

Speed Control of DFIG Wind Energy Conversion Using Horse Herd Optimization

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Abstract—This paper proposes an intelligent rotor speed control strategy for a doubly fed induction generator wind energy conversion system based on the Horse Herd Optimization algorithm. The proposed method aims to maximize aerodynamic power extraction by maintaining the optimal tip speed ratio under variable wind conditions. A realistic multi-sinusoidal wind profile is used to represent both slow and rapid wind variations. The Horse Herd Optimization algorithm determines the optimal rotor speed that maximizes the mechanical power captured by the wind turbine. The performance of the proposed strategy is evaluated through MatLab simulations considering mechanical and electrical variables including rotor speed, mechanical power, stator and rotor voltages, currents, and grid active power. The results demonstrate fast convergence of the optimization algorithm, accurate rotor speed tracking, and stable power injection into the grid. These results confirm the effectiveness of the Horse Herd Optimization based control strategy for improving the performance of doubly fed induction generator wind energy conversion systems under fluctuating wind conditions.

Keywords—Wind Turbine; Doubly Fed Induction Generator; Horse Herd Optimization

I. INTRODUCTION

The rapid expansion of wind energy within modern electrical networks has intensified the demand for sophisticated control approaches capable of maximizing energy capture while preserving grid power quality under varying environmental conditions. In this context, doubly-fed induction generator (DFIG)-based wind energy conversion systems (WECSs) have become one of the most widely adopted solutions owing to their variable-speed operation, reduced converter size and cost, and their ability to provide independent control of active and reactive power supplied to the grid [1, 2].

Despite these advantages, wind speed variability introduces significant nonlinearities and disturbances in the turbine-generator dynamics. These variations may lead to power oscillations, reduced energy capture, and degraded overall system performance. Traditional control strategies based on proportional-integral (PI) controllers integrated with field-oriented control (FOC) or direct power control (DPC) frequently encounter performance limitations in the presence of fast-changing wind conditions, model parameter uncertainties, and severe operating dynamics [3, 4]

In recent years, intelligent and metaheuristic optimization methods have gained considerable attention in renewable energy applications because of their capability to manage nonlinear systems without relying on an accurate mathematical model.

These algorithms provide strong global search capabilities and enhanced adaptability compared to conventional control techniques. Horse Herd Optimization (HHO), a bio-inspired optimization technique, has emerged as a promising solution for complex optimization tasks due to its high convergence speed and its efficient trade-off between global exploration and local exploitation [5, 6]

Building upon the strengths of the Horse Herd Optimization algorithm, this paper presents an HHO-based rotor speed control scheme for a doubly-fed induction generator wind energy conversion system (DFIG-WECS) subjected to variable wind profiles. Unlike traditional maximum power point tracking (MPPT) methods that rely on predefined analytical relationships, the proposed strategy directly optimizes the rotor speed to ensure operation at the optimal tip-speed ratio. Consequently, maximum aerodynamic power extraction is achieved over a wide range of wind conditions, leading to improved energy capture and system performance.

In order to validate the robustness of the proposed approach, a realistic multi-sinusoidal wind model is

considered, capturing both slow-changing and fast-varying wind dynamics. The system's dynamic behavior is assessed through several mechanical and electrical variables, including rotor speed, extracted mechanical power, grid-side active power, as well as three-phase stator and rotor voltages and currents. In addition, zoomed-in waveforms over three electrical periods are provided to examine the quality of the injected power.

The main contributions of this work can be summarized as follows: the development of an HHO-based rotor speed control strategy for DFIG-WECS aimed at enhancing energy extraction under highly variable wind profiles; the design of a realistic multi-sinusoidal wind model capable of reproducing both slow and rapid wind fluctuations; a comprehensive dynamic analysis of the system including both mechanical and electrical variables; a detailed power quality assessment based on three-phase electrical waveforms and zoomed-in electrical periods; and the validation of the proposed approach through MATLAB simulations, demonstrating accurate rotor speed tracking and stable power injection into the grid.

The rest of this paper is organized as follows. Section II introduces the modeling of the wind turbine and the DFIG system. Section III details the proposed HHO-based control approach. Section IV presents and discusses the simulation results under multi-sinusoidal wind conditions. Finally, Section V concludes the paper and highlights possible future research directions.

II. MODELING OF CONVERSION CHAIN

Figure 1 illustrates the overall structure of the DFIG-based wind energy conversion system (WECS). The wind turbine is mechanically coupled to the doubly-fed induction generator (DFIG) through a gearbox, while the stator is directly connected to the grid via a transformer. The rotor is interfaced with the grid through a back-to-back AC/DC/AC power converter composed of a rotor-side converter (RSC) and a grid-side converter (GSC) sharing a common DC-link capacitor. The pitch control system regulates the blade pitch angle to limit and optimize captured wind power, while the converters provide independent control of active and reactive power exchange between the generator and the grid.

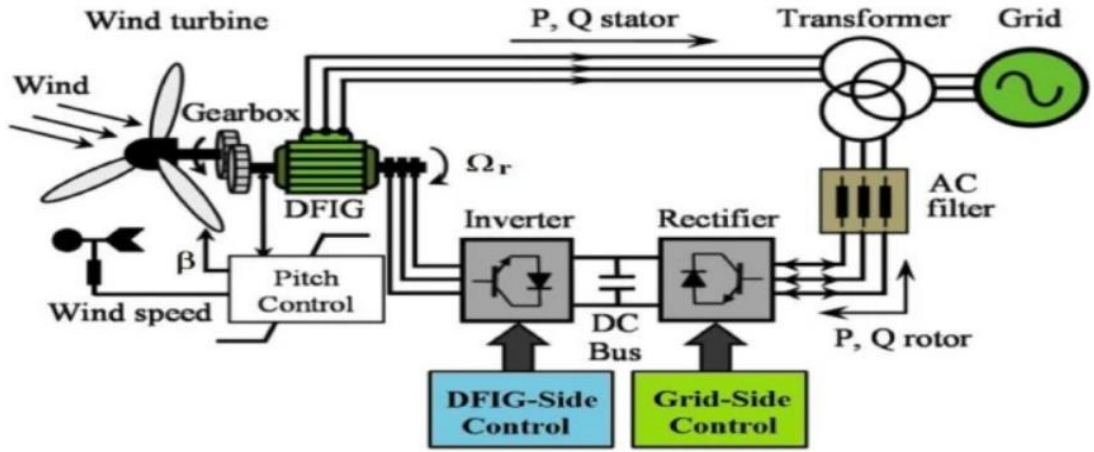


Fig. 1. Configuration of the DFIG [7].

