Adaptive fuzzy logic control for five-phase asynchronous machine

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Abstract. This study investigates the application of adaptive fuzzy control (AFC) to a five-phase induction machine. Unlike classical approaches such as vector control or static fuzzy logic, AFC dynamically adapts to parameter variations and external disturbances. Simulation results show that the proposed controller achieves enhanced dynamic performance during transients, perfect decoupling between torque and flux, and fast disturbance rejection within 0.1 s. Under a resistive load of 20 N·m, the rotor speed precisely tracks the reference model without overshoot or steady-state error, even when the rotor resistance varies by up to 200%. The system maintains stable flux dynamics and robustness against internal and external perturbations. These findings highlight AFC as a highly effective solution for complex electromechanical systems requiring precision, stability, and reliability under varying operating conditions.

1 Introduction

Three-phase asynchronous motors driven by voltage-source inverters remain the most established and widely deployed solution in industrial drives. Their design is well-mastered and they offer strong performance, especially with variable speed control. Multiphase machines—those with more than three phases—are gaining attention as a compelling alternative because they distribute power across additional phases, reducing the switching and winding stresses (e.g., lower commutation voltage at a given current) [1]. These machines also dampen torque ripple and increase its frequency, enabling more effective mechanical filtering and smoother operation. Moreover, multiphase topologies enhance fault tolerance: operations can continue even if one or more phases fail. This feature is especially crucial in applications demanding high service continuity, such as rail traction, marine propulsion, and aerospace systems [1], [2].

To achieve precise and efficient control of multiphase machines, industry commonly uses Field-Oriented Control (FOC), which regulates torque and speed accurately, even in cases of open-phase faults. Recent studies have focused on improving performance metrics like torque ripple, phase current balance, and copper losses by refining rotor control methods—though these require careful modeling to maintain magnetic field alignment and optimal performance [3]. In industrial reliability contexts, resilient algorithms such as model

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reference adaptive control, fuzzy logic, or vector control are regularly applied to adjust parameters in the face of partial failures. Yet, the challenge remains to keep computations lightweight enough for cost-efficient, deployable control systems [4]. Adaptive control tools like neural networks and fuzzy logic open promising new frontiers by effectively managing structured and unstructured uncertainties in multiphase motor drives. However, fuzzy logic alone lacks the ability to adapt dynamically, and neural networks struggle to embed human-like reasoning. Additionally, these approaches often demand significant computational resources, precise tuning, and can exhibit reliability issues in some applications [5].

Fuzzy control offers a robust, simplified solution for accommodating imprecise systems while maintaining accurate speed regulation. Unlike traditional methods like vector control or DTC, which can be sensitive to parameter uncertainties and nonlinearities (e.g., friction), fuzzy logic provides a more resilient and user-friendly alternative suitable for a wide range of industrial settings [6].

2 Literature review

Many researchers [7]– [11] have explored robust control strategies for multiphase electrical machines due to their inherent nonlinearities and fault-tolerant potential. Sliding Mode Control (SMC), particularly the super-twisting variant, has been applied to multiphase drives to enhance robustness against model uncertainties and reduce sensitivity to parameter variations [7], [12]. Al-Naemi et al. proposed a hybrid fuzzy-super-twisting controller that achieved fast convergence and improved dynamic performance for a three-phase induction motor under variable loads [8]. Abdelrahman et al. designed a fuzzy PI controller for a six-phase induction generator, demonstrating better torque ripple suppression and fault tolerance compared to classical PI control [9]. Model Predictive Control (MPC) techniques have also been applied to five- and six-phase machines, where Ibrahim et al. presented predictive current control strategies that enable constraint handling and high dynamic performance [10], [13].
Gain-scheduled LPV controllers have proven effective for PMSMs under temperature and speed variations, outperforming traditional FOC [15], while robust LQR controllers with observer design have been used for three-phase inverters with high stability [16]. Moreover, advanced methods such as Active Disturbance Rejection Control (ADRC), backstepping, and neural network-based adaptive controllers have shown promise in uncertain environments [11], [17]. Zhu et al. reviewed reinforcement learning (RL) strategies for AC drives, highlighting their potential to learn optimal control policies without explicit modeling [18].
Despite the effectiveness of these methods, fuzzy logic controllers offer a compelling advantage in situations where system modeling is incomplete or imprecise. They are intuitive to design, rely on human-like reasoning through IF-THEN rules, and demonstrate strong performance in handling nonlinear, time-varying behaviors without requiring accurate system parameters. As such, fuzzy logic remains a powerful and flexible tool in the robust control of multiphase machines.

