Research paper

Enhancing Wind Turbine Efficiency: A Comparative Study of Two Innovative MPPT Control Algorithms

Zina Larabi [a,b,*]**, Kaci Ghedamsi** [c]**, Djamal Aouzelag** [c]**, Fares Nafa** [d]

[a] *Departement of Electrical Engineering, University of Tizi-Ouzou, Algeria*

[b] *Departement of Electrical Systems Engineering, University of Boumerdes, Algeria*

[c] *Laboratoire de Maitrise des Energies Renouvelables, University of Bejaia, Algeria*

[d] *Laboratoire d'Ingénierie des Systèmes et des Telecommunications, University of Boumerdes, Algeria.*

ARTICLE INFO	ABSTRACT
	This paper presents two novel maximum power point tracking (MPPT) control strategies utilizing the gradient optimization algorithm to maximize the wind turbine's output power while minimizing the chattering effect resulting from intermittent control switching. In the first method, the gradient algorithm is integrated with sliding mode control (GSMC), and in the second technique, it is combined with adaptive fuzzy sliding mode control (GAFSMC). To assess the robustness and tracking capabilities of these techniques, numerical simulations were conducted under varying wind speed profiles. The results obtained demonstrate the superior performance of the two newly developed methods when compared to classical SMC and fuzzy logic approaches.

1. INTRODUCTION

Given environmental issues and the shortage of fossil energy sources in the near future, the use of "green" energy is becoming increasingly important for a much more sustainable world (Ndirangu, et al. 2016, George, et al. 2022). Among these resources, Wind power is one of the world's most interesting, it is inexhaustible, unlimited, and abundantly available everywhere (Tiwari, et al. 2016). However, wind power is principally dependent on the geographical and seasonal climate conditions. Therefore, it is necessary to design a system capable of generating maximum power under these conditions (Minh, et al. 2012, Tahiri, et al. 2018). This is known as maximum power point tracking (MPPT).

Extensive research has been conducted into various approaches for tracking wind energy systems' maximum power point (Zhu, et al. 2012, Kadri, et al. 2016). To date, numerous MPPT control

* *Corresponding author, E-mail address: zina.larabi@ummto.dz*
  Tel : + 213 550266115

techniques have been investigated, such as conventional Tip speed ratio (TSR) and optimal torque control (OTC) (Hannachi, et al. 2021, Zhang, et al. 2022), intelligent fuzzy logic (FL) (Gaied, et al. 2022, Zebraoui, et al. 2020), nonlinear sliding mode control (SMC) (Kahla, et al. 2017, Agarwal, et al. 2022), and other hybrid techniques like FLSMC and adaptive fuzzy sliding mode control (AFSMC) (Toriki, et al. 2021, Malobe, et al. 2020, Cherifi, et al. 2020). These techniques are distinguished by their simplicity, speed, price, and convergence efficiency (Malobe, et al. 2020).

As a non-linear control technique, sliding mode control is widely appreciated for its outstanding properties, such as high accuracy, fast dynamic response, stability, and ease of conception and implementation (Mousavi, et al. 2022). Nevertheless, a significant shortcoming of the SMC is the chattering effect created by the intermittent switching of the control (Cherifi, et al. 2020, Mousavi, et al. 2022). To remedy this problem, various solutions have been proposed in the literature (Malobe, et al. 2020, Cherifi, et al. 2020, Mousavi, et al. 2022, Benkahla, et al. 2018, Bellounis, et al. 2017), either by modifying the classical SMC or associating it with other control methods.

In this paper, the gradient optimization algorithm is suggested as a solution to minimize the chattering effect and enhance the robustness of the MPPT control methods of the wind turbine, specifically SMC and AFSMC. For this purpose, the remainder of the paper is structured as follows: Section 2 is reserved for describing and modeling the wind turbine considered in this study. Section 3 introduces two innovative methods, GSMC and GAFSMC, developed to track the maximum power point of wind power. Simulation results and discussion are presented in section 4. Finally, the main findings of this work are presented in section 5.

2. MODELING OF THE WIND TURBINE

The wind turbine is designed to convert a part of the wind's kinetic energy into mechanical power and then, via a generator, into electrical power (Atallah, et al. 2022).

The output power of the wind turbine can be calculated using the following formula (Hannachi, et al. 2021):

$$P_t = \frac{1}{2}\pi\rho C_P R^2 V_w^3 \tag{1}$$

Where: V_w : The wind speed; ρ: The air density; R: The turbine radius.

