

Enhancing power control in doubly fed induction generator based wind turbines: a performance comparison of fuzzy logic and sliding mode control methods

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Abstract. *Effective power regulation is critical for ensuring the stability and performance of Doubly Fed Induction Generator (DFIG)-based wind turbines. This study conducts a comparative study between two control methodologies: fuzzy logic control (FLC) and sliding mode control (SMC), to regulate power in DFIG-based wind turbines. The paper emphasizes the importance of power regulation in wind turbines and its impact on grid stability, presents mathematical equations governing DFIG-based wind turbine systems, encompassing machine equations, power equations, and control objectives related to power regulation. A comprehensive model of the DFIG-based wind turbine system is developed, accounting for dynamic machine behavior and grid interface considerations. The modeling process integrates relevant electrical and mechanical components, along with power regulation control strategies. Subsequently, FLC and SMC control methodologies are developed and implemented to regulate desired power. Detailed discussions on controller design and tuning are provided, aligning with specific power control requirements. The results highlight SMC's effectiveness in achieving precise power regulation within DFIG-based wind turbines, showcasing its superior response characteristics. The study offers valuable insights into the advantages and trade-offs associated with each control approach, aiding researchers and practitioners in selecting the most suitable control methodology for their operational needs. In summary, this paper contributes to the field of wind turbine control systems through a comparative study of FLC and SMC controllers, focusing on regulating power in DFIG-based wind turbines. The findings demonstrate SMC's superior performance in response, enhancing our understanding of control methodologies for optimizing wind turbine performance and grid integration in sustainable energy systems.*

Keywords Doubly Fed Induction Generator, System Wind Turbine, Fuzzy Logic Control, Sliding Mode Control.

1. Introduction

The global energy landscape is undergoing a profound transformation, with an increasing reliance on renewable sources of energy to mitigate the challenges posed by climate change and resource depletion [1]. Wind energy, in particular, has emerged as a pivotal contributor to sustainable power generation. Wind turbines, with their ability to harness the kinetic energy of the wind and convert it into electrical power, play a central role in this transition [2]-[3]. However, to fully unlock the potential of wind energy, it is imperative to optimize the

performance of wind turbines and enhance their integration into the electric grid [4]. One of the key challenges in wind energy systems is efficient power regulation. Maintaining stable and reliable power output in varying wind conditions is paramount for the seamless integration of wind energy into the grid. This regulation is especially crucial in wind turbines employing Doubly Fed Induction Generators (DFIGs), a prevalent technology in the wind energy sector. DFIG-based wind turbines offer advantages in terms of variable speed operation, improved power quality, and reduced mechanical stress on the drive train. Effective control strategies are at the heart of achieving precise power regulation and enhancing the overall performance of DFIG-based wind turbines [5]. In this context, this research embarks on a comprehensive exploration of two prominent control methodologies: Fuzzy Logic Control (FLC) and Sliding Mode Control (SMC). These control techniques have gained prominence due to their ability to handle complex and nonlinear systems such as wind turbines. To this end, this paper presents a detailed analysis of FLC and SMC in the context of power regulation for DFIG-based wind turbines. The study delves into the intricacies of these control methodologies, their implementation, and their impact on the performance of wind turbines. By conducting a thorough comparative analysis, the research aims to elucidate the advantages and limitations of these control strategies, ultimately providing valuable insights for optimizing the operation of DFIG-based wind turbines. This research addresses a critical aspect of wind energy technology, highlighting the pivotal role of control strategies in the performance and integration of wind turbines into the broader energy landscape. As the world transitions towards a more sustainable energy future, understanding and optimizing control mechanisms for wind turbines is vital to unlock their full potential and ensure a cleaner and more reliable energy supply.

2. Modeling

2.1. Wind Turbine model

Wind captured by turbine blades is converted to mechanical energy, driving the rotor of a Doubly Fed Induction Generator (DFIG), as shown in Figure 1. The DFIG system, which allows

the turbine to operate over varied speeds, enhances the efficiency of energy capture. Integral to this setup is the AC/DC/AC converter, which facilitates precise power control, ensuring that the electricity generated is consistent with demand. This dynamic, detailed in Figure 1, is crucial for the effective delivery of controlled power to the grid.

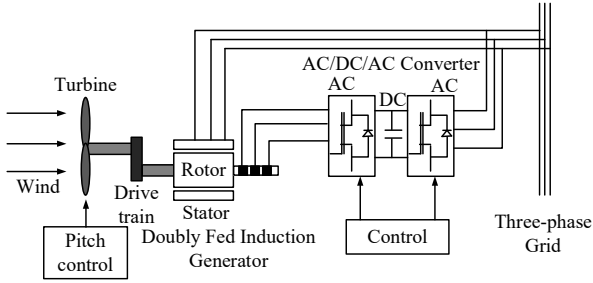


Fig. 1 Wind energy system

The power produced by the wind turbine is given by the equation:

$$P_T = \frac{1}{2} C_p(\lambda, \beta) \rho \pi R^2 V_w^3 \quad (1)$$

Where : P_T is the turbine power, $C_p(\lambda, \beta)$ is the power coefficient, ρ is the air density, R is the radius of the turbine, V_w is the wind speed, λ is the tip speed ratio and β is the pitch angle.