3 Description of the machine

The machine studied is a five-phase asynchronous squirrel-cage machine, consisting of two parts. A fixed part (stator) comprising in the slots of the magnetic circuit five windings which are identical, whose axes are separated from each other by an electrical angle equal to $\frac{2}{5}\pi$. The rotor is identical to that of the three-phase asynchronous machine (squirrel-cage rotor).
The proposed 5-phase, 2-pole induction machine is shown in
(Fig. 1.).

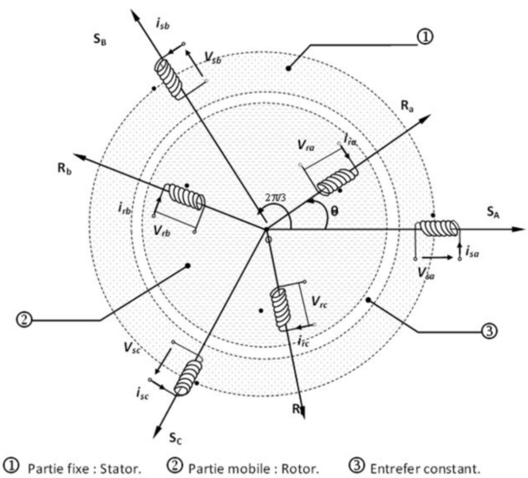


Fig. 1. Windings of the five-phase machine [19]

4 Application of park transformation to the machine

The electrical equations of the machine in the Park frame become:

A. Tension equations

$$\begin{cases} V_{sd} = R_s I_{sd} - \omega_s \varphi_{sd} + \dfrac{d\varphi_{sd}}{dt} \\ V_{sq} = R_s I_{sq} - \omega_s \varphi_{sq} + \dfrac{d\varphi_{sq}}{dt} \\ V_{rd} = R_r I_{rd} - \omega_r \varphi_{rd} + \dfrac{d\varphi_{rd}}{dt} \\ V_{rq} = R_r I_{rq} - \omega_r \varphi_{rq} + \dfrac{d\varphi_{rq}}{dt} \end{cases} \qquad (1)$$

B. Flux Equations

$$\begin{cases} \varphi_{sd} = (L_s + L_m) I_{sd} + L_m\, I_{rd} \\ \varphi_{sq} = (L_s + L_m) I_{sq} + L_m\, I_{rq} \\ \varphi_{rd} = (L_r + L_m) I_{rd} + L_m\, I_{sd} \\ \varphi_{rq} = (L_r + L_m) I_{rq} + L_m\, I_{sq} \end{cases} \qquad (2)$$

C. Electromagnetic Torque Equation

$$C_{em} = \frac{5}{2}\frac{P}{2}\left(\varphi_{sd} I_{sq} - \varphi_{sq} I_{sd}\right) \qquad (3)$$

Where
□□□, □□□: Two-phase stator voltages in the (d, q) frame
□r□, □r□: Two-phase rotor voltages in the (d, q) frame
□s□, □s□: two-phase stator current in the (d, q) frame
□□□, □□□: two-phase rotor current in the (d, q) frame
□□: The rotational speed of the stator field in (rpm)
□r: The rotational speed of the rotor field in (rpm)
□□□, □□□: Two-phase stator fluxes in the (d, q) frame
□r□, □r□: two-phase rotor fluxes in the (d, q) frame
□□□: electromagnetic torque in (N.m).

5 The five-phase inverter

A five-phase machine can be powered in two ways: either ach phase is powered independently using a single-phase inverter, or all phases are powered by a five-arm inverter.