A. Wind turbine modeling

Wind turbines convert the kinetic energy of wind into mechanical energy. The mechanical power extracted by the turbine rotor, as well as the electrical power delivered by the stator P_s , can be expressed as follows [7, 8]:

$$P_r = T_m \cdot \omega_r \quad (1)$$

$$P_s = T_{em} \cdot \omega_s \quad (2)$$

In the case of a lossless generator, the mechanical dynamics are expressed as:

$$J \frac{d\omega_r}{dt} = T_m - T_{em} \quad (3)$$

Under steady state conditions at fixed speed, the lossless generator satisfies, the following relationships:

$$T_m = T_{em} \quad (4)$$

$$P_m = P_s + P_r \quad (5)$$

$$P_r = P_m - P_s = T_m \cdot \omega_r - T_{em} \cdot \omega_s = -sP_s \quad (6)$$

Where s is aslip of the generator, defined by :

$$s = \frac{\omega_s - \omega_r}{\omega_s} \quad (7)$$

In addition, the theoretical maximum extractable power from a given wind speed is defined by the well-known Betz limit [9]:

$$C_p(\lambda, \beta) = 0.5176 \left(\left(\frac{116}{\lambda_i} - 0.4\beta - 5 \right) e^{\frac{-21}{\lambda_i}} + 0.0068\lambda \right) \quad (8)$$

With,

$$\lambda = \frac{\omega_m \cdot R}{V_w} \quad (9)$$

And ,

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (10)$$

The mechanical power is formulated as:

$$P_m = C_p \cdot P_e = \frac{1}{2} \rho \pi R^2 V_w^3 C_p(\lambda) \quad (11)$$

$$P_m = \frac{1}{2} \rho A V_w^3 C_p(\lambda, \beta) \quad (12)$$

turbine model. The fitness value is therefore defined as the mechanical power produced by the turbine:

$$J(\omega_r) = P_m(\omega_r) \quad (21)$$

Meanwhile, the grid-side converter (GSC) maintains the DC-link voltage at its reference level and guarantees stable power delivery to the electrical grid.

The HHO algorithm is a bio-inspired metaheuristic optimization technique based on the social behavior of horse herds. In this method, the population is typically divided into leaders, followers, and explorers, which provides an effective trade-off between exploration and exploitation throughout the search process [17, 18]. Within the HHO algorithm, each horse represents a potential solution to the optimization problem. In the present study, each horse corresponds to a candidate rotor speed value to be optimized [19–22].

$$x_i = \omega_{r_i}, \quad i = 1, 2, \dots, N_h \quad (22)$$

where N_h is the number of horses.

In this work, each horse represents a candidate rotor speed. The fitness function is defined as the extracted mechanical power:

$$J(\omega_r) = P_m(\omega_r) \quad (23)$$

$$J(\omega_r) = \frac{1}{2} \rho A V_w^3 C_p(\lambda, \beta) \quad (24)$$

The optimal horse is obtained as:

$$x_i^{k+1} = \operatorname{argmax} J(x_i) \quad (25)$$

The position of each horse is updated according to three behavioral components:

$$x_i^{k+1} = x_i^k + \alpha(x_{best} - x_i^k) \quad (26)$$

Where, $\alpha \in (0, 1)$ is the leadership coefficient.

$$x_i^{k+1} = x_i^k + \beta(x_{mean} - x_i^k) \quad (27)$$

Where, β controls herd cooperation and:

$$x_{mean} = \frac{1}{N_h} \sum_{i=1}^{N_h} x_i \quad (28)$$

To avoid premature convergence:

$$x_i^{k+1} = x_i^k + \gamma \cdot \operatorname{randn}(\cdot) \quad (29)$$

Where, γ is the exploration factor and $\operatorname{randn}(\cdot)$ is a Gaussian random variable.

Combining the three effects, the final update law becomes:

$$x_i^{k+1} = x_i^k + \alpha(x_{best} - x_i^k) + \beta(x_{mean} - x_i^k) + \gamma \cdot \operatorname{randn}(\cdot) \quad (30)$$

The Rotor speed is constrained as:

$$\omega_{rmin} \leq x_i \leq \omega_{rmax} \quad (31)$$

The algorithm stops when:

$$k > k_{max} \text{ or } |J^{k+1} - J^k| < \varepsilon \quad (32)$$

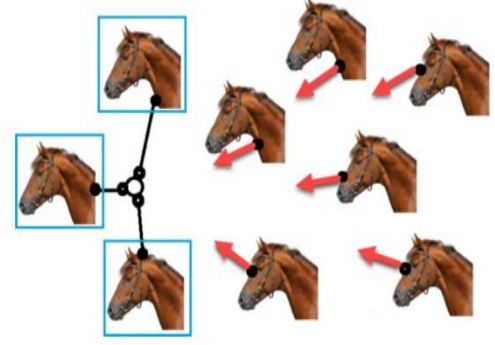


Fig. 3. The imitation behavior of the horses

After convergence, the optimal rotor speed reference is obtained:

$$\omega_r^* = x_{best} \quad (33)$$

which is applied to the rotor-side converter.

