Control of a Doubly Fed Induction Generator for Variable Speed Wind Energy Conversion Systems using Fuzzy Controllers optimized with a Genetic Algorithm

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ABSTRACT

This paper presents a comprehensive study of a wind turbine system operating under variable wind conditions, utilizing a Doubly Fed Induction Generator (DFIG) connected to the grid. The DFIG is controlled via a rotor-side transducer, allowing for independent regulation of the conductors to manage both active and reactive power flows effectively. The control strategy focuses on generating reference voltages for the rotor to ensure that active and reactive power align with the desired targets, optimizing the tracking of the maximum power point to maximize electrical output. The research analyzes the system's dynamic performance under fluctuating wind conditions, emphasizing control strategies for managing active and reactive energy. A notable innovation is the integration of fuzzy logic and genetic algorithm into the control strategy for the wind turbine's switching mechanism, which enhances system performance and efficiency. Simulation results demonstrate that this approach provides higher efficiency, improved performance, and greater stability compared to the traditional Proportional-Integral (PI) controllers.

Advanced artificial intelligence methods, such as fuzzy genetic algorithm control, were employed and the proposed system's effectiveness was validated with Matlab/Simulink simulations.

Keywords-Doubly Fed Induction Generator (DFIG); hybrid genetic algorithms; electrical network; fuzzy controller; Fuzzy Genetic Algorithm (FGA)

I. INTRODUCTION

Variable-speed wind turbines have gained significant popularity over fixed-speed systems due to their enhanced flexibility, higher efficiency, and improved power quality. These advantages enable better performance optimization and dynamic stability in grid disturbances. In modern applications, most wind energy conversion systems utilize Doubly Fed Induction Generators (DFIGs) [1]. The integration of fuzzy logic systems with genetic algorithms has proven effective across various theoretical studies, especially in fields such as robotics and electric motor control [2]. This approach offers significant robustness against disturbances and uncertainties in the model. However, the discontinuous nature of the control can lead to chattering phenomena, which can negatively impact actuators. To mitigate this, constant high-frequency commands are required to ensure convergence to the desired state, a practice that is often undesirable [3].

To address these challenges, one proposed solution is the implementation of sliding mode control with saturation functions, which replaces conventional switching functions [4]. This method, however, is merely a specific instance of fuzzy systems that employ genetic algorithms. The relationship between nonlinear fuzzy control and genetic algorithm-based fuzzy systems has been explored aiming to integrate the strengths of both approaches. This hybrid strategy combines the ease of implementation associated with fuzzy control and the theoretical stability and robustness provided by sliding mode control [5]. By merging the advantages of invariance against uncertainties and disturbances with the trajectory-tracking capabilities of fuzzy control, the issues of chattering in genetic algorithm-based fuzzy systems can be resolved while also reducing the complexity of fuzzy rule sets [6].

This paper presents a novel control method for an asynchronous generator powered by two sources, specifically focusing on a Fuzzy Genetic Algorithm (FGA) for DFIG speed control. This approach aims to maximize power output across a wide range of wind speeds while enhancing power gain [7]. The study incorporates intelligent controllers to improve the wind energy conversion system, utilizing an AI-based module to manage active and reactive power for the DFIG connected to the grid through the stator [8]. Through extensive experimentation, significant improvements in accuracy and overall performance have been achieved, compared to previously published works [9]. The proposed optimization algorithm is assessed against the traditional Proportional-Integral (PI) and fuzzy controllers, demonstrating superior response time and system stability. The key contributions of this research include a comprehensive study of the variable-speed wind turbine and asynchronous dual-feed machine system, validation of the regulator's effectiveness in active and reactive power management, and marked enhancements in response time, accuracy, and stability over prior studies.

II. GENERAL SYSTEM DESCRIPTION

The primary configuration of the DFIG discussed in this paper is illustrated in Figure 1. The wind turbine is mechanically connected to a doubly-fed induction generator via a shaft and gearbox coupling mechanism. The wound rotor induction generator is driven by various components [10]. The stator is directly connected to the grid, while the rotor is powered through a four-quadrant PWM converter (Rotor Side Converter and Grid Side Converter), linked to a battery through a DC link capacitor [11].

