Enhanced Robust Power Control of Double Fed Induction Generators through Fuzzy Logic Controller

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Abstract - This paper aims to explore a wind energy conversion system (WECS) utilizing a doubly fed induction generator (DFIG). In this system, the stator is directly connected to the grid, while the rotor is linked via a static converter. The primary objective is to develop a control system that effectively decouples the DFIG, thereby enhancing power quality. To achieve this, we propose a robust control technique that effectively manages the reactive and active power of the DFIG, leveraging fuzzy logic concepts. This control strategy exhibits notable advantages, particularly in the face of varying machine parameters. Through comprehensive simulations, the results demonstrate the superior performance and robustness of the proposed control strategies for the WECS-DFIG system.

Keywords - Doubly Fed Induction Generator, Field-Oriented Control, Fuzzy Logic Controller,PI Controller, Wind Energy Conversion System.

I. INTRODUCTION

Renewable energy has become increasingly popular in recent years, driven by growing environmental concerns, the finite nature of fossil fuel reserves, and the upward trend in energy prices. Among the various renewable energy sectors, the wind energy industry stands out as both highly competitive and rapidly expanding. This is primarily attributed to its advantageous features such as minimal space requirements and the absence of carbon emissions during operation[1].

Currently, the most commonly employed wind system in wind farms is the variable speed system utilizing the doubly-fed induction generator [2]. The configuration of the doubly fed wind power system is shown in Fig.1. As shown in this configuration, the stator is directly linked to the grid while the rotor is connected via two converters[3],[4].

In DFIG control, proportional integral controllers (PI) are used due to their simple structures and high performance[5]. In theory, the parameters of the PI controller are determined based on the DFIG parameters. However, in practice, these parameters tend to vary over time due to changes in the machine's parameters[2]. Therefore, the WECS-DFIG requires robust controllers. For this reason, we propose a control method called fuzzy logic control (FLC) for the power control of a DFIG[6].This method helps us to achieve stability, robustness and high efficiency[7], it is applied to the rotor side converter (RSC).

This paper is organized as follows: In the first section, we present the model of the WPCS-DFIG (mechanical part and electrical part) and in the second section; we develop a vector control for the control of the powers generated by the DFIG. In the third section, we present the methodology approach of fuzzy logic control.

The simulation results obtained with the proposed algorithm and the robustness tests performed are analysed in section four. Finally, a conclusion is presented.Is the first paragraph of a written research paper, and it should explain the nature of the previous work.

II. MODELING SYSTEM

The architecture of the wind power system that is illustrated in Fig. 1 consists of DFIG, rotor side converter (RSC), grid side converter (GSC), turbine and gearbox. The energy extracted from the wind is transmitted through the turbine to the DFIG, where it is transformed into electrical energy; this energy is injected into the electrical network and controlled by the RSC and GSC.

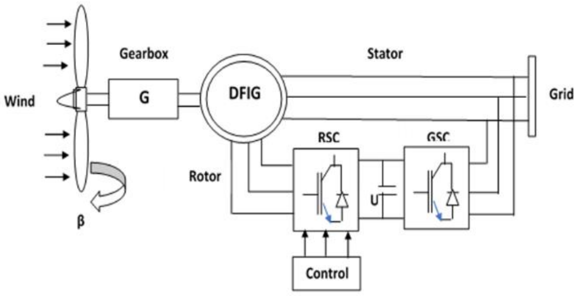


Fig. 1. Configuration of the WECS-DFIG.

A) *Wind Turbine Model*

The wind turbine model is given by those equations [1]:

$$P_{aero} = \frac{1}{2}\rho.\pi.R^2.C_p(\lambda,\beta).v_{wind}^3 \quad (1)$$

$$T_{aero} = \frac{P_{aero}}{\Omega_t} = \frac{1}{2}\rho.\pi.R^2.C_p(\lambda,\beta).v_{wind}^3.\frac{1}{\Omega_t} \quad (2)$$

$$C_p(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3.\beta - C_4\right)e^{-\frac{C_5}{\lambda_i}} + C_6.\lambda \quad (3)$$

With: $\frac{1}{\lambda_i} = \left(\frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1}\right)$

Where: P_{aero} refers to aerodynamic power extracted from the wind (W), ρ is air density (kg/m^3),T_{aero} presents the turbine torque (Nm),v_{wind} is the wind speed (m/s),C_p designates the power coefficient ($C_1, C_2, C_3, C_4, C_5, C_6$: Real constants),$\lambda$ is the speed ratio which is given by (4) , and β is the blade pitch angle (deg).

$$\lambda = \frac{\Omega_t.R}{v_{wind}} \quad (4)$$

With:R is the turbine radius (m) , Ω_t is the turbine speed (rad/s).