Figures (3) and (4) represent the imitation behaviour of horses and the HHO flowchart, respectively.

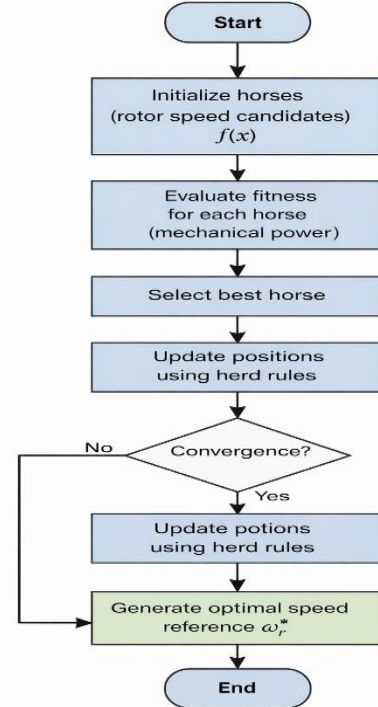


Fig. 4. HHO flowchart

IV. SIMULATION RESULTS

Before presenting the simulation results, the main parameters used in the proposed control strategy are summarized. Table I lists the parameters of HHO algorithm adopted in the optimization process, while Table II and Table III presents, respectively, the electrical parameters of the DFIG and turbine parameters used in the simulation model. These parameters were selected according to typical values reported in the literature to ensure realistic operating conditions for the wind energy conversion system.

TABLE I. HHO PARAMETERS

Parameter	Symbol	Value
Number of horses	Nh	20
Maximum iterations	kmax	100

Parameter	Symbol	Value
Leadership coefficient	α	0.5
Cooperation coefficient	β	0.3
Exploration coefficient	γ	0.1
Convergence tolerance	ε	10^{-6}

TABLE II. DFIG PARAMETERS

Parameter	Symbol	Value
Stator resistance	R_s	0.455Ω
Rotor resistance	R_r	0.19Ω
Stator inductance	L_s	0.07 H
Rotor inductance	L_r	0.0213 H
Mutual inductance	L_m	0.034 H
Nominal frequency	f_n	50 Hz
Moment of inertia	J	0.02 kg/m^2
Pole pairs	p	2

TABLE III. TURBINE PARAMETERS

Parameter	Symbol	Value
Power coefficient	ρ	1.225
Blade radius	R	3 m
Gearbox ratio	G	5.4

Figure 5 presents the convergence curve of the HHO algorithm. The objective function JJ, which represents the extracted mechanical power, rises sharply over the first few iterations before leveling off, indicating that the algorithm has converged to the optimal solution. This behavior demonstrates the rapid convergence and effectiveness of the HHO algorithm in identifying the optimal rotor speed for the wind turbine system.

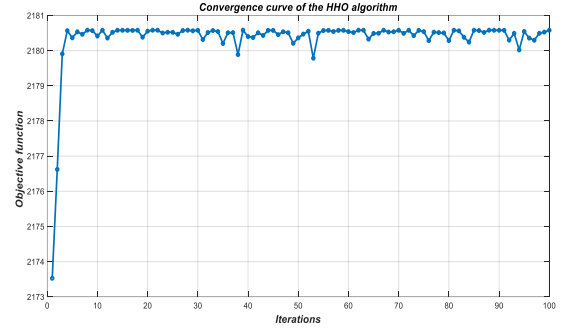


Fig. 5. Convergence curve of the HHO algorithm

However, in order to validate the approach and to analyse the behaviour of the essential quantities of the installation, we considered two (2) types of wind speed profiles: the case where the wind speed varies in steps, i.e., evolving abruptly from one speed to another, and a second case where we considered that the wind speed is random, which is closer to a real situation.

- *First case:*

Figure (6) shows the wind speed profile used for this simulation case. Indeed, for the simulation duration of 20s, the change in wind speed takes place in three (3) respective stages (8m/s, 4m/s and 6m/s).

The adopted profile replicates atmospheric conditions representing a forced and harsh dynamic, characterized by abrupt variations in wind speed. This profile induces dynamic variations in the turbine, which the HHO-based controller allows to maintain the optimal operating point despite these changes.

Figure (7) illustrates the behavior of the turbine-related quantities, namely the power coefficient (Fig. 7-a), aerodynamic torque (Fig. 7-b), mechanical speed (Fig. 7-c), and mechanical power (Fig. 7-d). It can be observed that all variables respond to wind speed variations with good dynamic performance.

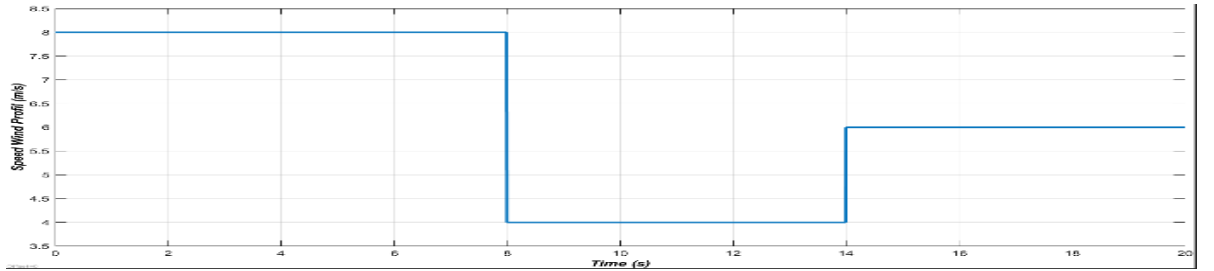
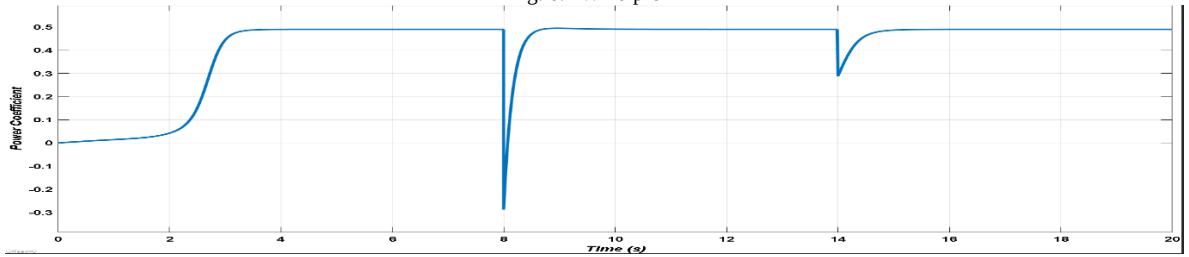