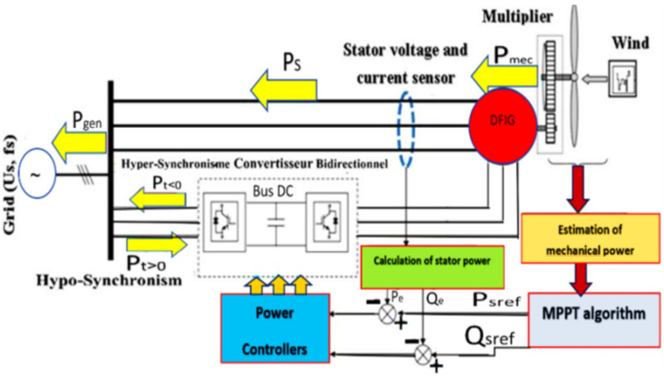
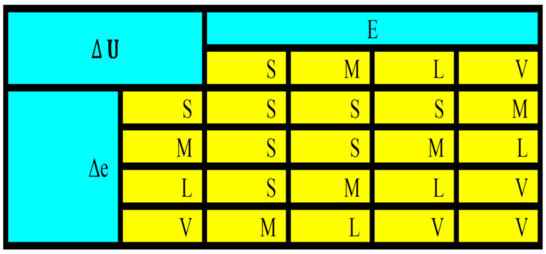


Fig. 1. A regulated wind turbine system integrated with the electrical grid.

III. FINDING THE RULE BASE USING GENETIC ALGORITHMS

We consider a fuzzy system characterized by two inputs, (x1 and x2) and a single output, y. The ranges for all three variables are segmented into four fuzzy sets, which are designated as "small," "medium," "large," and "very large." For convenience, these are abbreviated as "S," "M," "L," and "V," respectively (Figure 2). In this section, we will explore how to encode the following decision table into a string format [12].



ΔU		E			
		S	M	L	V
Δe	S	S	S	S	M
	M	S	S	M	L
	L	S	M	L	V
	V	M	L	V	V

Fig. 2. Rule set for the fuzzy controller.

The third entry labeled "M" in the second row states the following [13]:

IF x1 is medium and x2 is large, then y is medium.

For this approach, Type 2.5 genetic algorithms are particularly effective.

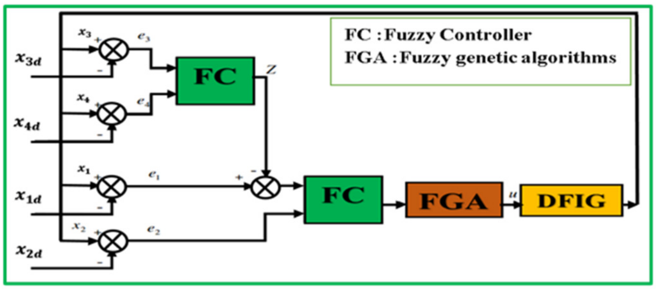


Fig. 3. Schematic representation of fuzzy systems utilizing the genetic algorithms for controlling state trajectory tracking.

The outlined production system consists of several steps: First, detectors collect explicit input values from the environment and transform them into a limited set of messages added to a message list. Next, classifiers compute the corresponding results, after which the message list is cleared [14]. Certain output messages from identical classifiers are then re-added to the message list, which is subsequently condensed into the fewest messages possible. The degree of matching with this process is quantified using a truth value between 0 and 1, determined by the maximum activity level of the messages. This value is applied to the activity level of the output messages, following Mamdani's principles. A summary of this fuzzy system, which employs genetic algorithms to tackle the state trajectory-tracking problem, is illustrated in Figure 3[15].

IV. ROTOR CURRENT ADJUSTMENT FOR DFIG

In this section, we will utilize the same vector control diagram, but with a modification: the rotor current regulators will be implemented as fuzzy logic systems optimized using genetic algorithms [16]. This approach aims to enhance the performance of the DFIG by leveraging the adaptability and efficiency of fuzzy logic combined with the optimization capabilities of genetic algorithms. This integration allows for improved regulation of rotor currents, enhancing overall system stability and response [17].

