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Robust Control System for DFIG-Based WECS and Energy Storage in reel Wind Conditions

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Abstract

This research work focuses on addressing the challenges of controlling a wind energy conversion system (WECS) connected to the grid, particularly when faced with variable wind speed profiles. The system consists of a Doubly-Fed Induction Generator (DFIG) connected to the grid through an AC/DC/AC converter, along with a Li-ion battery storage system connected to the Back-to-Back converter DC link via a DC/DC converter. The non-linearity and internal parametric variation of the wind turbine can negatively impact energy production, battery charging performance, and battery lifespan. To overcome these issues, the study proposes a robust control approach called Integral action Sliding Mode Control (ISMC) to enhance the dynamic performance of the WECS based on DFIG. Additionally, the battery charging and discharging controllers play a crucial role in efficiently distributing power to the grid and storage unit based on the battery's state of charge, extracted energy, and power injected into the grid. Two current regulation modes, buck charging and boost discharging, are employed to ensure proper energy distribution. Furthermore, a storage system energy management algorithm is implemented to ensure battery safety during one of the charging modes. The effectiveness and robustness of the proposed control method were validated through simulations of a 1.5 MW wind power conversion system using Matlab/Simulink. The results confirmed the method's efficiency and efficacy.

Keywords: Backstepping control, Doubly-Fed Induction Generator (DFIG), Storage system, WECS

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1. Introduction

The world is prioritizing renewable energy to address climate change and achieve carbon neutrality. Morocco, along with many other countries, is actively increasing its use of renewable energy sources as a response to global warming [1, 2]. Morocco has set ambitious targets, aiming to surpass 52% renewable energy utilization and 20% wind power generation by 2030 [3]. Wind energy is favored for its cost-effectiveness, environmental cleanliness, and sustainability. Horizontal axis wind turbines are widely adopted due to their superior power efficiency compared to vertical axis turbines. However, a new technology called multi-rotor wind turbines has emerged as an alternative to traditional turbines, offering 20-30% higher energy output [4, 5]. This technology has undergone ex-tensive scientific research and boasts durability and reduced implementation costs. Nonetheless, it presents challenges such as high expense, complex control systems, and numerous mechanical components [6]. Among various types of electric generators, the doubly-fed induction generator (DFIG) remains popular due to its affordability, robustness, ease of control, and suitability for variable wind speeds [7].

Wind energy generation systems utilize strategies grouped into four categories: linear (direct power control [8] and direct torque control [9]), nonlinear (sliding mode control [10]), smart (neural networks [11]), and hybrid approaches. Energy storage systems are crucial for providing continuous and reliable electricity in isolated or remote areas lacking transmission lines [12]. Research on electric energy storage [13] emphasizes battery control and mathematical modeling. Battery manufacturing, control, and protection have received increased attention due to their significance in electric cars, constituting about 90% of their weight [14]. Lithium-ion batteries are commonly used, offering high energy density, specificity, and voltage [15]. Various studies explore battery aspects such as mathematical modeling, charging regulation, capacity assessment, and hazard prevention using techniques like neural networks [16], extended Kalman filter (EKF) [17], fuzzy logic [18], and unscented Kalman filter [19]. Implementing these methods requires data analysis, computations, and learning algorithms to reliably evaluate battery terminal voltage.