The power coefficient C_P is a non-linear function of the blade pitch angle β and the tip speed ratio (TSR) λ. The considered model in this paper is described by [Yaakoubi, et al. 2019]:

$$C_p = 0.5 \left(\frac{116}{\lambda'} - 0.43\beta - 5\right)e^{-\frac{21}{\lambda'}} \tag{2}$$

With:
$$\lambda' = \frac{1}{\lambda + 0.008\beta} - \frac{0.035}{1 + \beta^3} \tag{3}$$

and:
$$\lambda = \frac{\Omega_t R}{V_w} \tag{4}$$

Where: Ω_t: The angular speed of the wind turbine.

In this study, we consider a low-speed generator driven directly by the mechanical torque developed on the rotor shaft of the turbine as presented in Fig. (1). This torque is described by (Atallah, et al. 2022):

$$T_m = \frac{P_t}{\Omega_t} \tag{5}$$

The dynamic of the angular velocity of the turbine is given by (6).

$$\dot{\Omega}_t = \frac{1}{J_t} \left(T_m - T_g - f_v \, \Omega_t \right) \tag{6}$$

Where: J_t: The total moment of inertia; T_g: The generator torque; f_v: The viscous friction coefficient.
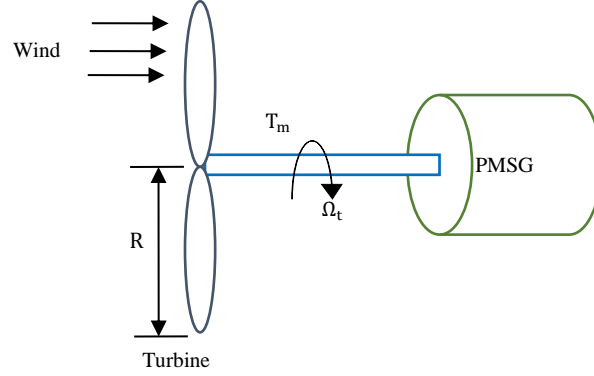

Fig 1. Diagram of a studied part of the wind turbine conversion system

3. DESIGN OF THE PROPOSED METHODS

In wind turbines, the MPPT control algorithm is utilized to achieve the maximum output power value during fluctuations in wind speed. This section introduces two novel MPPT control strategies based on the gradient algorithm, which aim to improve the wind turbine's efficiency.

3.1 Gradient sliding mode control

The gradient sliding mode control principle is based on optimizing the turbine's power coefficient by the gradient ascent algorithm to get the optimum speed corresponding to the maximum power extracted from the wind. However, sliding mode control adjusts the turbine's angular speed to its optimum reference, allowing it to adapt to wind fluctuations while maintaining its optimum operation.

To maximize the energy extracted from wind power, it's important to maximize the power coefficient C_P concerning λ and β. To achieve this goal, the gradient ascent algorithm is used. In the remainder of this work, we consider $\beta=0°$.

By minimizing the criterion: $J = \frac{1}{2} c_p^2$ the dynamics of λ_{opt} can be given by:

$$\dot{\lambda}_{opt} = \eta . \nabla_\lambda c_p . c_p = \eta \frac{\partial c_p}{\partial \lambda} c_p \tag{7}$$

Where: $\eta > 0$

A discrete expression of Eq. (7) can be given by:

$$\lambda_{t+1} = \lambda_t + \eta \frac{\partial c_p}{\partial \lambda} c_p \, \Delta t \tag{8}$$

Thus, the optimal speed of the wind turbine can be deduced by:

$$\Omega_{opt} = \lambda_{opt} \frac{V_w}{R} \tag{9}$$

The SMC control is defined as the sum of the equivalent control T_{geq} and the switching control T_{gs}.

$$T_g^* = T_{geq} + T_{gs} \tag{10}$$

The sliding surface (S) is chosen to be equal to the turbine speed error $\widetilde{\Omega}$ defined by:

$$S = \widetilde{\Omega} = \Omega_t - \Omega_{opt} \tag{11}$$

Recalling Eqs. (6) and (9), the dynamics of S is given by :

$$\dot{S} = \dot{\widetilde{\Omega}} = \dot{\Omega}_t - \dot{\Omega}_{opt} \tag{12}$$

Or:

$$\dot{S} = \frac{1}{J_t} \left(T_m - T_g - f_v \, \Omega_t \right) - \dot{\Omega}_{opt} \tag{13}$$