The power coefficient $C_p(\lambda, \beta)$ is calculated by the following equations :

$$C_p(\lambda, \beta) = C_1 \left(\frac{C_2}{\lambda_i} - C_3\beta - C_4 \right) e^{\frac{C_5}{\lambda_i}} + C_6\lambda \quad (2)$$

With $\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$, $C_1 = 0.52$, $C_2 = 116$, $C_3 = 0.4$, $C_4 = 5$, $C_5 = 21$, $C_6 = 0.0068$ and $\lambda = \frac{R\omega_{mech}}{v_w}$

The mechanical torque of the turbine is obtained by dividing the turbine power by the speed rotation as detailed in this function:

$$T_t = \frac{P_t}{\Omega_t} = \frac{1}{2\Omega_t} C_p(\lambda, \beta) \rho \pi R^2 V_w^3 \quad (3)$$

Where Ω_t is the mechanical angular speed of the turbine.

Figure 2 illustrates the relationship between the power coefficient (C_p) and the tip speed ratio (λ) for various pitch angles (β). The graph highlights that an increase in β leads to a reduction in the power coefficient, consequently decreasing output power. The optimum C_p value is 0.39, achieved at $\lambda = 9.886$ and $\beta = 0$. The system must identify the optimal rotational speed. Maintaining λ at its optimal value (λ_{opt}), as depicted in Fig. 2, ensures that the coefficient is at its peak. The optimal power can be calculated using the following equation:

$$P_s^* = \frac{1}{2} C_{pmax}(\lambda_{opt}) \rho \pi R^2 V_w^3 \quad (4)$$

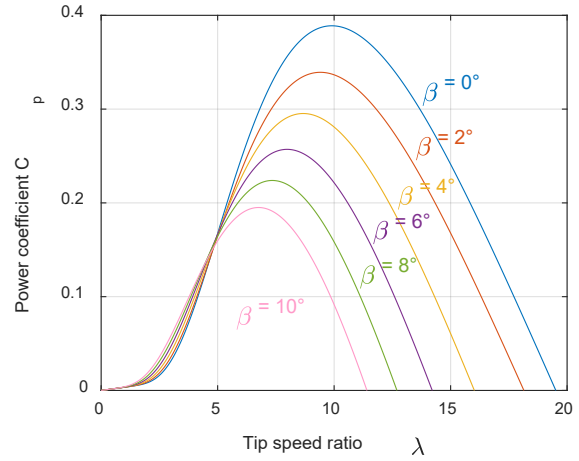


Fig. 2 Efficiency coefficient curve versus tip speed ratio.

2.2. DFIG model

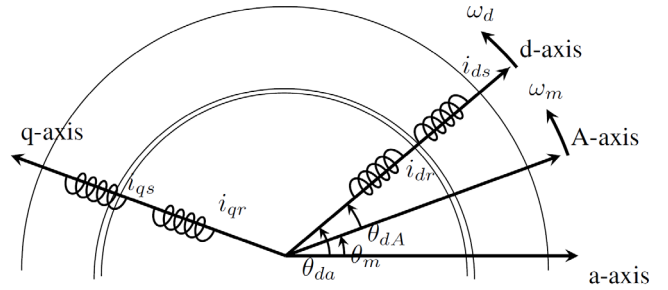


Fig. 3 Stator and rotor are represented by equal dq winding currents[6].

Following the park transformation and mathematical development in[7], we discover:

- Electrical equations

$$v_{ds} = R_s i_{ds} + \frac{d}{dt} \Phi_{ds} - \omega_d \Phi_{qs}$$

$$v_{qs} = R_s i_{qs} + \frac{d}{dt} \Phi_{qs} + \omega_d \Phi_{ds} \quad (5)$$

$$v_{dr} = R_r i_{dr} + \frac{d}{dt} \Phi_{dr} - \omega_{dA} \Phi_{qr}$$

$$v_{qr} = R_r i_{qr} + \frac{d}{dt} \Phi_{qr} + \omega_{dA} \Phi_{dr} \quad (6)$$

- Magnetic equations

$$\Phi_{ds} = L_s i_{ds} + L_m i_{dr}$$

$$\Phi_{qs} = L_s i_{qs} + L_m i_{qr} \quad (7)$$

$$\Phi_{dr} = L_r i_{dr} + L_m i_{ds}$$

$$\Phi_{qr} = L_r i_{qr} + L_m i_{qs} \quad (8)$$

- Angular equations

The cross-section angle in radians between the A-axis and the a-axis θ_m , satisfies

$$\theta_{dA} = \theta_{da} - \theta_m \quad (9)$$

$$\frac{d}{dt} \theta_{dA} = \omega_{dA} \quad (10)$$

$$\text{and} \quad \theta_m = \int \omega_m(t) dt + \theta_0 \quad (11)$$

Where ω_m is the electrical rotational speed and θ_0 is the initial angle by which rotor and stator coils are offset in electrical space.

from Eq.9 and we know that $\omega_d = \frac{d\theta_{da}}{dt}$

$$\omega_d = \omega_{dA} + \omega_m \quad (11)$$

We can calculate θ_{da} using Clarke transformation from (v_a, v_b, v_c) to (v_α, v_β)

$$\theta_{da} = \tan^{-1} \frac{v_\alpha}{v_\beta} \quad (12)$$

$$\text{And} \quad \omega_d = \omega_{syn} = 2\pi f_{syn} \quad (13)$$

$$\text{we have} \quad \frac{d\omega_{mech}}{dt} = \frac{T_{em} - T_L}{J} \quad (14)$$

where ω_{mech} is the mechanical rotational speed and T_L is the load torque and J is the moment of inertia. Given that

$$\omega_m = \frac{P}{2} \omega_{mech} \quad (15)$$

where P is the poles number, we have the angular acceleration equation

$$\frac{d\omega_m}{dt} = \frac{P}{2} \frac{T_{em} - T_L}{J} \quad (16)$$

- Torque equation

The electromagnetic torque can be expressed as

$$T_{em} = \frac{P}{2} L_m (\phi_{qr} i_{dr} - \phi_{dr} i_{qr}) \quad (17)$$

where P is the number of poles.