A DFIG generator is utilized in wind energy applications for efficient charging of a battery and energy storage, employing a DC-DC inverter [20]. The inverter necessitates a highly efficient control strategy, which can be linear, non-linear, smart, or hybrid, depending on system complexity, protection, and cost considerations. The system cost rises with increased complexity and protection requirements. Control pulses for the battery charge inverter are commonly generated using pulse width modulation (PWM) [21] and space vector modulation (SVM) [22]. In addition, techniques such as neural PWM [23], neural SVM [24], and modified SVM [25] offer distinct advantages and outcomes. However, the battery charging performance and efficiency may deteriorate over time due to frequent load fluctuations and adverse weather conditions. To address this concern, a highly efficient control strategy is proposed to balance the energy of wind turbines between the direct current load and the battery. The overall system cost, electric current quality, and battery protection from internal and external risks are crucial factors to consider. Furthermore, selecting the fastest and easiest method for battery charging is essential. Nonetheless, the choice of DC-DC converter utilized in the charging process can increase system complexity and cost, underscoring the importance of selecting a converter that is easy to control and program [26]. To manage battery charging, an algorithm is proposed to ensure smooth transitioning between different operational modes, optimizing the charging process and extending battery life.

This study proposes a nonlinear robust control method for a wind energy con-version system (WECS) utilizing a doubly fed induction generator (DFIG) and a battery energy storage system. The WECS operates in variable speed mode, maximizing wind energy extraction with an ANN speed controller. Multi-loop non-linear ISMC controllers are developed to ensure efficient and robust control of the DFIG's powers, reducing chattering resulting from discontinuous control. This method enables the simultaneous capture of maximum wind power despite fluctuating wind speeds, while enhancing power quality by mitigating significant harmonics in the utility grid. The study addresses the intermittent nature of wind power by incorporating a storage system to maintain a constant power injection into the grid. Excess energy is stored during periods of high wind and released during times of low wind, ensuring a stable and consistent grid output. To ensure battery safety during charging and discharging, a DC/DC power electronic inter-face regulates power flow and extends battery lifetime. Numerical simulations using actual wind speed validate the efficacy of the proposed control approach, demonstrating the DFIG controller's capability to reduce steady-state error, minimize power fluctuations, and mitigate Total Harmonic Distortion (THD) in the grid's injected currents. Additionally, the MPPT controller enables the production of consistent grid power through the integration of an electrical storage system. The study's organization includes a discussion of WECS mathematical modeling, system control details, simulation results for a 1.5 MW DFIG-based WECS using the wind speed profile of Tetouan city in Morocco and concludes with a summary of key points and future prospects.

2. System Modelling

The depicted system, shown in Fig. 1, consists of a wind energy conversion system utilizing a doubly-fed induction generator (DFIG) and a battery-based energy storage system. Our goal is to develop a model and simulation of a wind turbine with a DFIG that incorporates robust independent control of active and reactive power using an ISMC approach. The energy storage unit helps ensure grid stability by maintaining consistent power production. The system model includes mechanical components, the generator with its rotor-connected inverter and control system, the rectifier for the DC bus, the energy storage system, and the electrical grid connection. Optimizing wind power production and seamless grid integration necessitates a holistic consideration of the entire system's functionality. There-fore, we will simplify various element models to enable simulation implementation and facilitate reasonable simulation times.

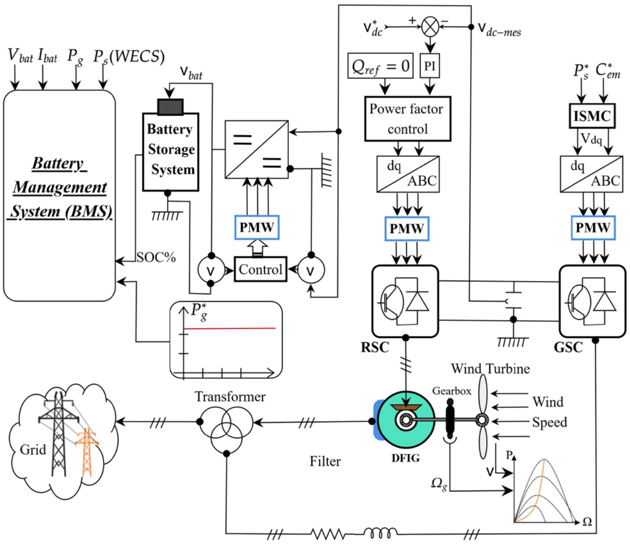

Figure 1. DFIG connection to the grid

In this section, we will introduce the mathematical model for each component of the turbine system required to control the overall system.