With:

$$\dot{\Omega}_{opt} = \dot{\lambda}_{opt} \frac{V_w}{R} + \lambda_{opt} \frac{\dot{V}_w}{R} \tag{14}$$

By definition, the equivalent control is deduced for $\dot{S} = 0$, and accordingly, Eq. (13) gives:

$$T_{geq} = -J_t \dot{\Omega}_{opt} + T_e - f_v \, \Omega_t \tag{15}$$

Let define now the following Lyapunov function candidate V as:

$$V = \frac{1}{2} S^2 \tag{16}$$

The times derivative of Eq. (16) yields to:

$$\dot{V} = \dot{S} S \tag{17}$$

Using Eqs. (10), (13), (14), and (15) and choosing the switching control T_{gs} as:

$$T_{gs} = (-k_1 \text{sign}(S) + Q_1 S) \, J_t \tag{18}$$

where $k_1 > 0$ and $Q_1 > 0$, the dynamics (Eq. (13)) becomes such as:

$$\dot{S} = -k_1 \text{sign}(S) - Q_1 S \tag{19}$$

Clearly, by replacing Eq. (19) in Eq. (17), one has:

$$\dot{V} = -k_1 |S| - Q_1 S^2 < 0, \quad \forall S \neq 0 \tag{20}$$

According to Lyapunov's theory, the system is globally asymptotically stable and converges to 0 in a finite time. That is $\Omega \to \Omega_{opt}$ as $t \to \infty$.

Consider the angular dynamics (Eq. (6)) and its optimal value (Eq. (9)). The control law given by Eqs. (10), (15), and (18) ensure all signals in the closed-loop system will be bounded and the sliding surface (Eq. (11)) converges to zero asymptotically.

3.2 Gradient adaptive fuzzy logic sliding mode control

In this case, the control of the wind turbine speed is ensured by the AFSMC and the optimal referential speed is obtained by the gradient ascent algorithm.

We suppose that the control input meets the condition of the universal approximation, and it can be approximated via the following fuzzy system:

$$T_g = \xi_z^T \theta \tag{21}$$

We suppose that there exists a fuzzy system in the form of Eq. (21) with some optimal parameters θ^* such that:

$$\sup_{T_g \in \Omega_z} \left| T_g - \xi_z^T \theta^* \right| \leq \epsilon \, ; \quad \epsilon > 0 \tag{22}$$

Then T_g^* can be expressed as:

$$T_g^* = \xi_z^T \theta^* + \varepsilon(z) \tag{23}$$

Where: ξ_z^T: is a set of fuzzy basis functions; $\varepsilon(z)$: is the fuzzy approximation error.

Let's define the error between the T_g^* and T_g as:

$$e_T = T_g - T_g^* \tag{24}$$

Using Eqs. (21) and (23), the Eq. (24) gives:

$$e_T = \xi_z^T \tilde{\theta} - \varepsilon(z) \, , \text{ with } \tilde{\theta} = \theta - \theta^* \tag{25}$$

Recalling that: $T_g = T_g - T_g^* + T_g^*$ and combining it with Eqs. (6), (12) and (14), gives:

$$\dot{\tilde{\Omega}} = \frac{1}{J_t} \left(T_e - T_g^* - e_T - f_v \, \Omega \right) - \dot{\lambda}_{opt} \frac{V_w}{R} + \lambda_{opt} \frac{\dot{V}_w}{R} \tag{26}$$

Using Eqs. (15) and (18), we get:

$$\dot{\tilde{\Omega}} = -k_1 \text{sign}(\tilde{\Omega}) - Q_1 \tilde{\Omega} - \frac{e_T}{J_t} \tag{27}$$

Consider now a quadratic cost function that measures the difference between the controller given in Eq. (10) and the fuzzy controller defined by:

$$J(\theta) = \frac{1}{2J_t} e_T^2 = \frac{1}{2J_t} \left(T_g^* - \xi_z^T \theta \right)^2 \tag{28}$$

Using the gradient descent method to minimize Eq. (28) for θ yields:

$$\dot{\theta} = -\eta_\theta . \nabla_\theta J(\theta), \text{ with } \eta_\theta > 0 \tag{29}$$

From formulae (27) and (29), we find:

$$\dot{\theta} = -\eta_\theta \xi_z^T \left[\dot{\tilde{\Omega}} + k_1 \text{sign}(\tilde{\Omega}) + Q_1 \tilde{\Omega} \right] \tag{30}$$