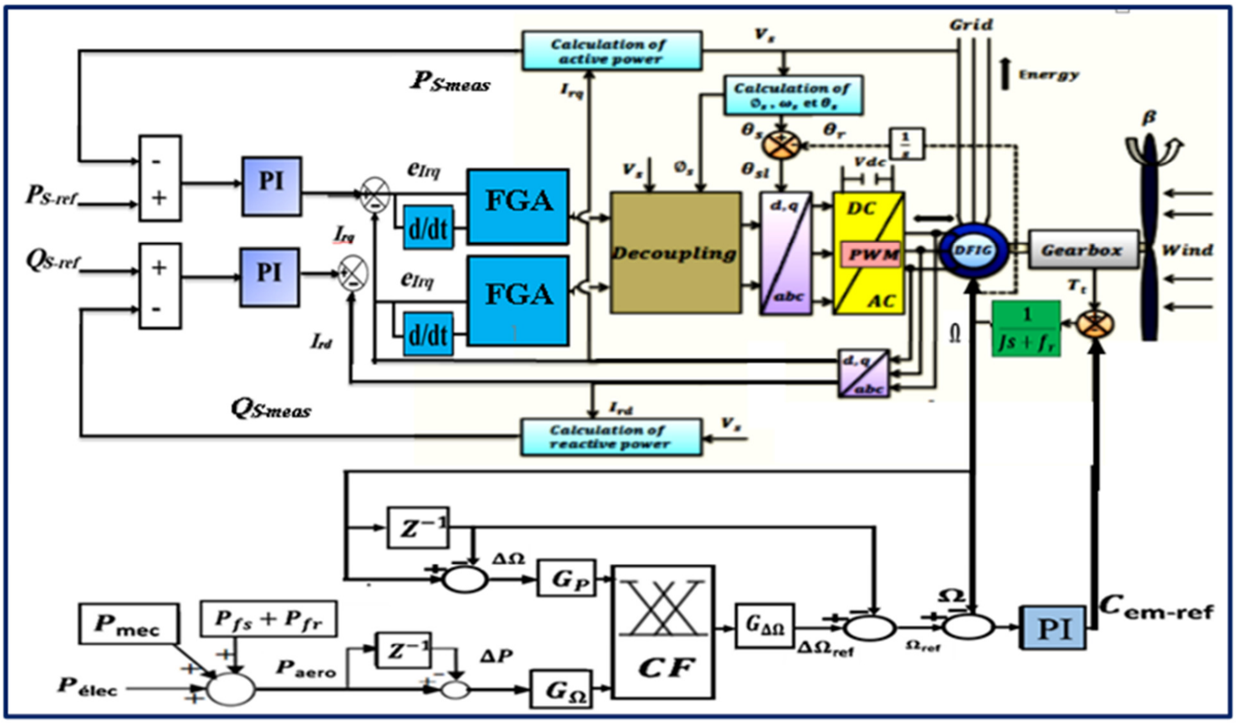


Fig. 4. Block diagram representing DFIG systems utilizing fuzzy logic controllers based on genetic algorithms for speed regulation of the power supply to the electrical grid.

V. OPTIMIZATION USING GENETIC ALGORITHMS

Genetic algorithms search for optimal solutions by iteratively generating new solutions from a set of candidates [7]. The process uses selection, crossover, and mutation operators on the current population, repeating until a stopping criterion is met. A simplified overview of the Genetic Algorithm process is illustrated in Figure 5 [18]. The various stages of the simple Genetic Algorithm [19] are:

- Initial Population Generation: Create a starting group of potential solutions.
- Evaluation of Individuals: Assess the performance of each solution within the population.
- Selection of the Best Individuals: Choose the top-performing solutions for reproduction.
- Reproduction: Combine and mutate the selected solutions to create new offspring.
- Formation of a New Generation: Assemble a new population that will undergo further evaluation.

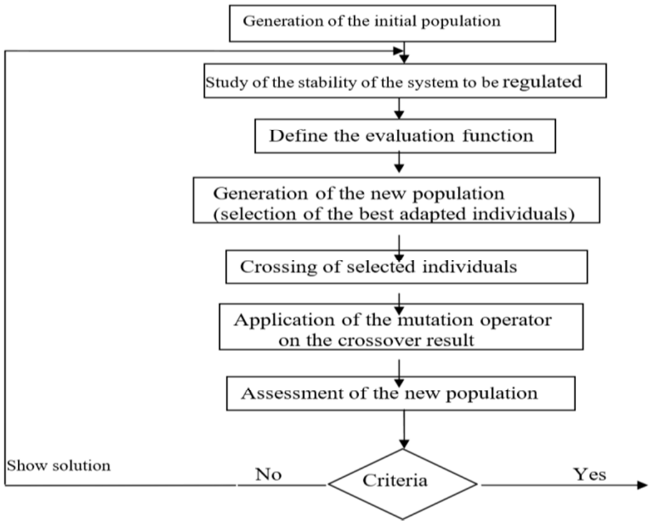


Fig. 5. Genetic algorithm block diagram.