2.1. Turbine Model

Equations (1) and (2) outline the mathematical representation of the WT, while expression (3) provides the equations for both electromagnetic and mechanical torques.

$$P_{aer} = C_p P_V = \frac{1}{2}\rho\pi R^2 V^3 C_p(\lambda,\beta) \tag{1}$$

$$C_p(\lambda,\ \beta) = 0.5\left(\frac{116}{\lambda i} - 0.4\beta - 5\right) exp\left(\frac{-21}{\lambda i}\right) + 0.0068\,\lambda \tag{2}$$

$$J\frac{d\Omega_g}{dt} = C_{mec} = C_g - C_{em} - C_f \tag{3}$$

2.2. DFIG Model

The mathematical model of the doubly-fed induction generator, crucial for sys-tem control and observation, is described by equations (4), (5), and (6).

$$\begin{cases} V_{sd} = R_s i_{sd} + \frac{d}{dt}\phi_{sd} - \omega_s \phi_{sq} \\ V_{sq} = R_s i_{sq} + \frac{d}{dt}\phi_{sq} + \omega_s \phi_{sd} \\ V_{rd} = R_r i_{rd} + \frac{d}{dt}\phi_{rd} - (\omega_s - \omega_r)\phi_{rq} \\ V_{rq} = R_r i_{rq} + \frac{d}{dt}\phi_{rq} + (\omega_s - \omega_r)\phi_{rd} \end{cases} \tag{4}$$

$$\begin{cases} P_s = \frac{3}{2} Re\{\vec{V_s} \times \vec{I_s^*}\} = \frac{3}{2}(V_{sd} i_{sd} + V_{sq} i_{sq}) \\ Q_s = \frac{3}{2} Im\{\vec{V_s} \times \vec{I_s^*}\} = \frac{3}{2}(V_{sq} i_{sd} - V_{sd} i_{sq}) \end{cases} \tag{5}$$

$$C_{em} = \frac{3}{2} p \frac{L_m}{L_s} Im\{\vec{\Psi_s} \times \vec{I_r^*}\} = \frac{3}{2} p \frac{L_m}{L_s}(\phi_{sq} i_{rd} - \phi_{sd} i_{rq}) \tag{6}$$

2.3. Description and Modeling of a Storage System

Utilizing a storage unit alongside a wind energy conversion system (WECS) offers advantages in efficiency, energy reliability, and grid stability [27]. The storage unit consists of a power electronic device and a rechargeable battery energy storage system (BESS) to store electrical energy and provide backup power during outages. It helps mitigate power fluctuations from the WECS [28]. The study specifically focuses on a battery energy storage unit (Fig. 2), incorporating bidirectional buck boost power converters and Li-ion battery packs. An LC filter with an inductor (L) and capacitor (C) is placed between the DC/DC converter and the storage unit to enhance the charging/discharging efficiency.

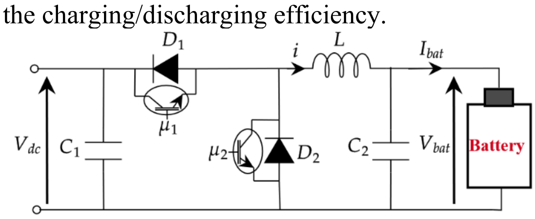

Figure 2. Diagram of the DC/DC converter and battery pack configuration

The buck boost converter is selected as the primary power interface connecting the Li-ion battery pack and the DC bus voltage, operating in buck or boost mode based on power flow direction. Buck mode facilitates battery charging, while boost mode ensures safe battery discharge. A PWM circuit generates switching signals µ1 and µ2 with values from {0, 1}. The initial step in designing a battery charger controller in-volves creating a precise system dynamics model. This study focuses on the electrical model of the battery, comprising a series resistance and voltage source. The battery's internal resistance accounts for energy losses, while the internal battery voltage represents the non-linear variation of the open circuit voltage Uocv with battery state of charge (SoC) percentage.

