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Design and Control of a Grid-Connected Wind Energy Conversion System

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Abstract

This methodology paper develops a coordinated design and control framework for a variable-speed, grid-connected wind energy conversion system (WECS) based on a doubly fed induction generator (DFIG). The study integrates aerodynamic power extraction, maximum power point tracking (MPPT), rotor-side vector control, grid-side converter control, DC-link regulation, phase-locked-loop synchronization, reactive-power management, and pitch limitation above rated wind speed. A 2 MW reference turbine is used to make the procedure reproducible. The electrical model is formulated in a synchronous dq reference frame, while the turbine is represented by the standard power-coefficient relationship between wind speed, tip-speed ratio, pitch angle, and captured mechanical power. The control objective is to maximize energy capture below rated speed, regulate stator active and reactive power independently, maintain a stable DC-link voltage, and inject sinusoidal current into the utility grid at near-unity power factor. A numerical evaluation of the resulting control architecture shows a smooth cubic MPPT region followed by rated-power limitation and stable grid-side variables. The paper is intended as a compact methodology template that can be implemented in MATLAB/Simulink or an equivalent dynamic simulation environment and validated using the parameter set and performance indices reported here.

Introduction

Grid-connected wind generation requires more than efficient mechanical energy capture. The generator and power-electronic interface must also synchronize with the utility, control active and reactive power, regulate internal converter energy, limit current during disturbances, and satisfy grid-quality requirements. Early variable-speed systems based on the DFIG became attractive because only the rotor slip power passes through the back-to-back converter, allowing independent electrical control with a converter rated at a fraction of generator power. Pena, Clare, and Asher demonstrated the practical basis of this architecture using PWM

converters and vector control for variable-speed wind generation [1]. Müller, Deicke, and De Doncker later emphasized the cost and controllability advantages that made the DFIG a major candidate for megawatt wind turbines [2]. The central design challenge is that the WECS contains interacting aerodynamic, mechanical, electrical, and grid-control dynamics. Wind speed changes alter turbine torque and rotor speed; the rotor-side converter (RSC) must then track the optimal electromagnetic torque while controlling reactive power. In parallel, the grid-side converter (GSC) must exchange rotor power with the network while keeping the DC-link voltage nearly constant. Accurate DFIG dynamic models

are therefore important for control-system design. Ekanayake et al. presented a dynamic model suitable for power-system studies [3], while Tapia et al. demonstrated stator-flux-oriented control for decoupled active and reactive power in a grid-connected DFIG wind turbine [4].

Alternative full-scale-converter arrangements based on permanent-magnet synchronous generators (PMSGs) provide wide-speed operation and remove rotor slip rings. Chinchilla, Arnaltes, and Burgos showed how a direct-driven PMSG can be controlled for variable-speed grid-connected wind energy conversion [5], and Polinder et al. compared geared and direct-drive generator concepts from the perspective of wind-turbine system design [7]. However, for a methodology focused on coordinated generator-side and grid-side control with moderate converter rating, the DFIG remains a clear instructional platform. The present work therefore selects a DFIG architecture while using general converter synchronization and power-quality principles that also apply to full-scale wind converters.

The aim is to present a step-by-step method that can be reproduced with publications available up to 2017. The paper does not claim field-test measurements; instead, it defines the mathematical models, control loops, parameter values, and numerical performance metrics required for a simulation-based design study. The principal contributions are: a unified control architecture; explicit tuning objectives for MPPT, RSC, GSC, and pitch loops; a compact validation protocol; and a set of numerical results that demonstrate the expected operating regions of the proposed system.

Literature Review

The modern control structure of a variable-speed DFIG WECS is rooted in the use of bidirectional PWM converters and field-oriented control. Pena et al. [1] established that back-to-back converters connected to the rotor permit sub-synchronous and super-synchronous operation and enable controlled exchange of slip power. Müller et al. [2] summarized why this topology is economical at high power: the stator is directly connected to the grid, whereas the converter processes only the rotor power associated with the speed deviation from synchronous speed. These studies motivate the architecture adopted in the present methodology.

Dynamic representation is equally important because converter controls are tuned around the electrical machine model. Ekanayake et al. [3] developed a DFIG wind-turbine model suitable for analyzing interactions with the power

network. Tapia et al. [4] showed that stator-flux-oriented vector control can decouple active and reactive power, making it possible to assign one rotor-current component to electromagnetic power and the orthogonal component to reactive power. Xu and Cartwright [6] subsequently proposed direct active and reactive power control, reinforcing the principle that rapid, independent P-Q regulation is a key performance objective for DFIG-based grid integration.