The turbine and the generator shaft are coupled using a gearbox; this model is defined as follows:

$$T_m = \frac{T_{aero}}{G} \quad (5)$$

$$\Omega_t = \frac{\Omega_m}{G} \quad (6)$$

Where: G is the multiplier ratio,T_m is the generator torque (Nm) and Ω_m defines the generator speed (rad/s).

The generator shaft can be modelled using the following mechanical equations:

$$J = \frac{J_t}{G^2} + \mathrm{J_m} \quad (7)$$

$$J.\frac{d\Omega_m}{dt} = \sum Torques = T_m - T_{em} - T_f \quad (8)$$

With: $T_f = f.\Omega_m$

Where J represents the total inertia, T_{em} and T_f designante the magnetic torque and the friction torque respectively, and f is the friction coefficient.

B) *DFIG Model*

Using the rotating field dq-reference frame ,we can develop a DFIG’s model from the following equations [2]:

$$\begin{cases} V_{ds}=R_s.I_{ds}+\frac{d\text{Ø}_{ds}}{dt}-\omega_s.\text{Ø}_{qs} \\ V_{qs}=R_s.I_{qs}+\frac{d\text{Ø}_{qs}}{dt}+\omega_s.\text{Ø}_{ds} \end{cases} \quad (9)$$

$$\begin{cases} V_{dr}=R_r.I_{dr}+\frac{d\text{Ø}_{dr}}{dt}-\omega_r.\text{Ø}_{qr} \\ V_{qr}=R_r.I_{qr}+\frac{d\text{Ø}_{qr}}{dt}+\omega_r.\text{Ø}_{dr} \end{cases} \quad (10)$$

$$\begin{cases} \text{Ø}_{ds}=L_s.I_{ds}+M.I_{dr} \\ \text{Ø}_{qs}=L_s.I_{qs}+M.I_{qr} \end{cases} \quad (11)$$

$$\begin{cases} \text{Ø}_{dr}=L_r.I_{dr}+M.I_{ds} \\ \text{Ø}_{qr}=L_r.I_{qr}+M.I_{qs} \end{cases} \quad (12)$$

$(V_{ds}, V_{qs}, V_{dr}, V_{qr})$, $(I_{ds}, I_{qs}, I_{dr}, I_{qr})$, $(\text{Ø}_{ds}, \text{Ø}_{qs}, \text{Ø}_{dr}, \text{Ø}_{qr})$: The dq components of stator and rotor voltages, currents and flux respectively, (R_s, R_r) denominate the stator and rotor resistances, (L_s, L_r, M) are the stator ,rotor and magnetizing inductances, and ω_s designate synchronous speed.

The electromagnetic torque is expressed by:

$$T_{em} = p.\left(\emptyset_{ds}.I_{qs} - \emptyset_{qs}.I_{ds}\right) \tag{13}$$

With: p: is the pole pair's number.
The reactive and active power can be formulated in the dq-reference frame as follow:

$$\begin{aligned} P_s &= V_{ds}.I_{ds} + V_{qs}.I_{qs} \\ Q_s &= V_{qs}.I_{ds} - V_{ds}.I_{qs} \end{aligned} \tag{14}$$

III. CONTROL STRATEGY

A) *Field Oriented Control*

Using a two-phase reference frame (d-q) related to the rotating field and aligning the stator flux vector ($\overrightarrow{\emptyset s}$) on the direct axis which allows writing[3]:

$$\begin{aligned} \emptyset_{ds} &= \emptyset_s \\ \emptyset_{qs} &= 0 \end{aligned} \tag{15}$$