VI. SIMULATION RESULTS AND ANALYSIS.

We focused on a 1.5 MW DFIG system, integrating control strategies and fuzzy system parameters optimized using genetic algorithms. This configuration was developed for a wind power system based on a doubly-fed asynchronous machine, with details outlined in Tables I and II. To evaluate the robustness of the control system—enhanced by fuzzy logic regulators and genetic algorithms—the effects of variations in rotor resistance, self-inductance, and mutual inductance were analyzed. Simulation results, which include the turbine and DFIG, confirm the effectiveness of the fuzzy logic-based control. The system starts under no-load conditions, followed by the application of a reference signal.

1. Active power:

- From T=0 s to T=0.2 s, the reference active power (Pref) is 0 W.
- From T=0.2 s to T=0.6 s, the reference active power is -20,000 W, indicating negative power.
- rom T=0.6 s to T= 1 s , the reference active power is -10,000 W

2. Reactive power:

- From T=0 s to T=0.2s , the reference reactive power is 0 VAR.
- From T=0.2 s to T=0.6 s, the reference reactive power is -5,000 VAR.
- From T=0.6 s to T=1 s, the reference reactive power returns to 0 VAR.

This analysis reflects a transition from zero active and reactive power, followed by negative values, and finally returning to neutral levels by the end of the specified time frame. Figure 6 presents a detailed block diagram using Simulink, illustrating the operation of the DFIG.