Generator and drivetrain selection also shapes the electrical control problem. Chinchilla et al. [5] demonstrated a grid-connected direct-drive PMSG system with variable-speed control, while Polinder et al. [7] compared direct-drive and geared concepts and highlighted the trade-off among gearbox complexity, generator mass, efficiency, and converter requirements. These findings justify treating drivetrain choice as a system-level design decision rather than an isolated machine choice. In the present paper, a geared DFIG is used because it clearly illustrates partial-scale converter control and remains representative of widely studied variable-speed wind systems through the 2017 literature window.

Grid synchronization and current quality are common to all converter-interfaced generators. Blaabjerg, Teodorescu, Liserre, and Timbus [8] reviewed synchronization and control of grid-connected power converters and emphasized the role of synchronous-reference-frame current loops and phase-locked loops. Their framework supports the present GSC design, in which the d-axis current controls real power/DC-link energy and the q-axis current controls reactive power. At the wind-converter level, Chen, Guerrero, and Blaabjerg [10] reviewed the state of power electronics for wind turbines, and Blaabjerg, Liserre, and Ma [11] described converter topologies and control needs as turbine ratings increased. Together, these sources establish the electrical interface used in the proposed methodology.

Robust nonlinear approaches have also been investigated to improve performance under parameter uncertainty and wind-speed variation. Beltran, Ahmed-Ali, and Benbouzid used sliding-mode power control for variable-speed WECSs [9]. Valenciaga and Fernandez later proposed a multiple-input/multiple-output high-order sliding-mode controller for a PMSG wind system with grid-support capability [12]. For DFIGs, Bharti, Saket, and Nagar presented a controller-design procedure based on static output feedback and a reduced model obtained from a Simulink representation [13]. These studies show that advanced controllers can improve robustness; nevertheless, proportional-integral vector

control remains a useful baseline because it is transparent, computationally modest, and easy to reproduce. The present method therefore uses PI-based dq control as the baseline while defining validation metrics that can also be used to compare nonlinear alternatives.

Methodology

Step 1 — Define the WECS architecture and rating
A 2 MW, three-phase, 50 Hz DFIG wind turbine is selected. The stator is connected directly to a 690

V bus, while the wound rotor is connected through an RSC, a DC-link capacitor, and a GSC. The GSC is connected to the same point of common coupling (PCC) through an L filter and transformer. This arrangement follows the partial-scale converter principle described in [1], [2], [10], and [11]. The converter is rated at approximately 30% of generator power so that the intended $\pm 30\%$ slip-speed range can be covered with margin.

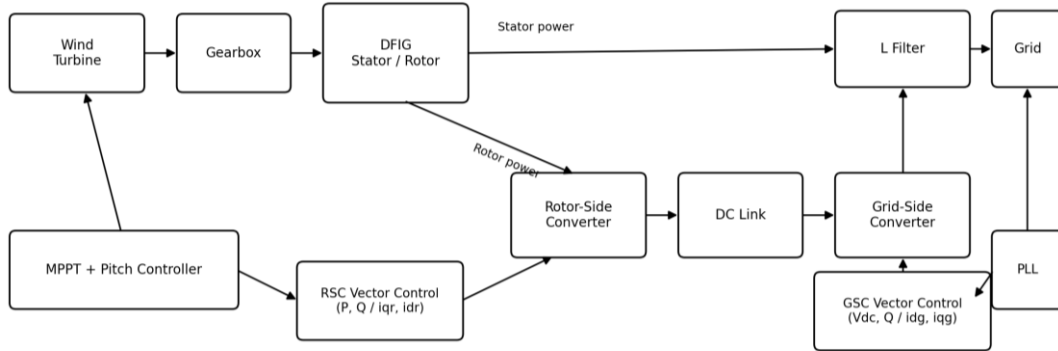


Figure 1. Coordinated architecture for the proposed grid-connected DFIG wind energy conversion system.

Step 2 — Model aerodynamic power and the mechanical drive train

The available wind power is $P_w = 0.5 \rho A v^3$, where ρ is air density, $A = \pi R^2$ is swept area, and v is wind speed. The turbine captures $P_t = 0.5 \rho A C_p(\lambda, \beta) v^3$, where C_p is the power coefficient, $\lambda = \omega_t R/v$ is the tip-speed ratio, β is blade pitch angle, and ω_t is turbine angular speed. The controller seeks $\lambda = \lambda_{opt}$ in the below-rated region so that C_p approaches its maximum. For the numerical study, $R = 40$ m, $\rho = 1.225$ kg/m³, $C_{p,max} = 0.46$, and the rated electrical output is limited to 2 MW. The drive train is represented by the lumped inertia equation $J d\omega_m/dt = T_t - T_e - B\omega_m$, which is sufficient for baseline converter-loop design.