Fig. 6. Wind profil



7-a

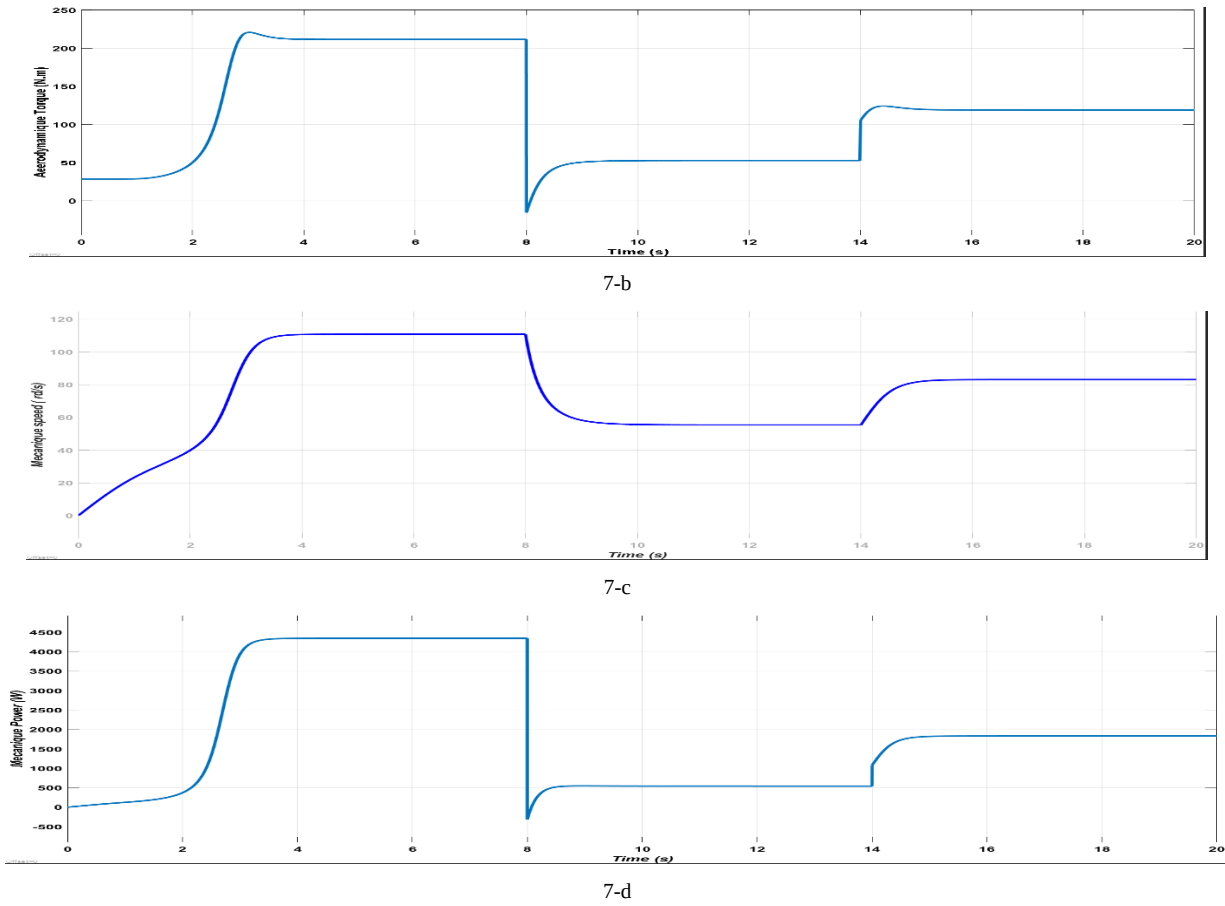


Fig. 7. Wind turbine characteristics

Figure (8) presents the DC bus reference voltage (red), set at 550 V, together with the actual regulated voltage (blue) obtained using a proportional-integral (PI) controller. The regulated voltage reaches the reference value at approximately 0.8 s without overshoot. It can also be observed that the voltage accurately tracks its reference despite wind speed variations at 8 s and 12 s.