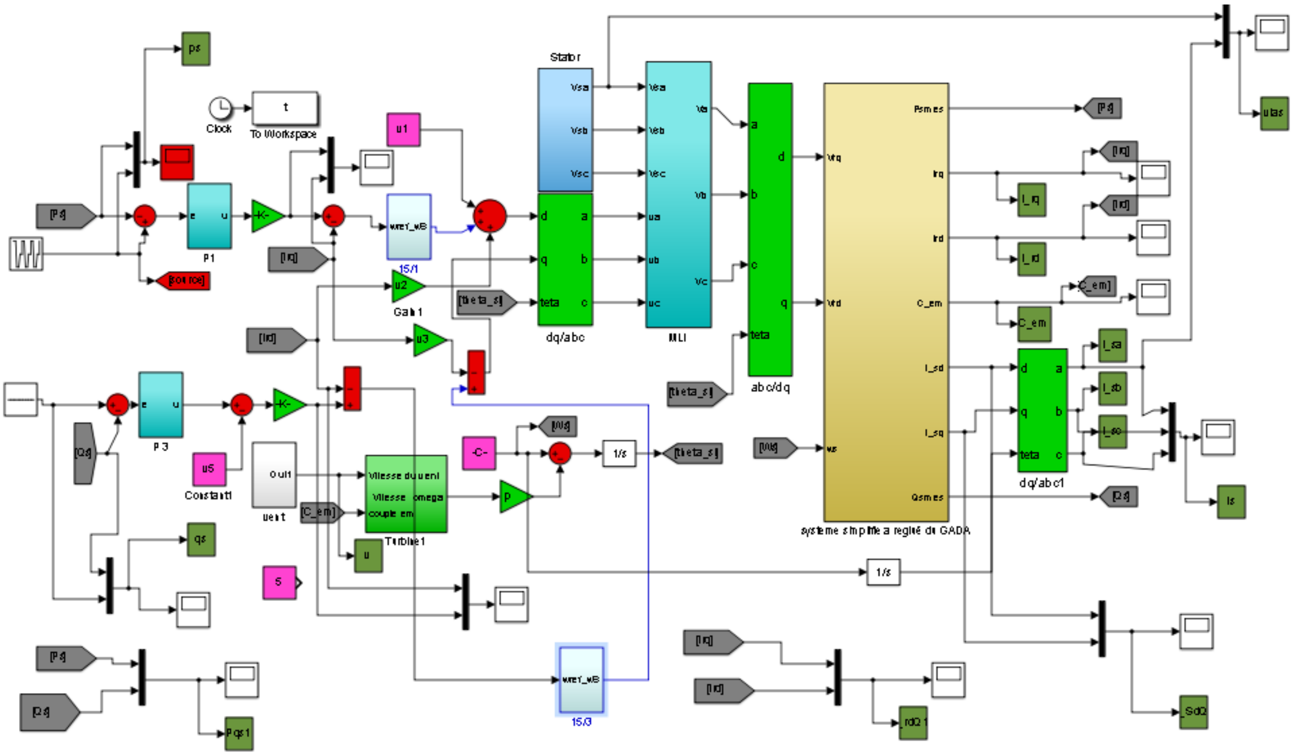


Fig. 6. Simulink block diagram illustrating DFIG systems employing fuzzy logic controllers enhanced by genetic algorithm.

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TABLE I. PARAMETERS OF 1.5 MW DFIG

Symbol	Parameters	Value
Pn	Rated Power	1.5 MW
Vs	Stator Voltage	300 V
Fs	Stator Frequency	50 Hz
Rs	Stator Resistance	0.012 Ω
Ls	Stator Leackage Inductance	0.0205 H
Rr	Rotor Resistance	0.021 Ω
Lr	Rotor Leackage Inductance	0.0204 H
M	Mutual Inductance	0.0169 H
P	Pairs of poles number	2
J	Rotor inertia	1000 Kg.m^2

TABLE II. PARAMETERS OF THE TURBINE

Symbol	Parameters	Value
R	Blade radius	35.25 m
N	Number of blades	3
G	Gearbox ratio	90
J	Moment of inertia	1000 Kg.m^2
fV	Viscous friction coefficient	0.0024 N.m.s^{-1}
V	Nominal wind speed	16 m/s
Vd	Cut-in wind speed	4 m/s
Vm	Cut-out wind speed	25 m/s

The following is a summary of the simulation results for fuzzy control systems using Genetic Algorithms. Figures 7 and 8 demonstrate the system's performance using fuzzy controllers optimized by the genetic algorithm. The results show that the generator effectively tracks the reference values for both active and reactive power, although a coupling effect is evident, where adjusting the setpoint of one power influences the other. The controllers' performance during both transient and steady-state phases can be assessed based on three key criteria: maximum error (overshoot), which measures how much the power exceeds the target during changes; recovery or stabilization time, indicating how long the system takes to return to steady-state after a disturbance; and residual (steady-state) error, reflecting the difference between the final value and the desired reference after the transient period. Figures 9 and 10 show the forward (ird, isd) and quadrature (irq,isq) components of the rotor and stator currents, which represent the control errors. The main observations are: the PI regulators effectively maintain the rotor currents at their reference values, which are determined by stator voltage regulation. Reducing the load results in a corresponding decrease in rotor current. The control accuracy is high, with ird and irq tracking errors approaching zero, indicating precise control of the system.

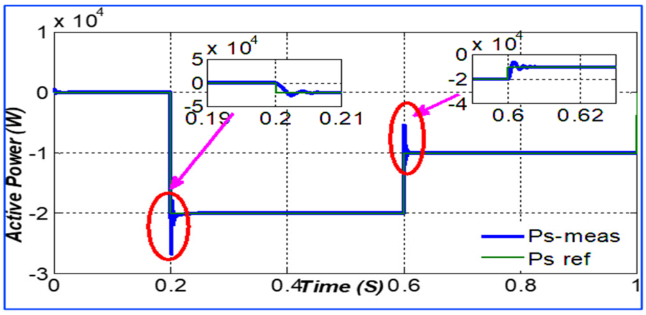

Fig. 7. Stator active power stator.

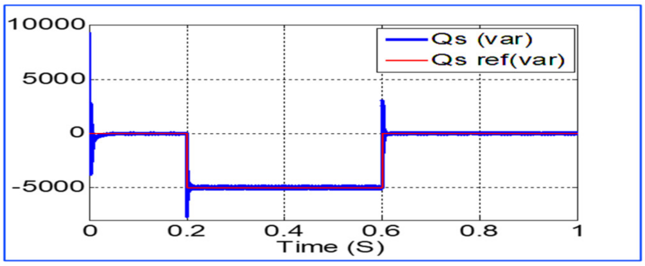

Fig. 8. Stator reactive power.