A discrete expression of Eq. (30) can be given by:

$$\theta_{t+1} = \theta_t - \Delta t\, \eta_\theta \xi_z^T \left[\dot{\tilde{\Omega}} + k_1 \text{sign}(\tilde{\Omega}) + Q_1 \tilde{\Omega} \right] \tag{31}$$

4. RESULTS AND DISCUSSION

The simulation of the modeling turbine with the suggested MPPT control methods is performed using a Matlab script. The developed methods are analyzed under two different wind speed profiles to evaluate their robustness and tracking capabilities. The results are then compared with the SMC and Fuzzy logic methods. The simulation parameters of the considered turbine are (Laverdure 2005, Bekka, et al. 2013, Teninge, et al. 2008): $R = 23.5$ m, $J_t = 222\,963$ kg. m^2, $f_v = 743.21$ N.m.s/rad.

4.1 Robustness test

The robustness of the two developed methods is investigated under the rapid changing of the wind speed as illustrated in Fig. (2). The characteristics of the power coefficient (Cp), the output power, and the angular velocity are presented in Figs. (3), (4), and (5), respectively. These figures demonstrate that the wind turbine operates at the optimal speed for each wind speed variation and achieves the maximum power point efficiently. The comparative study with the traditional SMC and fuzzy logic methods shows that the two proposed methods perform better. Indeed, we note the absence of the chattering effect in the GSMC method and the non-sensitivity of the GAFSMC method to sudden variations in wind speed.
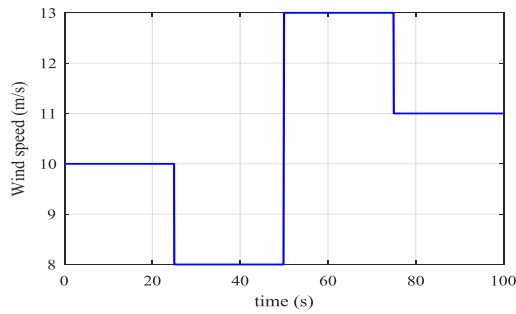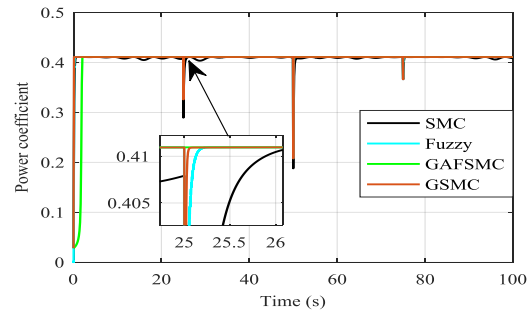

Fig 2. Wind speed profile

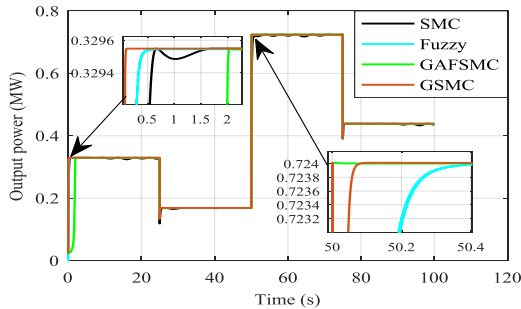Fig 3. Power coefficient characteristics
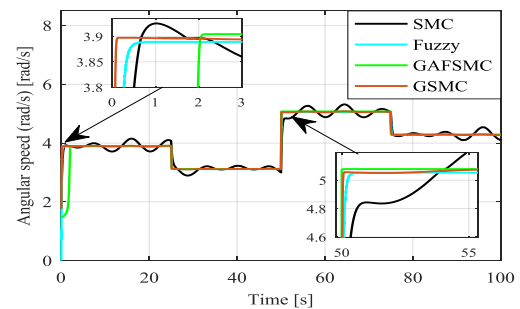