A. Model of a Five-Leg Inverter

This work focuses on the case where the machine's neutral is not connected to the midpoint of the source. Otherwise, the structure is equivalent to a ten-arm configuration. The main advantage of this type of coupling lies in the elimination of the zero-sequence component. This equality, of course, assumes that the machine is balanced. In degraded operation, it is impossible to obtain such a relationship.

B. Choice of Semiconductor Structure

Power components (switches) are chosen based on the power level and switching frequency. Generally, the higher the switching frequency (fast components), the lower the switched power, and vice versa [10].

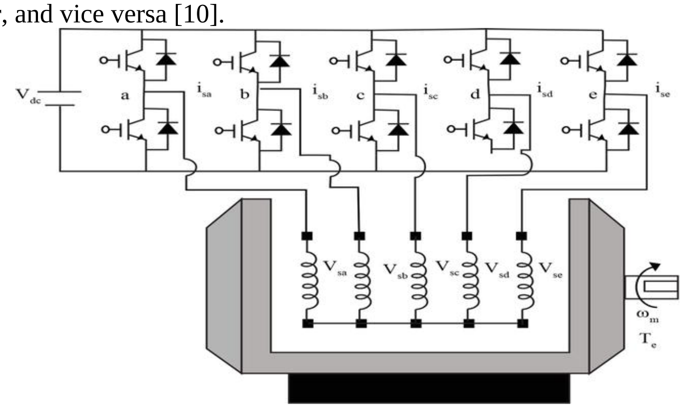


Fig. 2. POWER SUPPLY SYSTEM OF THE FIVE-PHASE ASYNCHRONOUS MACHINE [20]

6 GENERAL STRUCTURE OF A FUZZY SYSTEM

Each fuzzy logic-based system consists of four main blocks:

- A fuzzification interface at the input.
- A rule base.
- Decision-making logic (interference mechanism).
- A defuzzification interface at the output.

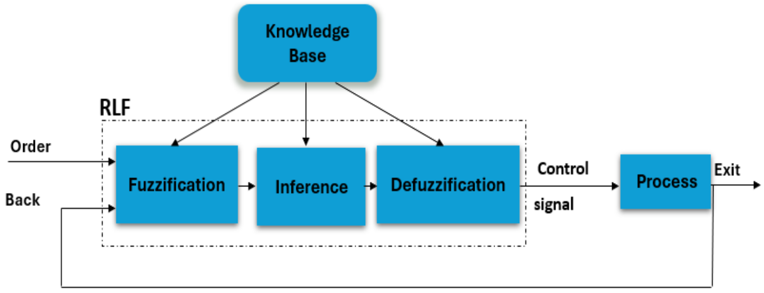


Fig. 3. Fuzzy regulator structure.

Table 1: RULE TABLE FOR THE SPEED FLC.

ΔE_Ω \ E_Ω	**NL**	**NM**	**NS**	**Z**	**PS**	**PM**	**PL**
NL	NL	NL	NL	NL	NM	NS	Z
NM	NL	NL	NL	NM	NS	Z	PS
NS	NL	NL	NM	NS	Z	PS	PM
Z	NL	NM	NS	Z	PS	PM	PL
PS	NM	NS	Z	PS	PM	PL	PL
PM	NS	Z	PS	PM	PL	PL	PL
PL	Z	PS	PM	PL	PL	PL	PL

TABLE 2: THE DIFFERENT FUZZYERDFGHJGFDSSSS.

NL	Negative Large	**NS**	Negative Small
PS	Positive Small	**PL**	Positive Large
NM	Negative Medium	**PM**	Positive Medium
Z	Zero		

Since the system to be controlled only receives deterministic (non-fuzzy) values, an FLR should convert deterministic values at its input to fuzzy values, process them with the fuzzy rules, and convert the control signal values to deterministic values for application to the process.

7 ADAPTIVE CONTROL

Adaptive control refers to several control techniques that share the property of real-time adaptation of the parameters of the controllers or the model used. These include adaptive controllers, programmed gain controllers, and reference model adaptive control (MRAC).

MRAC (Figure 4) is the most commonly encountered adaptive control technique in publications on electrical machine control. The other two are more commonly used in industrial applications.