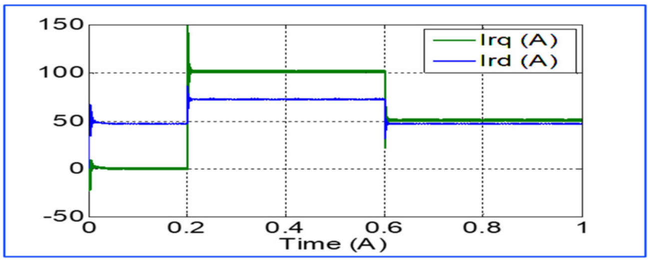

Fig. 9. Direct currents and rotor quadrature.

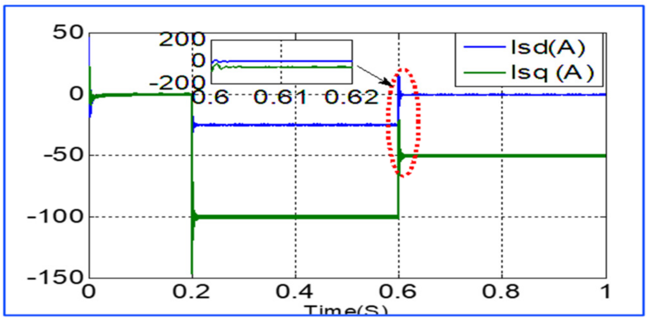

Fig. 10. Direct currents and stator quadrature.

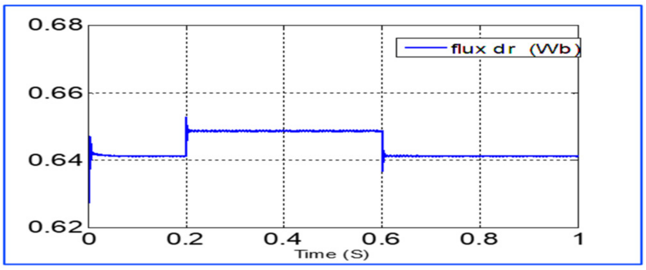

Fig. 11. Direct rotor flux.

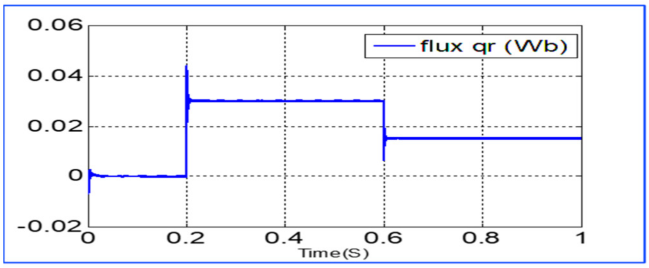

Fig. 12. Quadrature rotor flux.

Figures 11-13 show that the rotor flux and electromagnetic torque consistently align with their reference values, ensuring stable dynamic performance with reduced oscillations and minimal overshoot. Figure 14 depicts the waveform of the stator voltage and current. It can be observed that the stator voltage matches that of the grid, while the current waveform corresponds to the active and reactive power outputs. Figures 15 and 16 demonstrate that the stator and rotor currents in a DFIG are directly proportional to the generated active power. Both current waveforms of stator and rotor exhibit an almost perfect sinusoidal shape, which suggests that the power delivered to the grid is of high quality. Importantly, the fuzzy controllers integrated with genetic algorithms show no overshoot during transient states. Overall, their performance is similar to that of PI regulators.

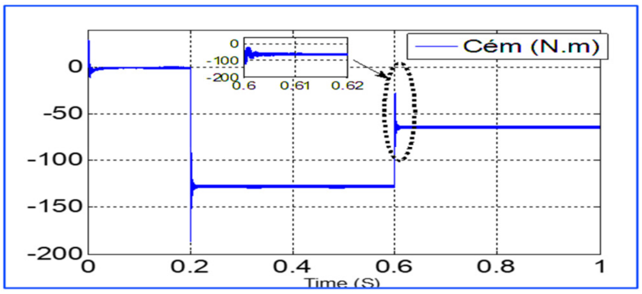

Fig. 13. Electromagnetic torque.