Fig 4. Output power of the wind turbine

Fig 5. Angular speed of the wind turbine

4.2 Tracking test

The tracking test of the two proposed strategies is analyzed under the intermittent wind speed profile which is illustrated in Fig. (6). The different characteristics of the wind turbine are presented in Fig. (7) to Fig. (10). These results show good tracking capabilities of the proposed methods and well-ensured MPPT control. Also, it reveals an excellent dynamic response of the GSMC compared to the other methods.
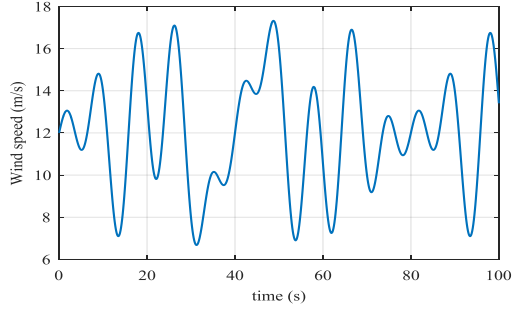
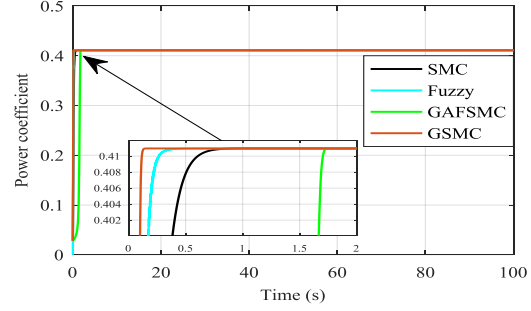

Fig 6. Intermittent wind profile
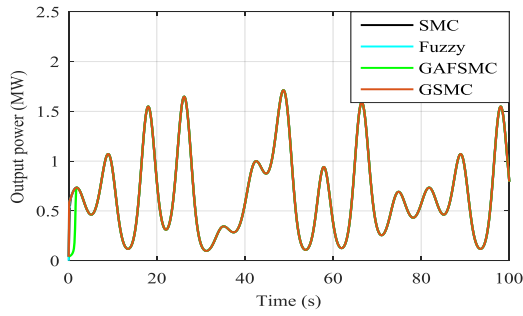

Fig 7. Power coefficient characteristics
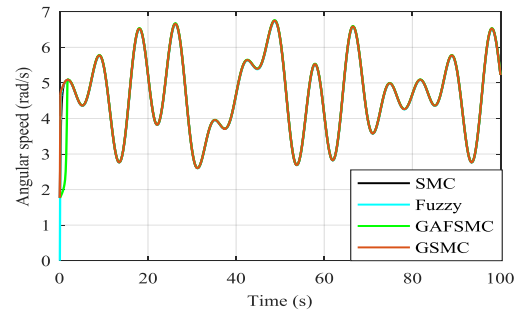

Fig 8. Output power of the turbine
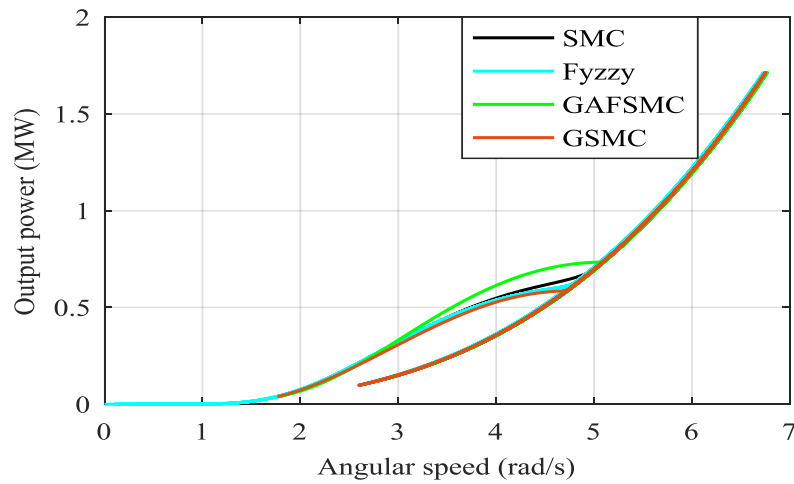

Fig 9. Angular speed of the wind turbine

Fig 10. Output power versus angular speed

5. CONCLUSION

Two innovative methods, GSMC and GASMC, have been developed to maximize power extraction from wind sources. Their performance is thoroughly analyzed and compared against two traditional methods, SMC and Fuzzy Logic. The incorporation of the gradient ascent algorithm enhances the performance of these newly proposed methods by minimizing the chattering effect associated with SMC and improving its dynamic response. Additionally, it enhances their reliability and tracking capabilities, ensuring effective MPPT control. This study establishes the consistency and effectiveness of these methods beyond doubt.

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