based and other wind energy conversion systems. This benchmarking enables a fair evaluation of the proposed method relative to state-of-the-art strategies, thereby clarifying its advantages, limitations, and overall contribution to the field. It is worth noting, however, that for some criteria marked with (–), the corresponding data were not reported in the original references.

8. Conclusion

This paper presents a novel power vector control strategy for DFIG operating in stand-alone mode, successfully implemented and validated through real-time testing. The

proposed approach replaces traditional PI controllers with IP controllers for regulating the rotor current components I_{rd} and I_{rq} , which directly control reactive power (Q_s) and active power (P_s), respectively. Experimental validation was conducted using dSPACE DS1103 hardware and ControlDesk software platform across varying rotor speeds.

The test results successfully demonstrated both sub-synchronous and super-synchronous operational modes, confirming the control strategy's effectiveness under dynamic wind conditions. Experimental validation confirmed the superior performance of the proposed control system,

particularly in response speed, overshoot minimization, and accuracy in current and power regulation.

To advance this research further, the following directions are recommended:

- Power Quality Enhancement: Integrate Shunt Active Power Filter (SAPF) technology to reduce harmonic distortion and improve power quality for load or microgrids integration.
- Grid Integration Extension: Adapt the control scheme for grid-connected operation, incorporating synchronization protocols, grid support features, and fault ride-through capabilities.
- Robustness Assessment: Evaluate system performance under realistic conditions including electrical faults, load variations, and communication delays for comprehensive reliability analysis.
- Comparative Performance Studies: Conduct benchmarking against advanced control methodologies such as H-infinity control, Model Predictive Control (MPC), and Artificial Neural Network (ANN)-based approaches to quantify the proposed method's advantages.

Abbreviations and acronyms

DFIG	Double fed induction generator
WT	Wind Turbine
VSWECS	Variable Speed Wind Energy Conversion Systems
dSPACE	Digital Signal Processing and Control System
RSC	Rotor Side Converter
GSC	Grid Side Converter
SAPF	Shunt Active Power Filter
TSR	Tip Speed Ratio
DPC	Direct Power Control
PI	Proportional Integral
IP	Integral Proportional
MPPT	Maximum Power Point Tracking
OLTF	Open Loop Transfer Function
CLTF	Closed Loop Transfer Function
TF	Transfer Function
VPC	Vector Power Control
PDPC	Predictive Direct Power Control
PWM	Pulse Width Modulation
PLL	Phase-Locked Loop
MPC	Model Predictive Control.
ANN	Artificial Neural Network

Appendix

Table 4. The DFIG parameters

Parameters:	Values:
Rated power:	4.5 kW
Stator resistance:	$R_s = 0.4 \Omega$
Rotor resistance:	$R_r = 0.8 \Omega$
Stator inductance:	$L_s = 0.082 \text{ H}$
Rotor inductance:	$L_r = 0.082 \text{ H}$
Mutual inductance:	$L_m = 0.081 \text{ H}$
Rated Voltage Δ/Y :	$V_s/U_s = 220/380 \text{ V}$
Number of pole pairs:	$P = 2$
Rated speed:	$n = 1395 \text{ rpm}$
Friction coefficient:	$f_{DFIG} = 0.001 \text{ N m/s}$
The moment of inertia:	$J = 0.2 \text{ kg.m}^2$

Table 5. The operational parameters of the emulator turbine (SCIM)

Parameters:	Values:
Rated power:	4.0 kW
Rated voltage Δ/Y :	$V_s/U_s = 220/380 \text{ V}$
$\cos \phi$:	0.82.
Gain:	$G = 3.9$
Rated speed:	$n = 1440 \text{ rpm}$

Table 6. The RL-balanced load parameters

Parameters:	Values:
Resistance:	$R_{LOAD} = 80 \Omega$
Self-inductance:	$L_{LOAD} = 50 \text{ mH}$

Table 7. The simulation and experimental conditions using Matlab/Simulink.

Type:	Fixed-Step.
Ode-4:	Range Kutta Order4
Fixed-step Size (Fundamental sample time):	Simulation study: 1e-5.
Fixed-step Size (Fundamental sample time):	Experimental study: 1e-4
Tasking mode for periodic sample time:	Auto.

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Author Contributions

Conceptualization, F. A., and B. F.; methodology, F. A., and A.C.; software, F. A., B. F., and A.C.; validation, F.A., A. C., B. F., and O. G.; formal analysis, F. A., O. G., H. I., and B.F.; investigation, F. A., A. C., B. F., H. B., H.I., and G. O.; resources, F. A., B. F., H. B., G. O., and A. C.; data curation, F. A., A. C., H. B., G. O., and H. I.; writing-original draft preparation, F. A., B. F., A. C., and H. I.; writing-review and editing, F. A., B. F., A. C., I. H., O. G., and H. B. ; visualization, F. A., B. F., A. C., H. I., and O. G.; supervision, B. F.; project administration, F.A., B.F., and A.C.;. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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