If we neglect the resistance of the stator windings R_s[4],we get :

$$\begin{aligned} V_{dr} &= R_r.I_{dr} + \sigma.L_r.\frac{dI_{dr}}{dt} - S.\omega_s.\sigma.L_r.I_{qr} \\ V_{qr} &= R_r.I_{qr} + \sigma.L_r.\frac{dI_{qr}}{dt} + S.\omega_s.\sigma.L_r.I_{dr} + S.\frac{M.V_s}{L_s} \end{aligned} \tag{16}$$

$$\begin{aligned} P_s &= -V_s.\frac{M}{L_s}.I_{qr} \\ Q_s &= \frac{V_s^2}{\omega_s.L_s} - \frac{V_s.M}{L_s}.I_{dr} \end{aligned} \tag{17}$$

$$T_{em} = -p.\frac{M}{\omega_s.L_s}.V_s.I_{qr} \tag{18}$$

With:S: is the slip ratio and $\sigma = 1 - \left(\frac{M^2}{L_r L_s}\right)$

Figure 2 shows a simplified DFIG model block diagram.

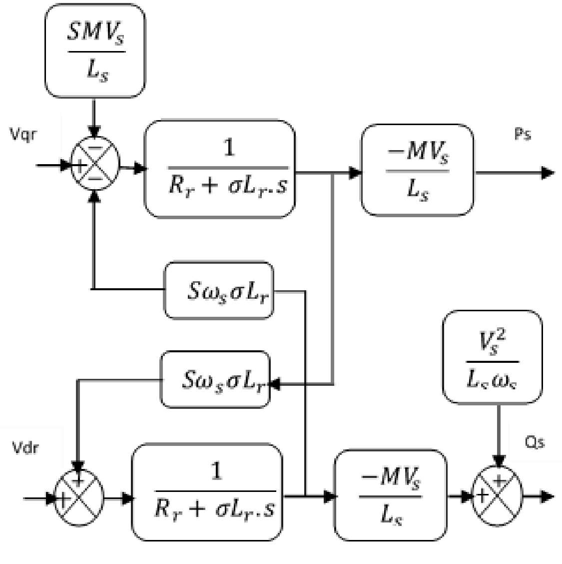


Fig. 2. Simplified scheme of DFIG.

B) *Fuzzy Logic Control*

The problem of parameter variation, which has an impact on system performance and, in extreme cases, system instability, can be solved using intelligent control techniques such as fuzzy logic, in which the controller adapts to the system's operating conditions.

According to Fig.3, fuzzy logic controllers (FLCs) are designed following four main steps[5] .

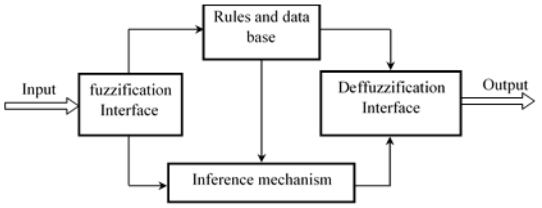


Fig. 3. Fuzzy logic control structure

-Fuzzification

Each variable was chosen as a membership function using triangular and trapezoidal shapes, as shown in Fig. 4:

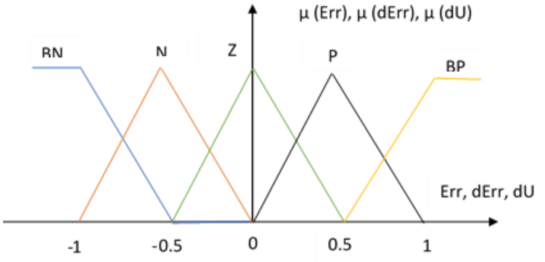


Fig. 4. Membership functions for input and output variables.

BN: Big Negative;
N: Negative;
Z: Zero;
P: Positive;
BP: Big Positive.

-Inference

The inference matrix is given in Table 1.

Table 1. Power fuzzy regulator inference matrix.

DU		DErr				
		BN	N	Z	P	BP
Err	BN	BN	BN	BN	N	Z
	N	BN	N	N	Z	P
	Z	BN	N	Z	P	BP
	P	N	Z	P	P	BP
	BP	Z	P	BP	BP	BP

-Defuzzification

We use the center of gravity method for defuzzification[5]; it is frequently cited in the literature.

Based on the structure of the fuzzy logic control, we will proceed to its application to our DFIG for the independent control of reactive and active powers, where we will have a regulator on each of the loops, those of the powers, as illustrated in Fig.5.