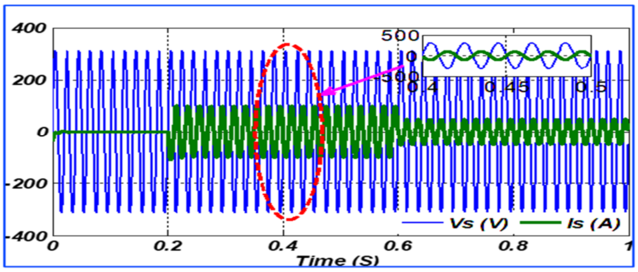

Fig. 14. Stator current and voltage.

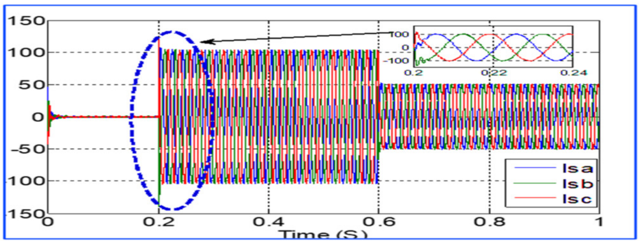

Fig. 15. Stator three-phase currents (A).

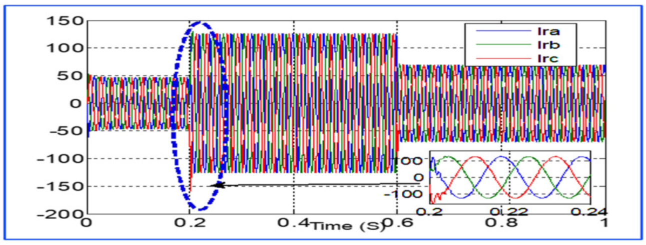

Fig. 16. Rotor three-phase currents (A).

VII. DISCUSSION AND COMPARISON WITH OTHER WORKS

The main innovation of this work lies in the integration of fuzzy logic control systems with genetic algorithms to enhance the performance of DFIGs. This approach represents a significant advancement in control systems, providing higher flexibility and accuracy compared to traditional methods. Unlike previous studies that primarily focused on using conventional controllers, such as PI controllers or standalone fuzzy control systems, this study leverages genetic algorithms to optimize the parameters of the fuzzy control systems, leading to improved stability and reduced residual errors during transient processes and in steady-state conditions.

The number of iterations was increased in this study to achieve more accurate results and reduce errors. The results showed that increasing the iterations significantly contributed to enhancing performance and accuracy. Through this approach, the proposed system is able to reduce the interaction between active and reactive power, improving control precision, delivering high-quality power to the grid, and minimizing sudden fluctuations, which represents a notable advancement compared to the traditional methods used in earlier studies. Figure 17 shows the improvement in the value of the objective function applied to these results.

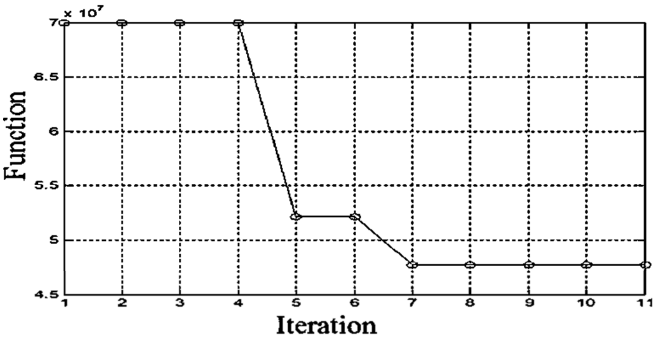

Fig. 17. Improvement of the objective function.

VIII. CONCLUSION

The article explores the control of a wind power conversion system using an asynchronous twin generator, employing fuzzy logic systems integrated with genetic algorithms to create two controllers for active and reactive power management. The findings emphasize the system's significance in wind turbine applications, ensuring the durability and quality of the electricity produced through careful control parameter selection. While simulation results demonstrate that this approach outperforms conventional control systems, a minor error was observed in response to rapid wind speed changes due to the adaptive law's slower reaction. Reducing sampling time could mitigate this but would increase computation time. Maintaining control continuity can enhance energy efficiency and extend component lifespan. Overall, the algorithms balance simplicity and the ability to solve complex problems, though they face limitations based on stopping criteria like population size and mutation rates. Future research will focus on leveraging artificial intelligence, particularly neural networks, to improve DFIG control robustness, exploring optimization methods beyond Genetic Algorithms, and applying these strategies in real-world settings.

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