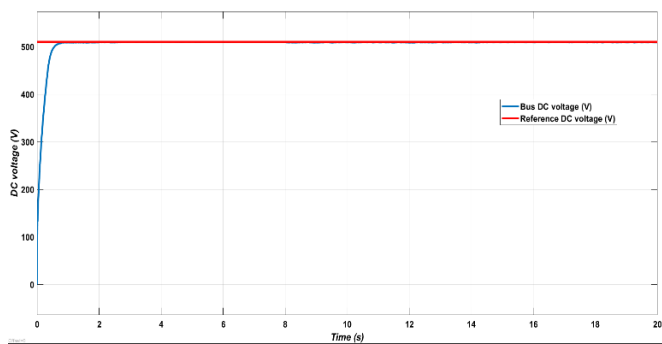
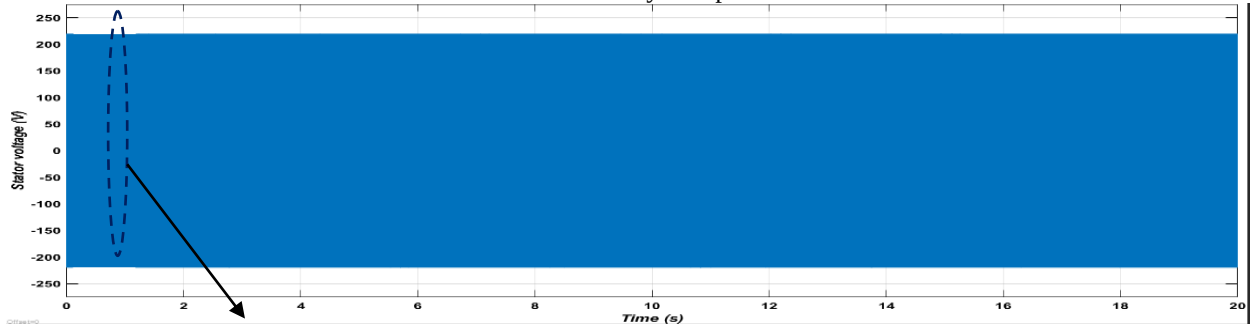


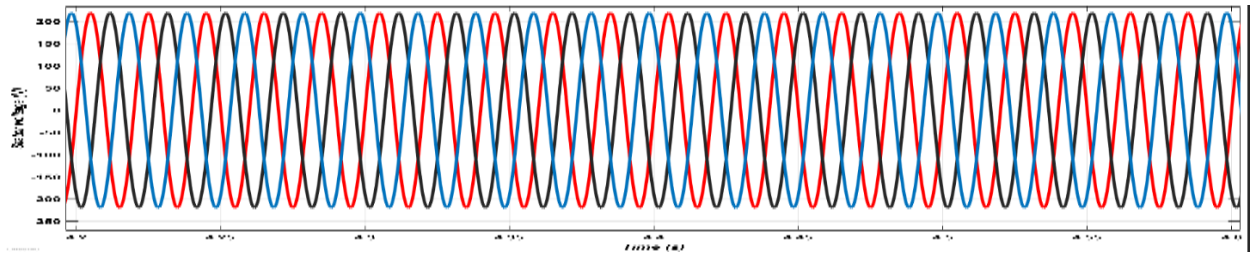
Fig. 8. DC Bus voltage

As a continuation of the performance analysis on the DFIG side, Figure (9) shows the three-phase stator voltages, along with a zoomed view (Fig. 9-a). It can be observed that they remain perfectly sinusoidal and are not affected by variations in wind speed.

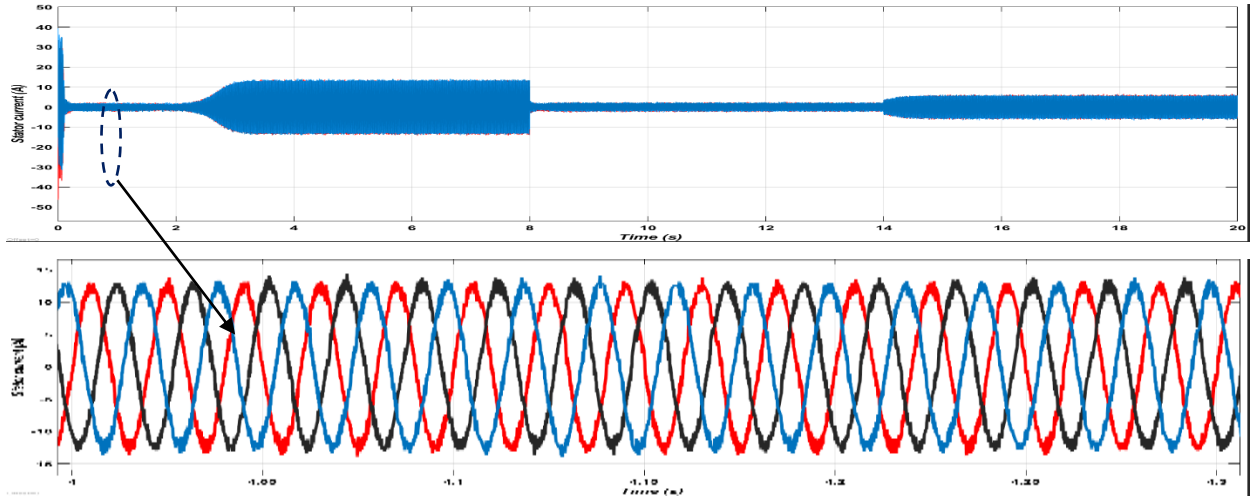
In contrast, the stator currents and electromagnetic torque, along with their zoomed views, are shown in Figures 9(b) and 9(c), respectively. It can be observed that they respond effectively to variations in wind speed.

Additionally, the rotor speed (Fig. 9(d)), along with the active and reactive powers overlaid on their respective reference values, is shown in Figs. 9(e) and 9(f). The rotor speed and active power vary in response to wind speed fluctuations, with the active power precisely following its reference. Meanwhile, the reactive power remains at zero, as required by its setpoint, thereby ensuring a unity power factor. $(\cos(\varphi)=1) \Rightarrow (\cos(\varphi)=1) \Rightarrow (\cos(\varphi)=1)$ as required by the specifications.