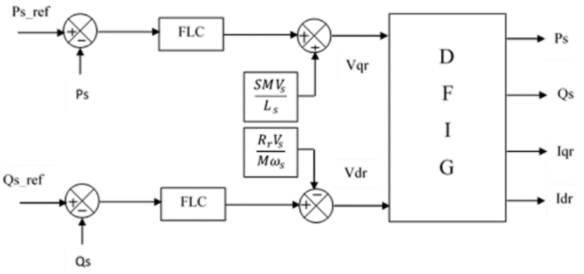


Fig. 5. System control diagram

The two quantities, namely the error Err and its variation dErr, present the inputs of the FLC.The increment of the control signal is the output (Fig. 6).

After integrating the FLC output, a control signal U is obtained.

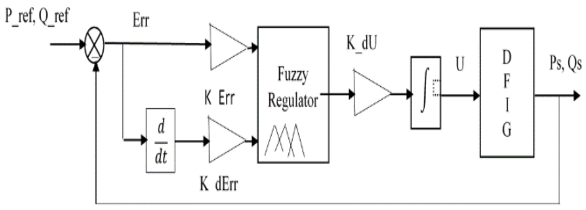


Fig. 6. Diagram of DFIG control by fuzzy logic

IV. SIMULATION RESULTS

Simulation using MATLAB/SIMULINK software has demonstrated the effectiveness of power regulation in the Doubly Fed Induction Generator through the implementation of a PI regulator and FLC. The specific parameters utilized in the simulation are provided in Table 2.

Table 2. DFIG's parameters.

Pn	Vs	Rs	Rr	Ls	Lr	M
1.5 MW	400 V	0.01 Ω	0.02 Ω	0.0137 H	0.0136 H	0.0135 H

A) *Field Oriented Control*

According to Fig. 7 and Fig. 8, the system response follows the references for the active and reactive generated power, but it presents a small coupling effect between the two control axes.

Fig. 9 and Fig. 10 show that the stator and rotor currents have a sinusoidal form and less disturbed.

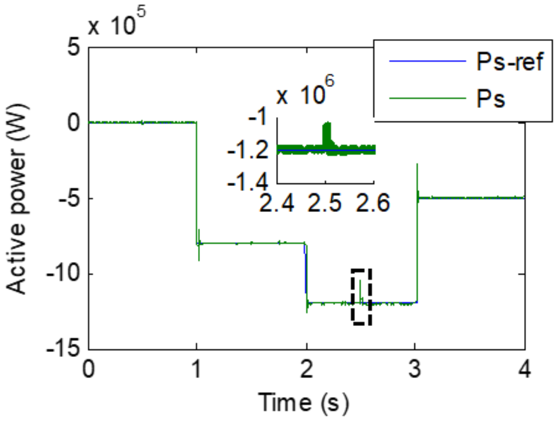


Fig. 7. Active power.

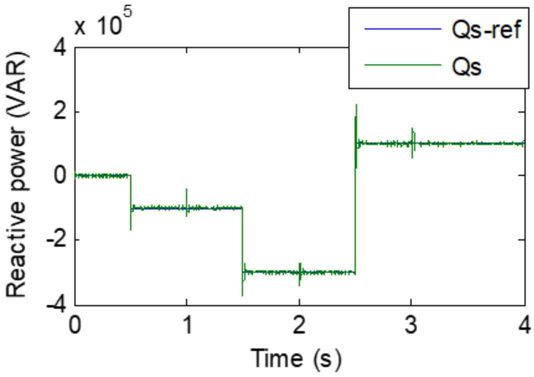


Fig. 8. Reactive power.