- Power equations

Given that the stator real and reactive power can be obtained as

$$P_s + jQ_s = (v_{ds} + jv_{qs})(i_{ds} + ji_{qs})^H \quad (18)$$

Where the superscript H denotes the conjugate of the given complex-valued vector, we have

$$P_s = v_{ds} i_{ds} + v_{qs} i_{qs} \quad (19)$$

$$Q_s = v_{qs} i_{ds} - v_{ds} i_{qs} \quad (20)$$

Similarly, for the rotor we have

$$P_r = v_{dr} i_{dr} + v_{qr} i_{qr} \quad (21)$$

$$Q_r = v_{qr} i_{dr} + v_{dr} i_{qr} \quad (22)$$

From Eq.7 & Eq.8

$$\begin{bmatrix} \phi_{ds} \\ \phi_{qs} \\ \phi_{dr} \\ \phi_{qr} \end{bmatrix} = \underbrace{\begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix}}_{[M]} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \quad (23)$$

From Eq.23, currents can be calculated by using the inverse of matrix [M]:

$$\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} = M^{-1} \begin{bmatrix} \phi_{ds} \\ \phi_{qs} \\ \phi_{dr} \\ \phi_{qr} \end{bmatrix} \quad (24)$$

From Eq.5 & Eq.6, we can obtain fluxes with voltages as Input

$$\begin{aligned} \frac{d}{dt} \phi_{ds} &= v_{ds} - R_s i_{ds} + \omega_d \phi_{qs} \\ \frac{d}{dt} \phi_{qs} &= v_{qs} - R_s i_{qs} - \omega_d \phi_{ds} \end{aligned} \quad (25)$$

$$\begin{aligned} \frac{d}{dt} \phi_{dr} &= v_{dr} - R_r i_{dr} + \omega_{dA} \phi_{qr} \\ \frac{d}{dt} \phi_{qr} &= v_{qr} - R_r i_{qr} - \omega_{dA} \phi_{dr} \end{aligned} \quad (26)$$

From Eq.9, and replacing the fluxes in terms of rotor currents we get :

$$\begin{aligned} v_{dr} &= \underbrace{R_r i_{dr} + \sigma L_r \frac{d}{dt} i_{dr}}_{v'_{dr}} - \underbrace{\omega_{dA} \sigma L_r i_{qr}}_{v_{dr,comp}} \\ v_{qr} &= \underbrace{R_r i_{qr} + \sigma L_r \frac{d}{dt} i_{qr}}_{v'_{qr}} - \underbrace{\omega_{dA} \sigma L_r i_{dr}}_{v_{qr,comp}} \end{aligned} \quad (27)$$

Where $\sigma = 1 - \frac{L_m^2}{L_s L_r}$

$$\text{From} \quad v'_{(dq)r} = R_r i_{(dq)r} + \sigma L_r \frac{d}{dt} i_{(dq)r} \quad (28)$$

and after Laplace transformation

$$i_{(dq)r} = \frac{1}{R_r + S \sigma L_r} v'_{(dq)r} \quad (29)$$

In which S is the complex number frequency parameter.

Using Eq.19, and given that $v_{qs} = 0$, $i_{ds} \approx -\frac{L_m}{L_s} i_{dr}$, we get

$$P_s = v_{ds} i_{ds} \approx -\frac{L_m}{L_s} v_{ds} i_{dr} \quad (30)$$

using Eq.20, and $v_{qs} = 0$, $\phi_{qs} = L_m i_{qr} + L_s i_{qs} \approx -\frac{v_{ds}}{\omega_d}$, we have

$$Q_s = -v_{ds} i_{qs} \approx v_{ds} \left(\frac{v_{ds}}{\omega_d L_s} + \frac{L_m}{L_s} \right) i_{qr} \quad (31)$$

Table 1. Specifications of DFIG and Wind Turbine [8].

Parameter	Definition	Value	Unit
R_r	Rotor Resistance	1.5	$m\Omega$
R_s	Stator Resistance	2.0	$m\Omega$
L_r	Rotor leakage	0.0024	H
L_s	Stator leakage	0.0024	H
L_m	Mutual leakage	0.0023	H
f_{syn}	Rated frequency	60	Hz
P	Poles	6	.
J	Moment of inertia for DFIG	75	$Kg.m^2$
J_{Turb}	Moment of inertia for Wind turbine	2.4×10^6	$Kg.m^2$
ρ	Density of Air	1.2	$Kg.m^3$
D	Rotor Diameter for the Wind Turbine (2R)	70.5	m

3. Controllers

3.1. Sliding Mode Control

The Sliding Mode Control (SMC) principle involves guiding the system state trajectory towards a sliding mode surface, denoted as S(X), and maintaining its proximity to this surface by incorporating a discontinuous signal, $\text{sign}(S(X))$. The following equation can express the SMC law :

$$u = u_{eq} + u_n \quad (32)$$

The initial phase in developing the Sliding Mode Controller (SMC) involved designing the sliding mode function as [9] :

$$S = \left(\lambda + \frac{d}{dt} \right)^{r-1} e \quad (33)$$

Where e is the tracking error, r is the system order and variable λ must satisfy the Hurwitz condition.