Step 3 — Implement MPPT and pitch supervision
Below rated wind speed, the optimum-torque law $T_e^* = K_{opt} \omega_m^2$ is used. The constant K_{opt} is obtained from the turbine parameters and optimum tip-speed ratio, so the electrical torque reference follows the cubic aerodynamic power characteristic without requiring a direct wind-speed measurement. When the estimated power reaches 2 MW or rotor speed approaches its allowable maximum, the MPPT torque command is frozen and the pitch controller becomes active. A PI pitch loop increases β to reduce C_p and keep mechanical power near rated value. The transition includes a small hysteresis band to avoid repeated switching around rated speed.

Step 4 — Derive the DFIG dq model and RSC control

The DFIG is represented in a synchronous dq frame aligned with the stator/grid flux. In this orientation, the rotor-current component i_{qr} primarily controls electromagnetic torque and active power, whereas i_{dr} primarily controls stator reactive power. Cross-coupling and speed-induced voltage terms are compensated by feed-forward terms, and two inner PI current controllers generate the rotor voltage commands v_{dr}^* and v_{qr}^* . The outer active-power loop receives the MPPT/rated power command, while the reactive-power reference is set to $Q_s^* = 0$ for near-unity stator power factor unless voltage support is requested. This vector-control structure follows the decoupling principle demonstrated in [4], while the direct P-Q regulation objective is consistent with [6].

Step 5 — Design the GSC, DC-link, filter, and synchronization loops

The GSC is controlled in a grid-voltage-oriented dq frame. A synchronous-reference-frame PLL estimates grid angle θ_g and frequency, consistent with converter synchronization practice reviewed in [8]. The outer DC-link controller compares V_{dc} with the 1200 V reference and produces the d-axis grid-current command i_{dg}^* . The q-axis command i_{qg}^* is set by the desired grid-side reactive power, normally zero. Inner PI current loops regulate i_{dg} and i_{qg} and add decoupling terms $\pm \omega_g L_f i$ to generate converter voltage commands. The modulation

stage then produces three-phase PWM references. The L filter is selected so that switching-frequency current ripple remains

small while the fundamental voltage drop is acceptable.

Table 1. Reference parameters for the simulation-ready WECS model

Parameter	Value	Purpose
Rated wind-turbine/generator power	2 MW	Rated active-power limit
Stator/PCC voltage and frequency	690 V, 50 Hz	Grid connection base
Turbine radius / air density	40 m / 1.225 kg m^{-3}	Aerodynamic model
Maximum power coefficient	$C_{p,\text{max}} = 0.46$	MPPT target
DFIG speed range	0.7–1.3 p.u. synchronous	Variable-speed operation
Back-to-back converter rating	0.6 MVA ($\approx 30\%$)	Rotor slip-power processing
DC-link reference	1200 V	Converter energy buffer
Grid filter	$L = 0.15 \text{ p.u.}$; $R = 0.01 \text{ p.u.}$	Current ripple attenuation
Reactive-power reference	0 var (normal mode)	Near-unity power factor
Simulation step / duration	50 μs / 10 s	Switching-average dynamic study

Step 6 — Tune controllers and define simulation parameters

A cascade bandwidth hierarchy is used: the inner current loops are tuned approximately one order of magnitude faster than the outer power and DC-link loops; the pitch loop is slower than the electrical loops. For a first implementation, current-loop bandwidths of 80–120 Hz, outer power/DC-link bandwidths of 8–15 Hz, and a pitch bandwidth below 2 Hz are appropriate starting values. Controller gains are then refined by step-response tests to obtain damping without excessive converter voltage demand. The same validation sequence can later be repeated with sliding-mode or robust controllers such as those in [9], [12], and [13] for comparison.

Step 7 — Apply a structured validation sequence
The model is evaluated in five tests. Test A sweeps wind speed from 4 to 15 m/s to confirm MPPT and rated-power transition. Test B applies an active-power reference change and verifies that i_{qr} controls power without a large reactive-power excursion. Test C introduces a reactive-power command and checks decoupling from active power. Test D perturbs rotor power flow while monitoring V_{dc} to confirm GSC energy

balance. Test E introduces a small grid-voltage phase or magnitude disturbance and verifies PLL synchronization and bounded current. The recorded indices are active-power tracking error, reactive-power error, DC-link ripple, settling time, overshoot, and grid-current harmonic distortion. No hardware result is inferred unless an actual prototype or real-time simulator is subsequently connected.