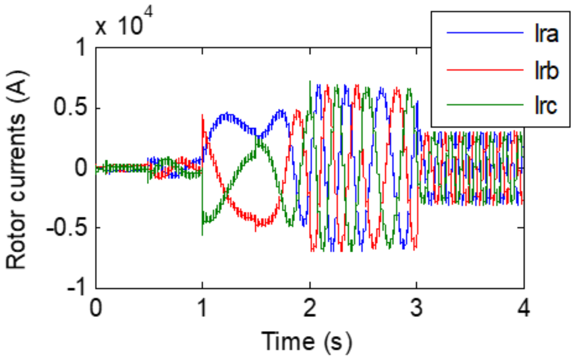
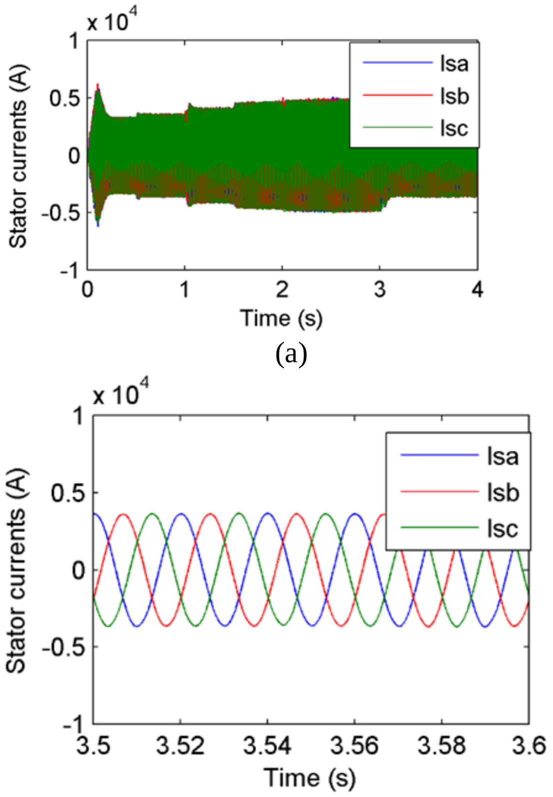


Fig. 9. Rotor currents.



(a)

(b)

Fig. 10. (a) Stator currents. (b) Zoom

B) *Fuzzy Logic Control*

The results illustrated in Fig.11 and Fig.12 demonstrate that the active and reactive power accurately follow their respective reference values, exhibiting no overshoots or coupling effects. This observation indicates that the FLC approach effectively achieves a complete decoupling between the control axes, ensuring independent and precise control of both active and reactive power.

Fig.13 and Fig.14 depict the stator and rotor currents, respectively, exhibiting a sinusoidal waveform with minimal disturbances.

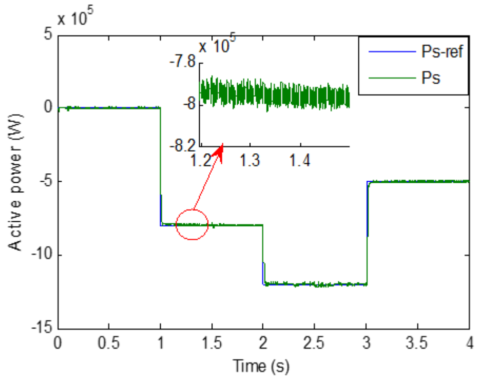


Fig. 11. Active power.

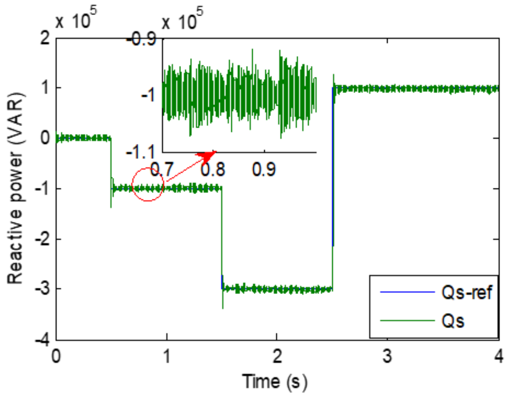


Fig. 12. Reactive power.