By analyzing the combination of a DC-DC converter and the battery's equivalent circuit shown in Figure 5 using Kirchhoff's laws, we derive the following set of differential equations.

$$L\frac{di}{dt} = \mu V_{dc} - V_{bat} \tag{7}$$

$$C\frac{dV_{bat}}{dt} = i - I_{bat} \tag{8}$$

$$I_{bat} = \frac{V_{bat} - U_{ocv}}{R_b} \tag{9}$$

$$U_{ocv} = f(SOC) \tag{10}$$

The equation provided below represents the expression for the PWM input control signal μ.

$$\mu = S\mu_1 + (1 - S)(1 - \mu_2)$$

(11)

3. Controller Design

3.1. ISMC for RSC

The Sliding Mode Control (SMC) is a non-linear strategy that enhances the performance and effectiveness of wind systems. It offers durability advantages, remaining largely unaffected by changing system parameters, unlike linear strategies such as field-oriented control [29]. However, SMC faces limitations due to the chattering problem caused by its use of a discontinuous component. To address this issue, several approaches have been proposed, including fuzzy logic [30], neural networks [33] and super twisting algorithms [34]. Integral sliding mode control (ISMC) is a suggested solution that effectively overcomes traditional strategy problems, improving current quality while minimizing power ripples [35].
The control components, which are equivalent to $V_{\_rdq\hat{}eq}$, can be derived from the previous equations and represented as follows:

$$\begin{cases} \dot{S}(I_{rd}) = \dot{I}^*_{rd} - (\frac{V_{rd}}{\sigma L_r} - \frac{R_r}{\sigma L_r} i_{rd} + (\omega_s - \omega_r) i_{rq} + K_i e) \\ \dot{S}(I_{rq}) = \dot{I}^*_{rq} - (\frac{V_{rq}}{\sigma L_r} - \frac{R_r}{\sigma L_r} i_{rq} - (\omega_s - \omega_r)(\frac{M}{\sigma L_r L_s} \phi_s + i_{rd}) + K_i e) \end{cases}$$

(12)

3.2. Design of controllers for battery energy storage systems

In order to enhance performance, extend lifespan, and guarantee safety and reliability of a rechargeable battery, a battery command signal is employed. This study introduces a command signal, depicted in equation (13), which necessitates constant monitoring of both available wind power and grid nominal power. This ensures seamless switching between operating modes regardless of weather conditions.

$$\mu = \frac{L}{aV_{dc}} \left[(c_1^2 - 1) z_1 - (c_1 + c_2) z_2 + a^2 i + \frac{a}{L} V_{bat} - \frac{a^2}{R_b} V_{bat} + \frac{a^2}{R_b} U_{ocv} \right] \quad (13)$$