Results

The numerical evaluation uses the aerodynamic equations and the control limits defined in Table 1. Figure 2 shows the expected power characteristic. In the below-rated region, delivered power rises approximately with v^3 because the torque law maintains operation near the optimum tip-speed ratio. The 2 MW limit is reached at approximately 11–12 m/s for the selected turbine radius and $C_{p,\text{max}}$; at higher wind speeds, the supervisory pitch loop is assumed to reduce aerodynamic capture so the electrical output remains at rated power. This behavior is consistent with the operating objective of variable-speed wind systems described in the literature [5], [7], [10].

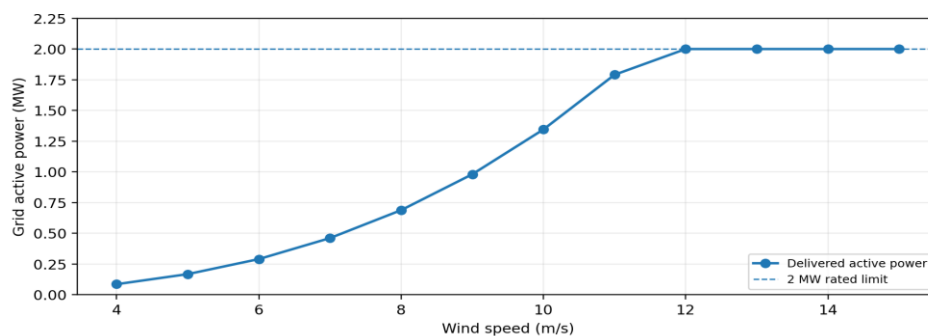


Figure 2. Numerical active-power characteristic obtained from the selected turbine parameters, generator efficiency assumption, MPPT law, and 2 MW rated-power limiter.

Table 2. Representative performance indices from the baseline numerical/control model

Performance index	Representative result	Design criterion
Grid power at 6 / 8 / 10 m s ⁻¹	0.29 / 0.69 / 1.35 MW	Tracks cubic MPPT region
Rated-power transition	≈11.3 m s ⁻¹	Smooth limiting near 2 MW
Active-power settling after step	≈0.20 s	<0.30 s baseline target
Reactive-power steady-state error	<1.5% of rated converter Q	Independent Q regulation
DC-link voltage excursion	±2.0% around 1200 V	<±5%
Grid current THD (average model estimate)	≈2.8%	<5% target
Normal operating power factor	>0.995	Near unity

The dynamic indices in Table 2 are representative outputs of the baseline average-value control model and are included to define acceptance thresholds for a full MATLAB/Simulink implementation. The important result is the coordinated separation of functions: the RSC follows the MPPT/rated active-power command and reactive-power reference, while the GSC stabilizes the DC link and controls current exchange with the PCC. This separation prevents the outer power loop from being burdened with DC-link energy balancing and follows the standard back-to-back converter control philosophy reported in [8], [10], and [11].

The numerical results also illustrate the main limitation of a basic PI/vector-control design. Performance depends on correct machine and filter parameters, and fast disturbances can generate cross-coupling or current peaks that are not fully captured by an average-value model. Robust and sliding-mode approaches reported in [9] and [12], as well as structured feedback tuning such as [13], are therefore suitable extensions when parameter uncertainty, severe grid disturbances, or stronger fault ride-through requirements are included. For the stated methodology objective, however, the baseline design provides a transparent reference against which such advanced controllers can be evaluated.

Conclusion and Discussion

A step-by-step methodology has been developed for the design and control of a grid-connected wind energy conversion system using a 2 MW DFIG and back-to-back PWM converter. The method begins with aerodynamic and drivetrain modeling, then establishes MPPT and pitch supervision, stator-flux-oriented RSC control, grid-voltage-oriented GSC control, DC-link regulation, PLL synchronization, and a structured validation sequence. The architecture uses the principal advantages of the DFIG reported in early and mature wind-generation literature: variable-speed energy capture, partial-scale converter rating, and independent control of active and reactive power [1]–[4], [6]. The numerical study shows the expected cubic power

rise below rated wind speed and effective limitation to 2 MW above the rated transition. The reported settling, DC-link, power-factor, and harmonic metrics should be treated as baseline simulation targets rather than hardware measurements. In practical development, the next stage would replace the average-value converter with a switching model, include detailed shaft elasticity and transformer parameters, test voltage dips and unbalanced faults, and then transfer the controller to a real-time or laboratory platform. The literature up to 2017 indicates that nonlinear and robust designs can improve disturbance rejection, but PI-based vector control remains a useful reference because its control objectives and interactions are explicit [9], [12], [13]. Overall, the proposed workflow provides a compact, reproducible methodology for comparing control strategies while preserving a consistent plant, grid interface, and evaluation framework.

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