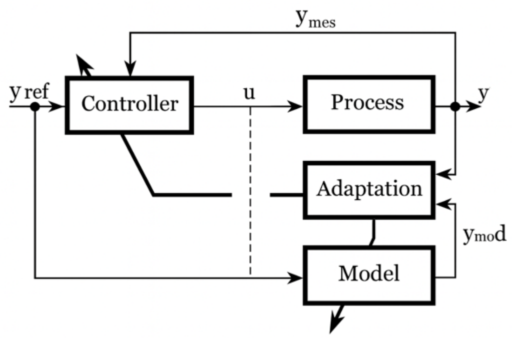


Fig. 4. Example of a reference model order.

The "process" block corresponds to the actual process. It is characterized by the input vector *u* and the output vector *y*. The "command" block defines the control variable u, so that the process follows the reference vector y_{ref}. Other inputs can act at this block: the vector of the process outputs (as feedback). The "model" block is the simulation of the process, i.e. a simplified and idealized model of the process, built according to the analysis hypotheses. Often, the input of this block is the same as that of the process. The output y_{mod}, is used by the adaptation block.

A. Behavioral Model Control:

Using the same four-block representation, the principle of CMC is illustrated in Figure 5

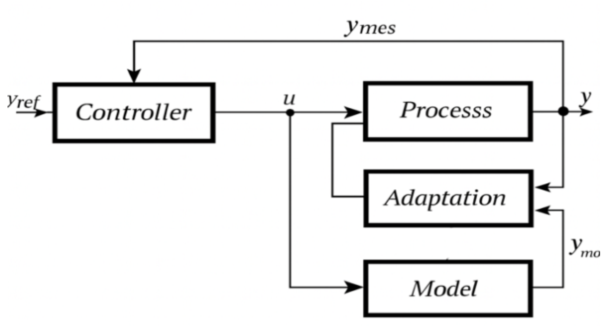


Fig. 5. Example of a behavior model command.

B. Behavioral Loop Analysis:

The behavior model control (block diagram) is illustrated in Figure .6:

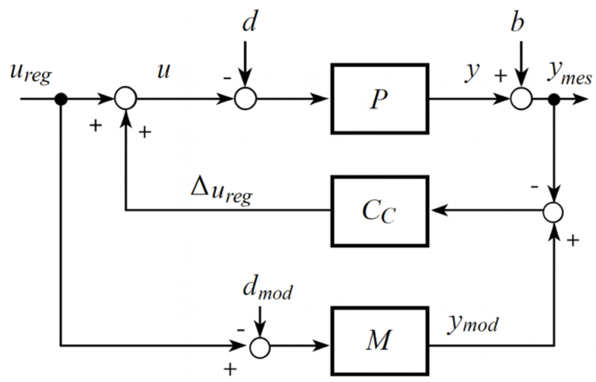


Fig.6. Behavior Model Control (functional diagram).

We clearly find the four blocks of Figure 6. The actual process is represented by P, subject to the adjustment u and the perturbation d; it is modeled by M, which is associated with the perturbation d_{mod}. Even if we are not looking for a perturbed model, the presence of the perturbation model is necessary in a general study phase. The adaptation block, CC, is a corrector called a behavior corrector. Depending on the complexity of the process and that of the model, this corrector is a simple proportional gain or a more complex function. The corrector Cp is the main corrector, which will be used to control the model. There are several solutions regarding the choice of model: for the intended applications, we have chosen first-order, linear, and stationary models. Still in the control section, the disturbance is compensated, by d_{mod}, in accordance with the inversion principle.