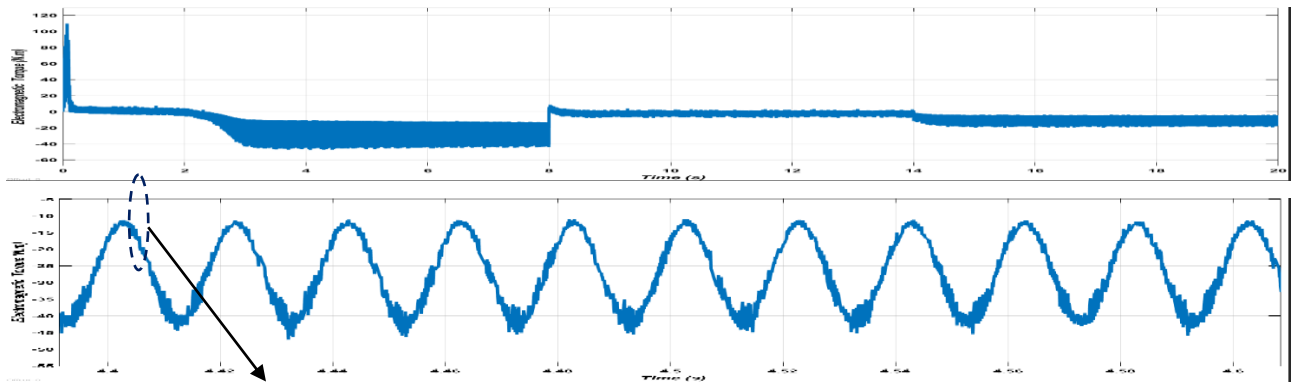




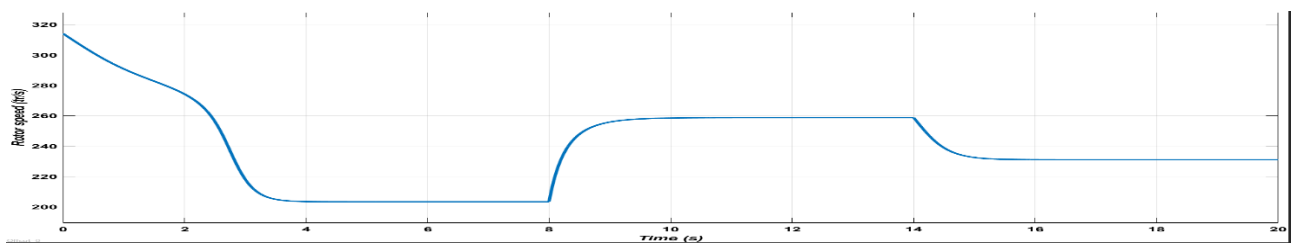
9-a



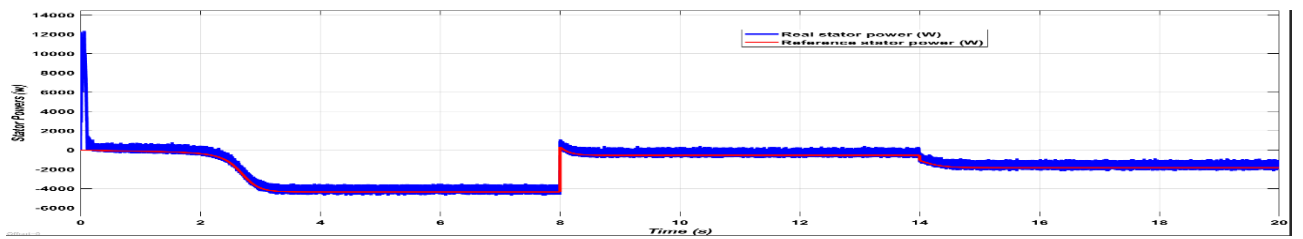
9-b



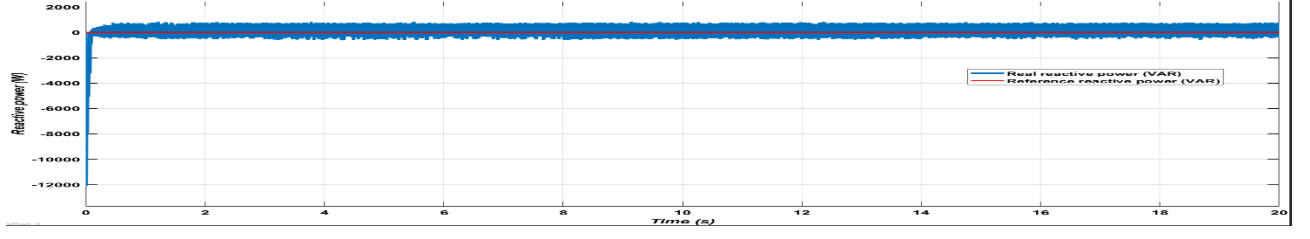
9-c



9-d



9-e



9-f

Fig. 9. Evolution of DFIG quantities

- Second case:

Regarding the case of a random wind speed profile considered in this part of the analysis, the pattern is represented by Figure 10, below:

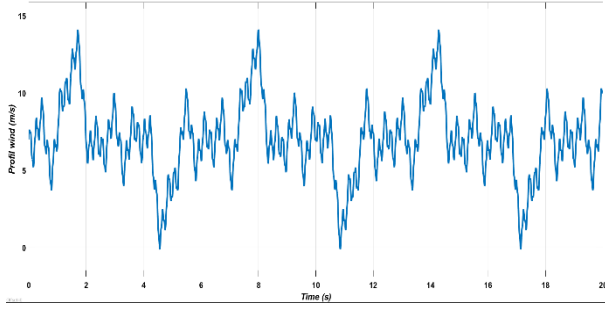
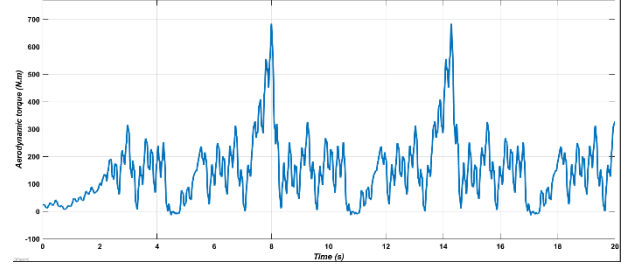