From Eq.28 we know that $r = 1$, so our surface is

$$S = e = I_{dqrDesired} - I_{dr} \quad (34)$$

Define the Lyapunov function as

$$V = \frac{1}{2} S^2 \quad (35)$$

To guarantee the stability condition, the derivation of the Lyapunov function in Eq.(35) must be $\dot{V} < 0$ as $S\dot{S} < 0$

The derivation of the sliding mode function is

$$\dot{S} = \dot{e} = \dot{I}_{dqrDesired} - \dot{I}_{dr} \quad (36)$$

$$\dot{S} = \dot{e} = \dot{I}_{dqrDesired} + \frac{(R_r I_{dqr} - V_{dqr})}{\sigma L_r} \quad (37)$$

Thus the derivation of the Lyapunov function $\dot{V}$ is

$$S\dot{S} = S \left(\dot{I}_{dqrDesired} + \frac{(R_r I_{dqr} - V_{dqr})}{\sigma L_r} \right) \quad (38)$$

To satisfy the condition $S\dot{S} < 0$, the sliding mode controller is designed as

$$u_{dqr}^{eq} = \sigma L_r (\dot{I}_{dqrDesired} + R_r I_{dqr}) \quad (39)$$

Finally, a discontinuous control ($\text{sign}(S)$) has been added to calculate the final law of sliding mode control as shown in Eq.40 :

$$u_{dqr} = u_{dqr}^{eq} + u_n = u_{dqr}^{eq} + K \text{sign}(S) \quad (40)$$

Substitute Eq.40 to Eq.38 where $u = V_{dqr}$, then we get

$$S\dot{S} = -K \text{sgn}(S) < 0 \quad (41)$$

3.2. Fuzzy Logic Control

Fuzzy logic is becoming an essential area of study for many scientists. Consumer technological spin-offs (cameras, washing machines, etc.) and industrial technological spin-offs (regulation and management of complex processes related to energy, transportation, material transformation, robotics and machine tools) are currently accessible.

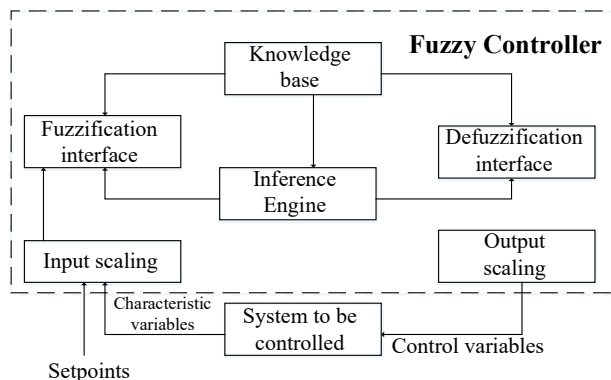


Fig. 4 Basic structure of a fuzzy controller [10].

Fuzzy control derives its name from automated control applications, but its various uses today extend well beyond this framework to anywhere mathematical modeling is problematic. This control method works on a fundamental principle: it does "interpolation" between a small number of known instances

provided by an expert in the form of fuzzy rules such as "if x is small and y is moderate, then u must be very large." The construction of the predicates triggered by these rules is typically done empirically, although other learning approaches are increasingly being used with the goal of producing self-adaptive control systems.

A Fuzzy Logic Controller (FLC) is designed by creating a system that can efficiently control the behavior of a dynamic process. FLC can be used to improve the performance of a Doubly Fed Induction Generator (DFIG)-based wind turbine by improving its control approach. One method for developing an FLC is to start with a Proportional-Integral-Derivative (PID) controller. To begin designing the FLC, a PID controller may be used to operate the DFIG-based wind turbine. This PID controller acts as a baseline control mechanism, allowing the system to function and respond to a variety of situations. The wind turbine is subjected to variable wind speeds throughout this phase, and the PID controller creates control signals depending on the error (difference between expected and actual performance) signals it receives. These control signals change the characteristics of the turbine to attain the desired operational condition.

After extracting the Input and output data of the PID controller, we can define the membership functions in a Fuzzy Logic Controller describing the relationship between input variables (error) and output variables (adjustments). Membership functions may be built by examining the input-output data from the PID controller's operation. The input membership functions classify the mistake as "Low," "Medium," or "High," whereas the output membership functions establish linguistic phrases like "Negative Large," "Zero," and "Positive Large" corrections.

Figures [5-6] show the input-output relationship of a Proportional-Integral (PI) controller to demonstrate the fundamental control method used in DFIG-based wind turbines (this result was obtained from an old study in [6]). The performance characteristics of the PI controller are encapsulated in this figure, which serves as a forerunner in creating the Fuzzy Logic Controller (FLC) for optimizing wind turbine operations.