The initial equations are:

$$\begin{cases} y(s) = P(s)\left[u_{reg}(s) + \Delta u_{reg}(s) - d(s)\right] \\ \Delta u_{reg}(s) = C_c(s)\{M(s)\left[u_{reg}(s) - d_{mod}(s)\right] - y(s) - b\} \end{cases} \quad (4)$$

$$\begin{cases} y = \frac{P(1+MC_c)}{1+PC_C} u_{reg} - \frac{PMC_c}{1+PC_c} d_{mod} - \frac{P}{1+PC_c} d - \frac{PC_c}{1+PC_c} b \\ y_{mod} = Mu_{reg} - Md_{mod} \end{cases} \quad (5)$$

We note that a large gain introduced by the behavior corrector simplifies the expression of y in (2). This gain translates into the following condition, valid for the desired bandwidth:

$$\begin{cases} MC_c(jw) \gg 1 \\ PC_c(jw) \gg 1 \end{cases} \quad (6)$$

After simplifying expression (2) we find:

$$\begin{cases} y = Mu_{reg} - Md_{mod} - \frac{1}{Cc} d - b \\ y_{mod} = Mu_{reg} - Md_{mod} \end{cases} \quad (7)$$

From where:

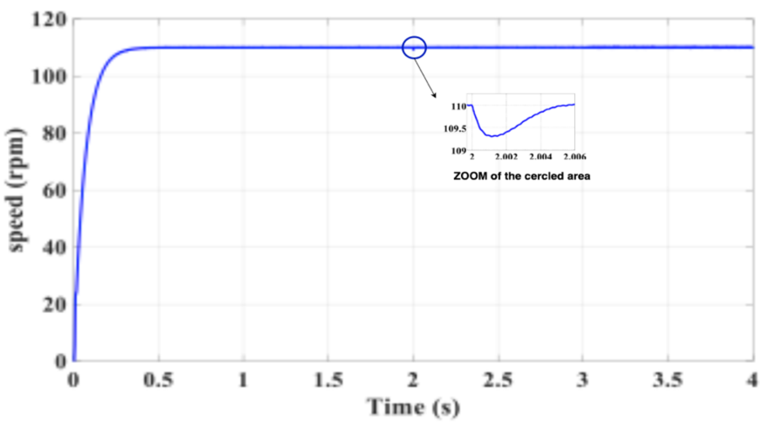
$$y = y_{mod} - \frac{1}{Cc} d - b \quad (8)$$

Table 3: machine parameters

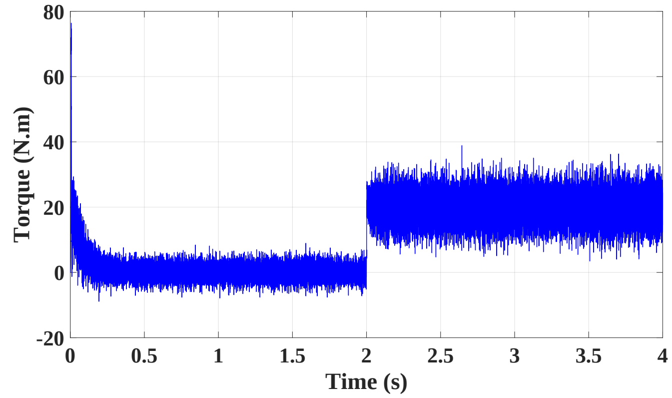
Rated RMS current	$□_□$ =3.6/6.2 A
Rated power	$□_□$ = 3 KW
Rated voltage	$□_□$ = 380 V
Rated rotational speed	$□_□$ = 1499 tr/min
Frequency	$□_□$ = 50 HZ
Rated flux	$□_□$ = 1.16 Wb
Power factor	cos □= 0.83
Stator resistance	R_s=2.5 Ω
Rotor resistance	R_r=1.9 Ω
Stator inductance	L_s=0.24 H
Rotor inductance	L_r=0.24 H
Mutual inductance	L_m=0.226 H
Number of pole pairs	P=2
Mechanical inertia	J=0.031 Kg.$□^2$
Viscous friction coefficient	F=0.0006 Kg.$□^2$ /s