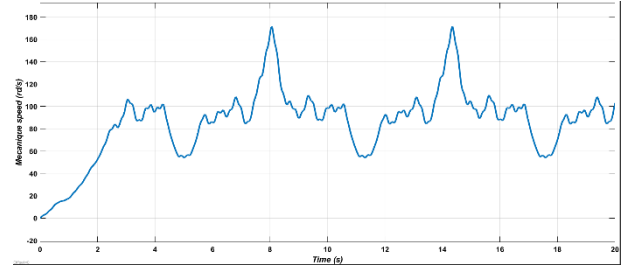
Fig. 10 Aleatory profile wind speed

The adopted multi-sinusoidal profile reproduces realistic atmospheric conditions characterized by both slow and rapid variations of wind velocity. This fluctuating behavior enables an assessment of the proposed control strategy's robustness under dynamic operating conditions. The continuous changes in wind speed induce corresponding variations in the aerodynamic power available to the turbine, thereby presenting a challenging scenario for the control system. Consequently, this profile is suitable for validating the ability of the HHO-based controller to track the optimal operating point despite significant wind disturbances.

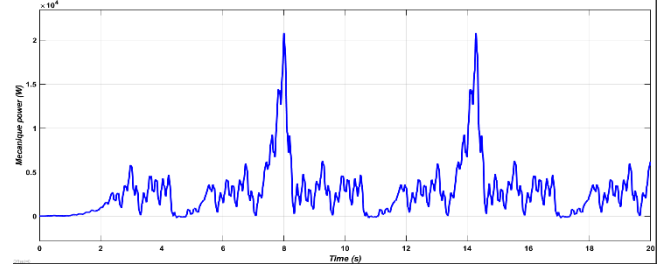
Figure (11) illustrates the evolution of the electromagnetic torque (11-a), mechanical speed (11-b), and mechanical power (11-c). These quantities respond instantaneously to variations in wind speed. In contrast, the DC bus voltage remains unaffected by these disturbances and accurately follows its reference signal (see Figure 12). Moreover, the rotor speed closely tracks the optimal reference generated by the HHO optimization algorithm, demonstrating the controller's ability to rapidly adapt to wind speed variations. Consequently, the mechanical torque evolves smoothly without significant oscillations, indicating stable electromechanical dynamics of the turbine-generator system. In the same way, the mechanical power extracted from the wind tracks the wind profile while staying properly regulated, confirming that the proposed strategy successfully ensures efficient energy harvesting.



11-a



11-b



11-c

Fig. 11. Wind turbine characteristics under a random profile

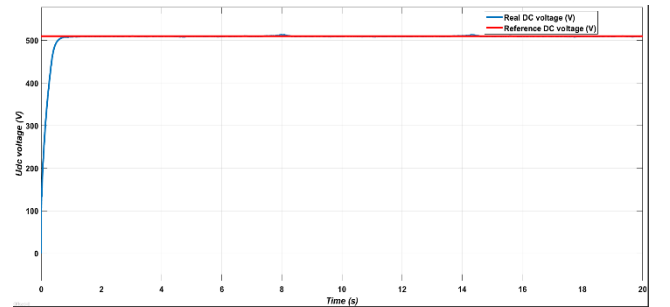
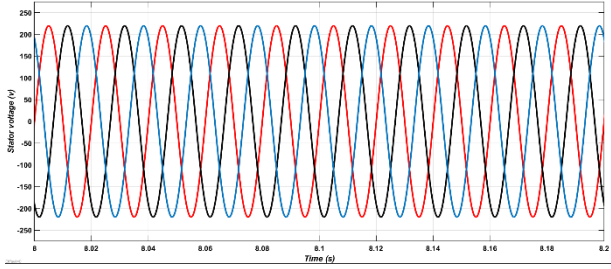


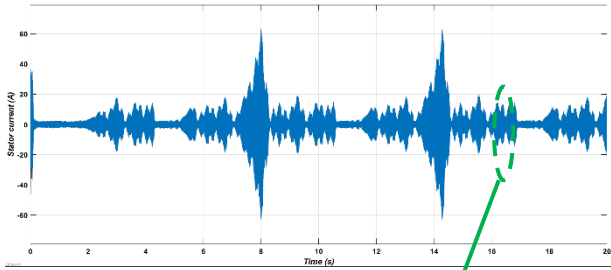
Fig. 12. DC Bus voltage under a random profile

Figures (13) presents respectively the zoom of voltage stator (13-a) and also the stator current (13-b), the voltage rotor (13-c), the rotor current (13-d) avec leurs zooms respectifs of the DFIG. The waveforms remain sinusoidal and stable despite the fluctuating wind conditions,

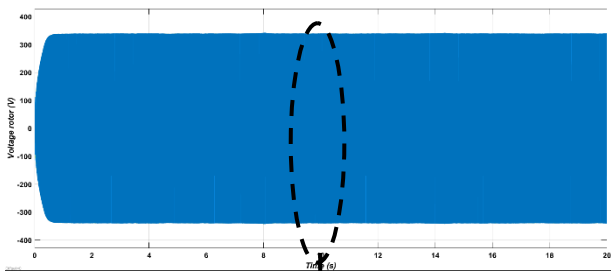
which indicates proper operation of the power converters and effective control of the electrical variables. The rotor quantities adapt to the slip variations induced by the rotor speed changes, while the stator variables remain synchronized with the grid. This confirms that, under the proposed control strategy, power transfer between the generator and the grid remains stable. The three-phase waveforms exhibit balanced sinusoidal behavior with negligible distortion, indicating good power quality at the rotor side. As operating conditions and slip variations change, so too do the amplitudes—demonstrating that the rotor-side converter is properly regulating the electromagnetic torque. Collectively, these findings confirm that the control system ensures stable electrical operation even under rapidly varying wind conditions.