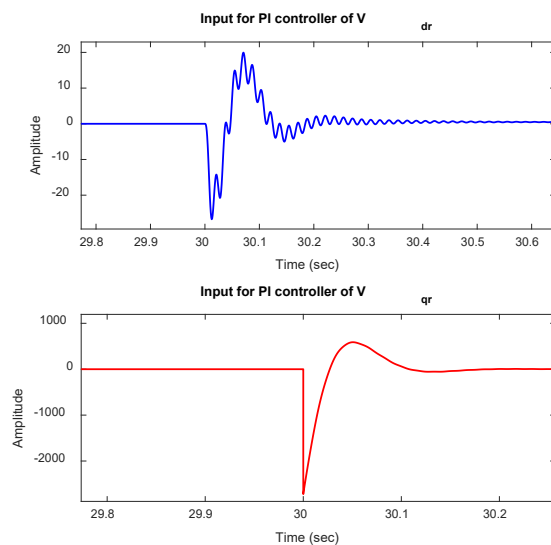


Fig. 5 PI controller input data

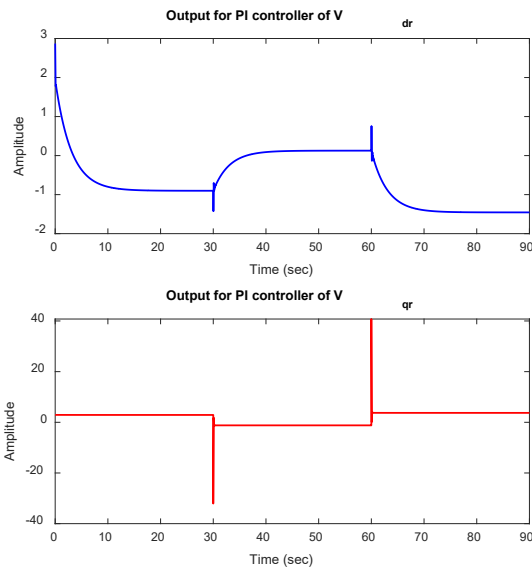


Fig. 6 PI controller output data

The foundation for constructing the Fuzzy Logic Controller (FLC) lies in extracting and analyzing input and output data from the Proportional-Integral (PI) controller's operation, as depicted in Figures 5 and 6. By leveraging this empirical data, we define membership functions that underpin the FLC's decision-making process.

3.2.1 Input membership functions

In the context of our FLC, input membership functions serve as a bridge between the error signal (the difference between expected and actual performance) and the control decisions. These functions categorize the error into linguistic terms, facilitating a human-like understanding of system behavior. Through rigorous data analysis, we have meticulously crafted these input membership functions. Figure 7 (as shown below) depicts the input membership functions that were derived from extensive data grouping and analysis:

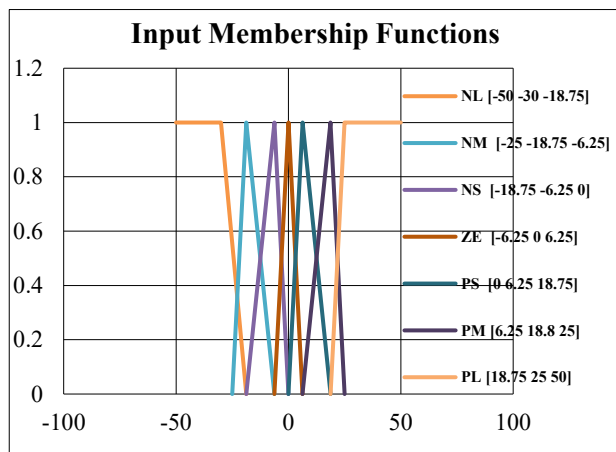


Fig. 7 Input membership functions-Error signal of I_{dr}

These input membership functions enable the FLC to discern between (and from left to right) "Negative Large", "Negative Medium", "Negative Small", "Zero Equal", "Positive Small", "Positive Medium" and "Positive Large" error magnitudes, forming the basis for nuanced control decisions.

3.2.2 Output membership functions

In tandem with input membership functions, output membership functions are instrumental in shaping the FLC's control strategy. These functions establish linguistic terms for the system's response, such as "Negative Large", "Negative Medium", "Negative Small", "Zero Equal", "Positive Small", "Positive Medium" and "Positive Large" corrections. Figures 8 (as depicted below) illustrate the output membership functions, meticulously formulated through the analysis of the PI controller's output data:

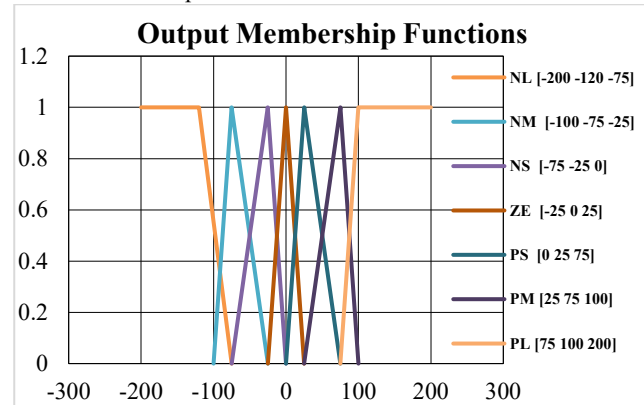


Fig. 8 Output membership functions – Control adjustments of V_{dr}'

These output membership functions guide the FLC in making precise adjustments to the DFIG-based wind turbine's parameters, enabling it to operate optimally under varying wind conditions.

3.2.3 Rules

The heart of our Fuzzy Logic Controller (FLC) lies in its rules. These rules define how the FLC interprets input conditions and determines appropriate control actions, enabling it to mimic human-like reasoning and adapt to complex control scenarios. The subsequent sections will delve into the practical application of these rules in enhancing the turbine's performance under varying wind conditions.