8 SIMULATION RESULT

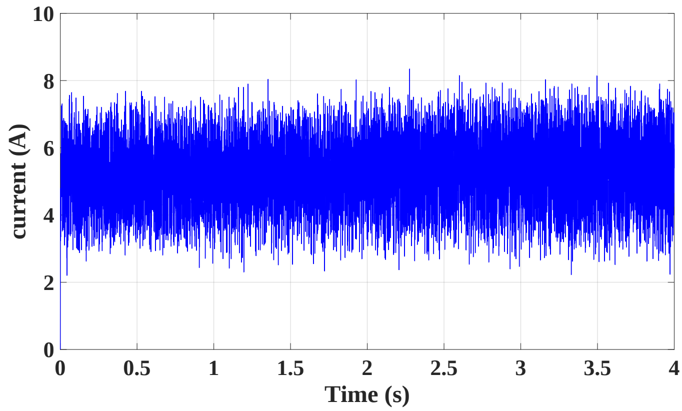
The application of the adaptive fuzzy controller gave an improvement in dynamic performance for transient regimes relative to all tests and the decoupling was maintained. The figure presents the performance of the adaptive fuzzy control with reference model under load after a no-load start. The load is presented by a resistive torque of value C_r = 20N.m at t = 2s. The rotor speed follows that generated by the reference model from t = 0.5s, without overshoot (a decrease in speed which is almost invisible). The disturbance rejection is carried out for a time of 0.1s. The electromagnetic torque has a damped sinusoidal shape until the electromagnetic al oscillates around zero. The presence of the resistive torque from t = 2s leads to an electromagnetic torque of value of approximately 20N.m corresponding to the resistive torque, the fluxes f_{rd}, f_{rq}, shows that the dynamics of the flux is stable after a transient regime, at the established regime the flux is well controlled and the decoupling between the flux and the torque is maintained (no oscillations when the direction of rotation is reversed figure (7), we notice a similarity between i_{qs} and C_{em}, as well as for ids and Φ_r.