4. Simulation and Discussion

This section evaluates the performance of a wind energy conversion system (WECS) with energy storage. Using MATLAB/SIMULINK, we created a simulation model for a 1.5 MW DFIG-based wind energy conversion chain and performed simulations using real wind speed data from Tetouan city (Fig. 3), ranging from 4 m/s to 12 m/s.
Fig. 4 illustrates the active power generation (Ps) curve. It is evident that the active stator power (Ps) decreases as the wind speed decreases. The maximum and minimum values of Ps are observed to be Ps_max = 1.45 MW and Ps_min = 0.1 MW, respectively.
Fig. 5 illustrates the power (PB) of the storage system, which can vary positively or negatively depending on wind conditions for battery charging or discharging. The storage unit's power output is limited to a maximum value of PBmax = 1 MW. Notably, the power curve of the storage unit (PB) follows the shape of the generated power (Ps), ensuring a constant difference between them. This stability guarantees a consistent power supply to the grid. When the generated power (Ps) exceeds 0.8 MW, the excess power charges the storage unit, whereas when Ps is below 0.8 MW, the storage unit discharges to provide the remaining power to the grid.
Fig. 6 illustrates the steady supply of active power to the grid from the complete WECS, comprising a DFIG-based wind turbine and a storage system. The power output remains around 0.8 MW with minimal fluctuations. This consistent power supply is achieved due to the presence of the storage system, which compensates for power deficits during low-wind conditions. Without the storage system, the power supply to the grid would have been intermittent, functioning only half of the time while the other half would be used to recharge the system. However, with the storage system, excess power can be stored and utilized later, ensuring a sustained power supply.
Fig. 7 depicts the state of charge (SOC) of a storage system relative to the power generated by a wind generator and the power injected into the grid during different simulation periods. The storage system ensures a consistent power supply to the grid during low-wind periods when the generator's power output is insufficient. Conversely, it stores excess power during high-wind periods for later use. Efficient management of this energy storage enables a year-round steady power supply, facilitating the integration of wind farms into the grid and relieving network managers. The storage system operates approximately half the time, recharging with surplus wind-generated power during the other half.
Fig. 8 illustrates the balance between grid voltage and current for phase "a." The opposite direction of the current in relation to the voltage indicates that the system maintains a unity power factor with a Qs value of 0 VAR.

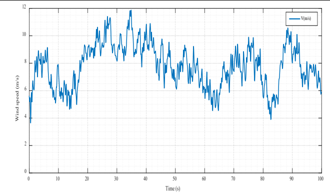

Figure 3. Wind speed.

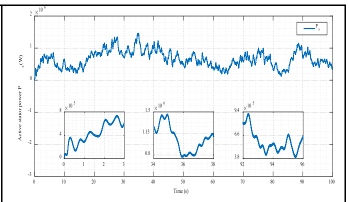

Figure 4. Active power.

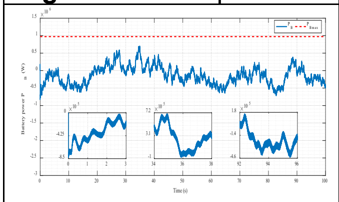

Figure 5. Battery Power.

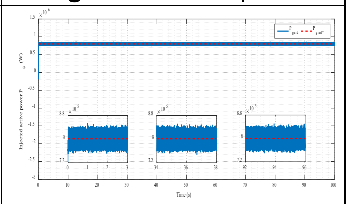

Figure 6. Injected power.

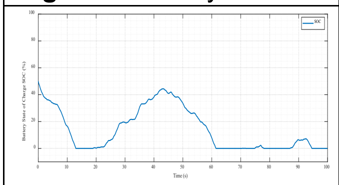

Figure 7. Battery State of Charge SOC (%).

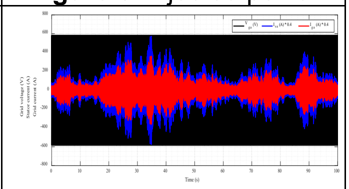

Figure 8. Balance of grid current and voltage.

5. Conclusion

Our research paper presents a comprehensive global model of a wind energy generation system, incorporating aerodynamic calculations to determine the relationships between wind speed, torque, and propeller speed. The system includes a storage unit and robust control mechanisms, ensuring a constant power supply to the grid, benefiting network managers and users by avoiding disruptions. Compared to storage-less turbines, our wind energy conversion system reliably provides a steady power supply despite fluctuations in wind speed. We have focused on the control of Doubly-Fed Induction Generator (DFIG) and developed a conclusive model after two years of research. Future plans involve building a test bench, validating simulations, and conducting additional testing with a small wind turbine and storage. Further studies are necessary to address emerging constraints related to grid stability, such as voltage dips resistance, fault tolerance, and grid independence, for effective integration of wind turbines into the grid and sustainable energy production.

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