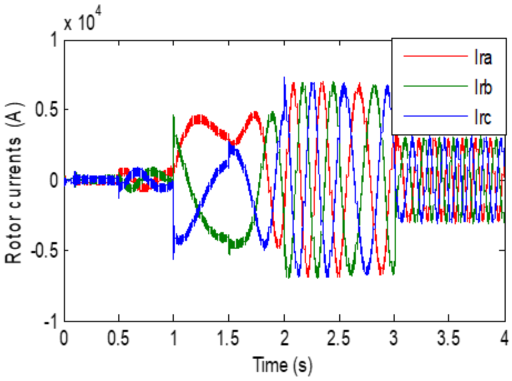
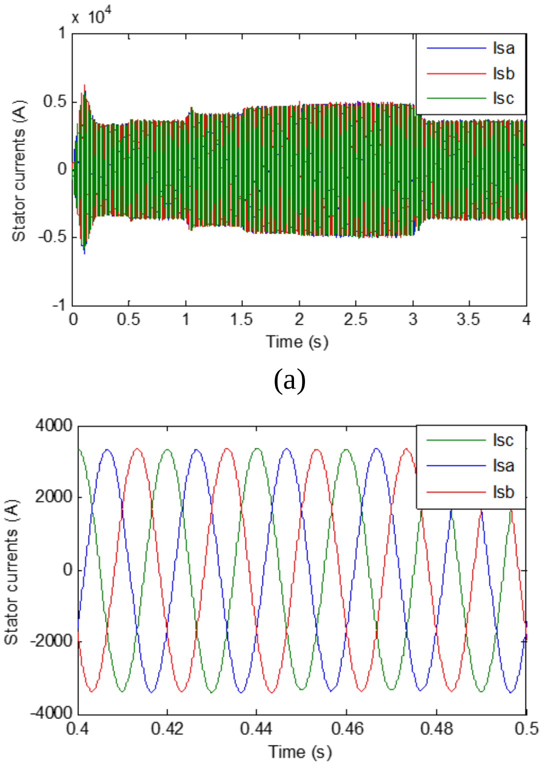


Fig. 13. Rotor currents



(a)

(b)

Fig. 14. (a) Stator currents. (b) Zoom

C) Robustness Tests

To evaluate the robustness of the proposed controllers, we conducted a test by introducing a 30% increase in the resistance R_r and inductance $L_r$of the machine parameters. The system response, as depicted in Fig.15 and Fig.16, demonstrates that the fuzzy logic control effectively maintains the output power at the reference level. Furthermore, the evolution of the active and reactive power remains unaffected, confirming the robustness of the FLC approach in the face of parameter variations.

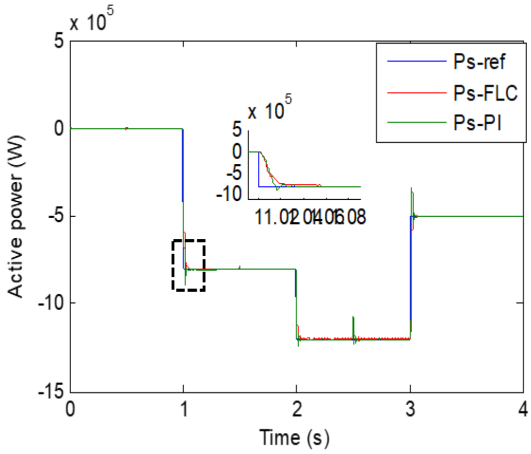


Fig.15. Active power under parameter variations.

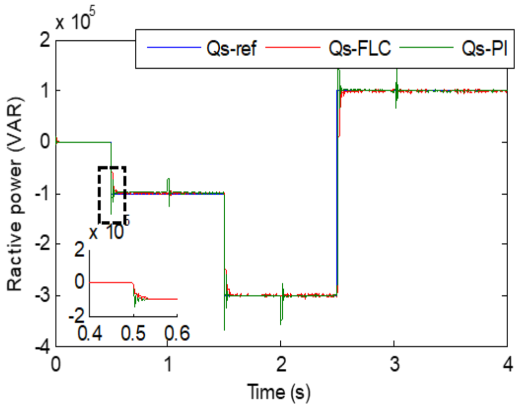


Fig. 16. Reactive power under parameter variations.

V. CONCLUSION

This paper presents a decoupled control approach for managing the active and reactive power generated by a Doubly Fed Induction Generator (DFIG) in a wind power system. The mathematical model of the system is first presented, followed by a discussion on a control technique based on FLC, which is then compared to conventional control methods. Additionally, robustness tests are conducted to evaluate the performance of the proposed control approach in the face of variations in machine parameters.

In order to test the robustness of the proposed control, we are introduced a variation on resistance R_r and inductance L_r. From the obtained results, the fuzzy logic control method showed an acceptable performance and a good robustness degree against the parameters variation compared with PI regulator.

The simulation results indicate that the fuzzy logic control (FLC) approach demonstrates robustness and delivers favorable performance in terms of parameters such as overshoot, response time, and static error.

VI. REFERENCES

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