The table below provides a comprehensive overview of these rules, each uniquely identified by a rule number. Each row in the table represents a distinct rule that guides the FLC's response to varying conditions.

Table 2. Rules for V_{dqr}' Fuzzy Controller

Condition (Input) Output	NL	NM	NS	ZE	PS	PM	PL
NL	X	-	-	-	-	-	-
NM	-	X	-	-	-	-	-
NS	-	-	X	-	-	-	-
ZE	-	-	-	X	-	-	-
PS	-	-	-	-	X	-	-
PM	-	-	-	-	-	X	-
PL	-	-	-	-	-	-	X

4. Results and discussion

A Matlab simulation environment was utilized to evaluate the effectiveness of the examined control strategies. This environment focused on two main aspects: reference tracking and variations in parameters. The study employed a Doubly Fed Induction Generator (DFIG), characterized by the parameters and specifications outlined in Table 1. This generator operates with a rated line supply voltage of $V_s = 398/690V$.

4.1 Reference tracking

A realistic wind speed profile was employed to assess the performance of both controllers in responding to this disturbance. The reference for active power (P_{sref}) was generated through the Maximum Power Point Tracking (MPPT) strategy, and the reactive power reference was kept at zero ($Q_{s-ref}=0$) to ensure a unity power factor. As observed in Figure 9, the power outputs closely follow their respective references, demonstrating effective decoupling between the two powers and achieving a unity power factor, as highlighted in Figure 13. The Sliding Mode Controller (SMC) showed smaller amplitude oscillations that occurred over a brief period and with less steady state error than the Fuzzy Logic Controller (FLC).

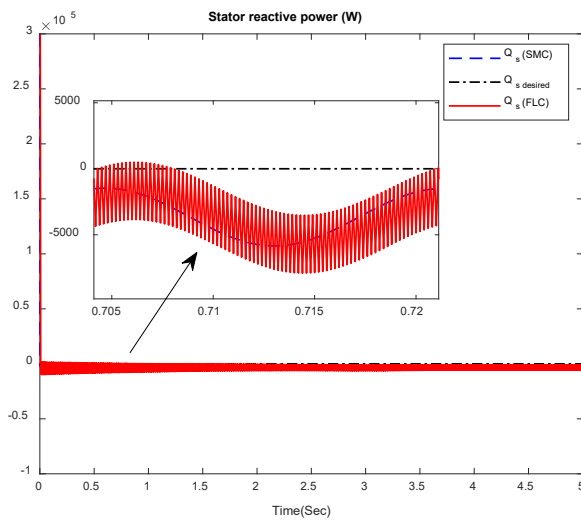


Fig. 9 Stator reactive power behavior

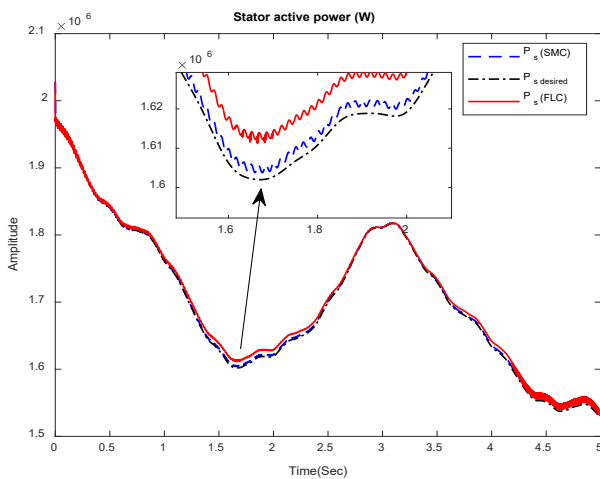


Fig. 10 Stator active power behavior

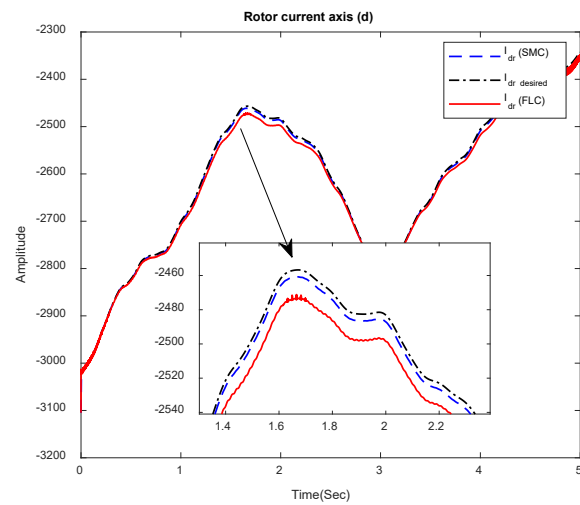


Fig. 12 Rotor current behavior axis (d)

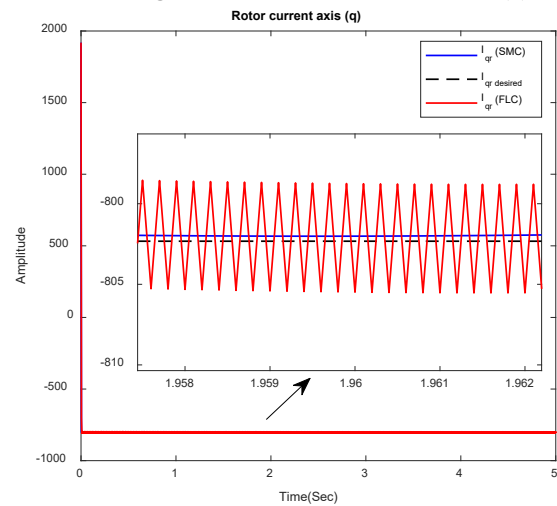


Fig. 12 Rotor current behavior axis (q)