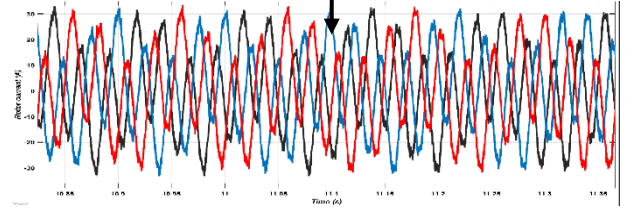
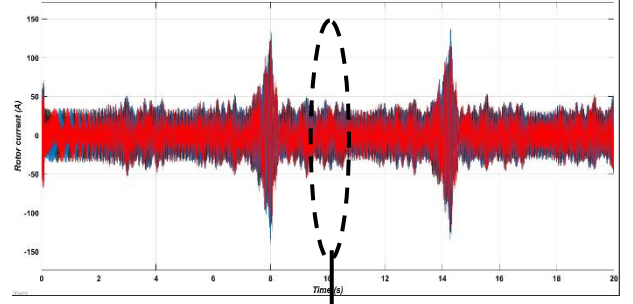
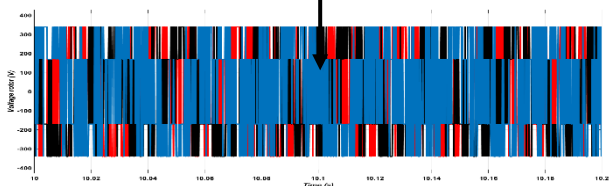
13-a



13-b



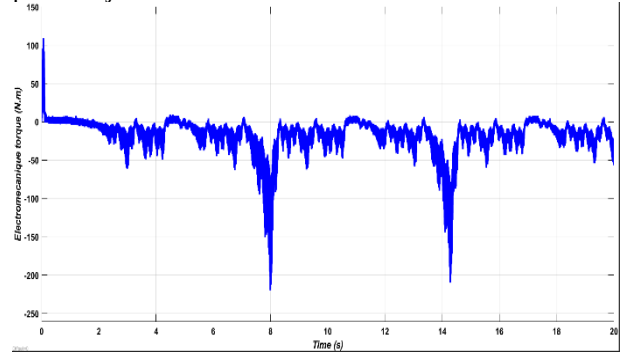
13-c



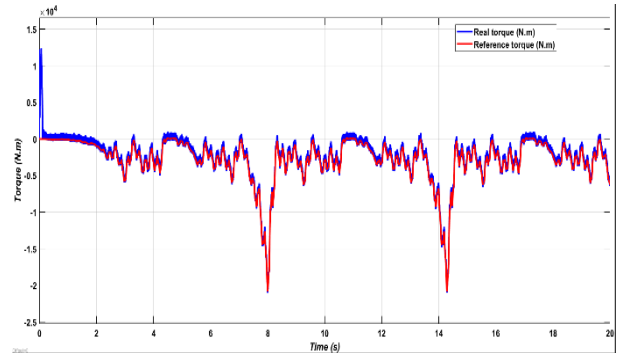
13-d

Fig. 13. Evolution of DFIG quantities under a random profile

Figure (14) presents the electromagnetic torque (14-a), the active power (14-b), and the reactive power (14-c) delivered by the DFIG to the grid, as well as their corresponding zoomed views. The active power follows the variations of the mechanical power extracted from the wind, confirming that the generator effectively converts aerodynamic energy into electrical energy. Meanwhile, the reactive power remains close to zero, indicating that the control system maintains a near-unity power factor and ensures proper voltage support of the grid. This behavior highlights the capability of the proposed HHO-based control strategy to provide stable and efficient power injection under variable wind conditions.



14-a



14-b

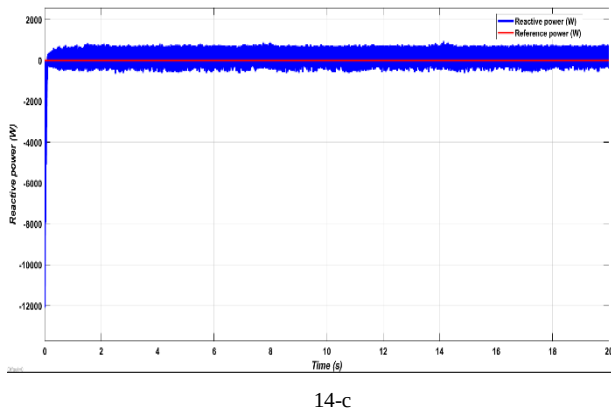


Fig. 14. Evolution of DFIG quantities under a random profile

V. CONCLUSION

This paper proposes an intelligent control strategy for rotor speed regulation in a DFIG-based wind energy conversion system, utilizing the Horse Herd Optimization (HHO) algorithm. By directly optimizing the rotor speed, the proposed method ensures the optimal tip-speed ratio is sustained, enabling maximum aerodynamic power extraction under changing wind conditions. Simulation results under a multi-sinusoidal wind profile demonstrate stable rotor speed tracking, smooth mechanical behavior, and well-balanced electrical variables. The active power generated responds to wind variations, with the reactive power held nearly at zero, thereby ensuring stable grid operation and good power quality. Together, these findings demonstrate the effectiveness of the proposed strategy in boosting the performance of DFIG-based wind energy systems.

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