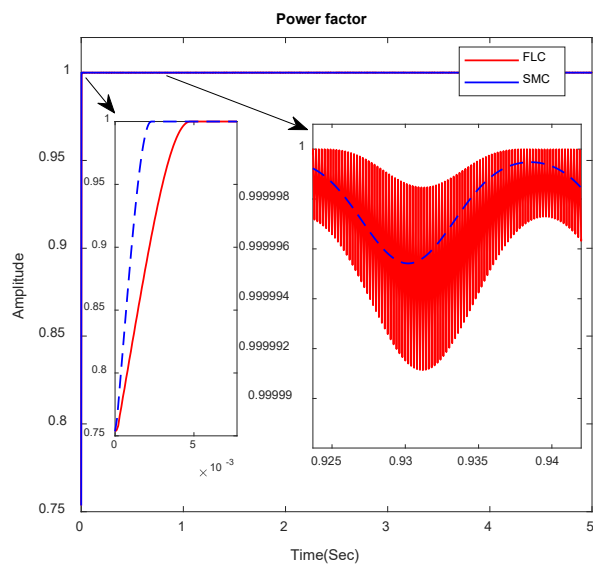


Fig. 13 Power factor

4.2 Robustness

A stepped wind speed profile was employed to provide a clear visualization of each controller's transient and steady-state responses. The robustness of both the SMC and FLC controllers was evaluated in terms of their ability to handle variations in DFIG parameters. The simulation results revealed that while both controllers effectively maintained active/reactive power decoupling, there was an observable coupling between reactive and active power. Notably, oscillations were detected in the active power at specific times (1 s and 1.7 s) for both the SMC and FLC controllers. The SMC exhibited a quicker settling time of 0.0037s compared to the FLC's 0.008s, and both managed to follow the responses accurately without any overshoots. A particular observation in Figure 16-17 highlighted an error in the system using the FLC controller between 1.6s and 2.5s, attributed to a highly active power value. Based on these simulation outcomes, the SMC is concluded to be more efficient and robust than the FLC controller, evidenced by its shorter settling time and reduced steady-state error.

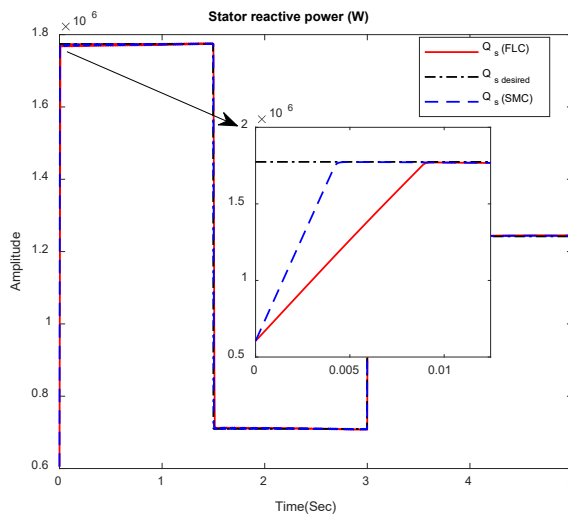


Fig. 14 Stator reactive power behavior with +40% variation of L_s

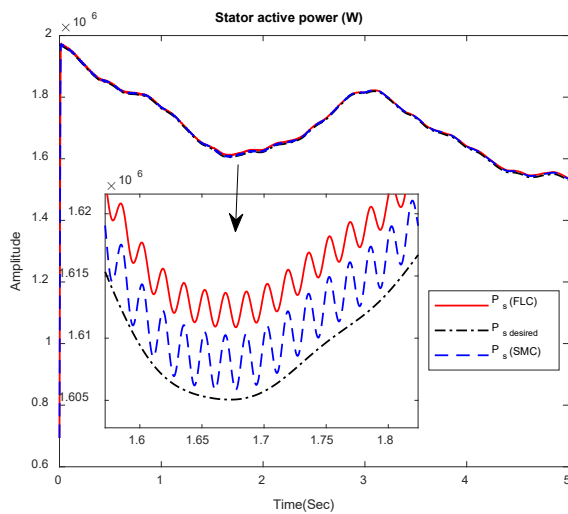


Fig. 15 Stator active power behavior with +40% variation of L_s

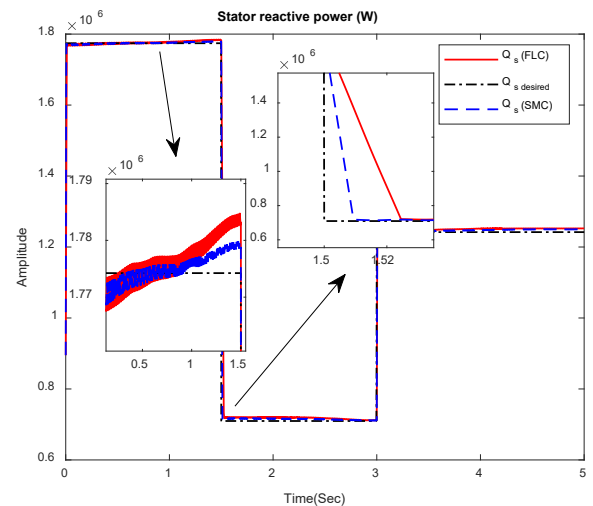


Fig. 16 Stator reactive power behavior with 100% Variation of R_r , 60% of L_r and 10% of L_m

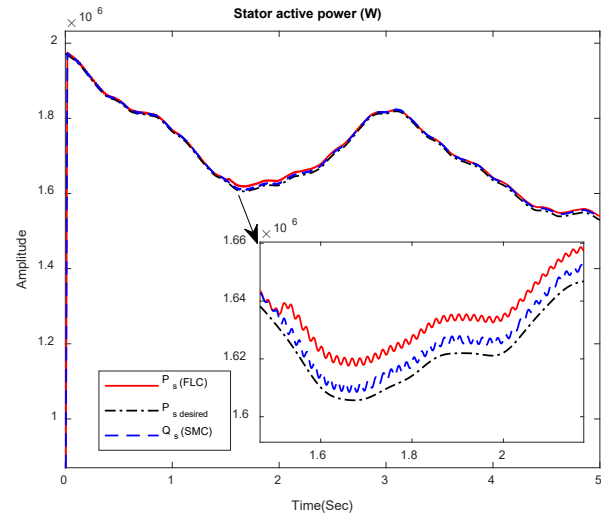


Fig. 17 Stator active power behavior with 100% Variation of R_r , 60% of L_r and 10% of L_m

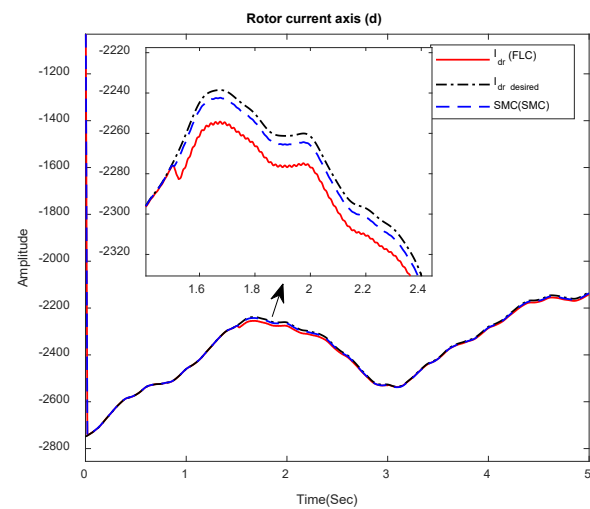


Fig. 19 Rotor Currents axis (d) with 100% Variation of R_r , 60% of L_r and 10% of L_m

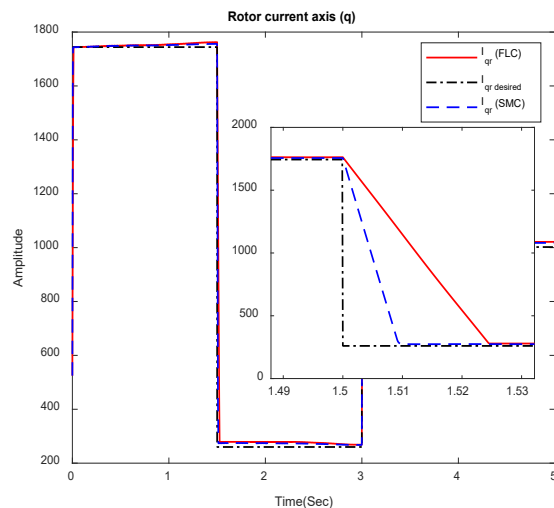


Fig. 19 Rotor Currents axis (q) with 100% Variation of R_r , 60% of L_r and 10% of L_m

4.3 Comparative analysis

To clarify and facilitate the comparison study, we present the following table:

Table 3. Performance comparison

Control Method	Response time	Overshoot (%)	steady-state error	Robust
SMC	0.0037	0.005%	1000 (0.00056%)	More
FLC	0.0080	0.0085%	2000 (0.0011%)	Less

The table above compares Sliding Mode Control (SMC) and Fuzzy Logic Control (FLC) based on key performance metrics. SMC demonstrates faster response time, lower overshoot, and greater robustness.

5. Conclusions

In our comparative study of Sliding Mode Control (SMC) and Fuzzy Logic Control (FLC) for power regulation in Doubly Fed Induction Generator (DFIG)-based wind turbines, we found that SMC demonstrates superior performance in terms of response characteristics and robustness. This makes it a potentially more suitable choice in scenarios requiring rapid and precise power regulation, aligning with the growing need for efficient renewable energy sources.

However, FLC's stable control capabilities, with minimal disturbances during setpoint adjustments, also make it a viable option, particularly where gradual and predictable control is desired. This suggests that the control strategy selection should be tailored to the specific operational demands and environmental conditions of each wind turbine installation.

The study paves the way for future research, especially in developing hybrid control systems that combine the strengths of both SMC and FLC. Such advancements could offer enhanced adaptability and performance in variable wind conditions.

Furthermore, integrating advanced technologies like machine learning into these control strategies could further optimize wind turbine efficiency and reliability. This progression is vital for the global transition towards sustainable energy systems, contributing significantly to grid stability and integrating renewable energy sources.

Overall, our findings provide valuable insights into wind turbine control mechanisms, underscoring their importance in the broader context of sustainable energy and climate change mitigation.

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