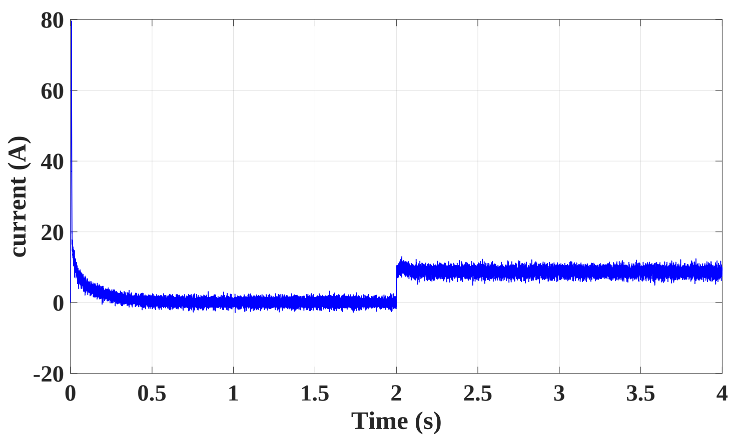
(a) Machine Speed



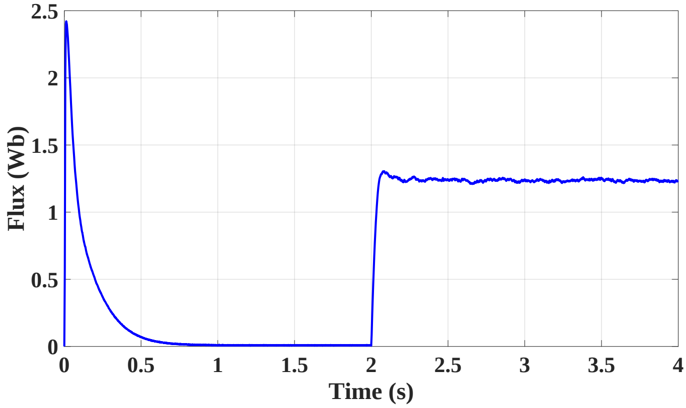
(b) Electromagnetic Torque



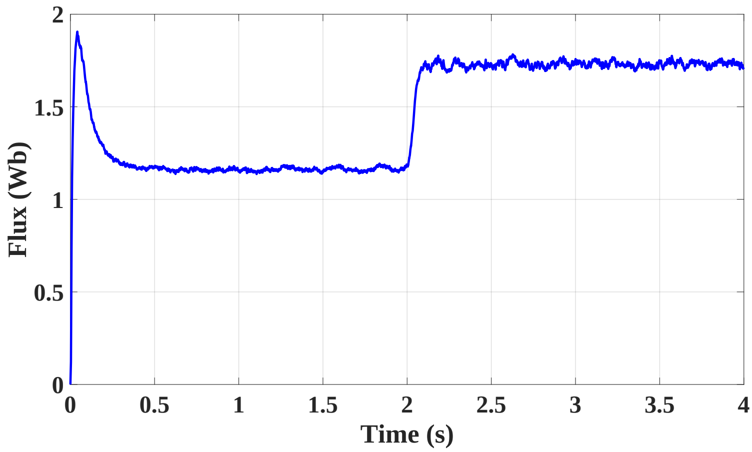
(c) Stator Current in the d-axis Reference Frame



(d) Stator Current in the q-axis Reference Frame



(e) Rotor Flux in the q-axis Reference Frame



(f) Rotor Flux in the d-axis Reference Frame

Fig. 7. Dynamic behavior of the system (MASP, Voltage Inverter) using RCLF regulators (on load)

8.1 Robustness Test

Resistance variation [illegible] 200%

Figure (8) shows that the decoupling between the flux and the torque is perfectly achieved at steady state. The flux is slightly disturbed during large variations in rotor resistance (200%) at t=3s. The speed follows its reference model with a slight error in transient conditions. It also shows the insensitivity of the speed to external disturbances. Finally, the speed response is without overshoot, without static error and with very fast disturbance rejection. Despite internal and external disturbances, the adaptive control maintains the desired performance.

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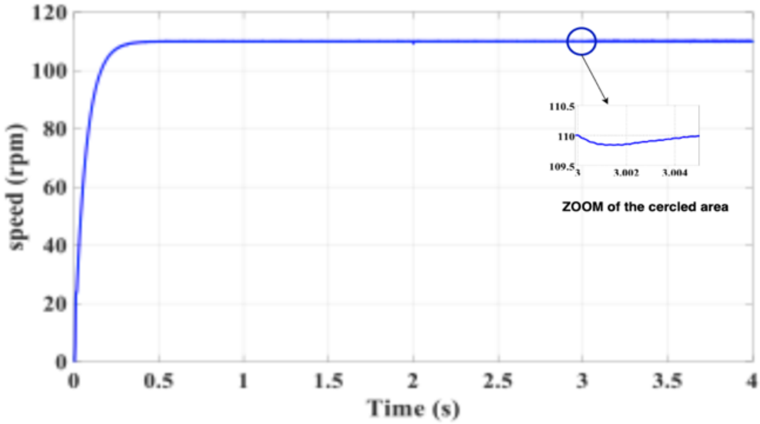
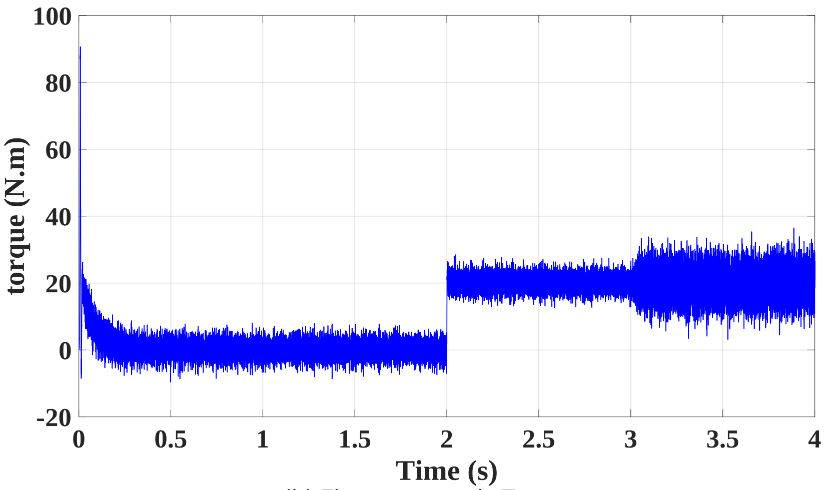
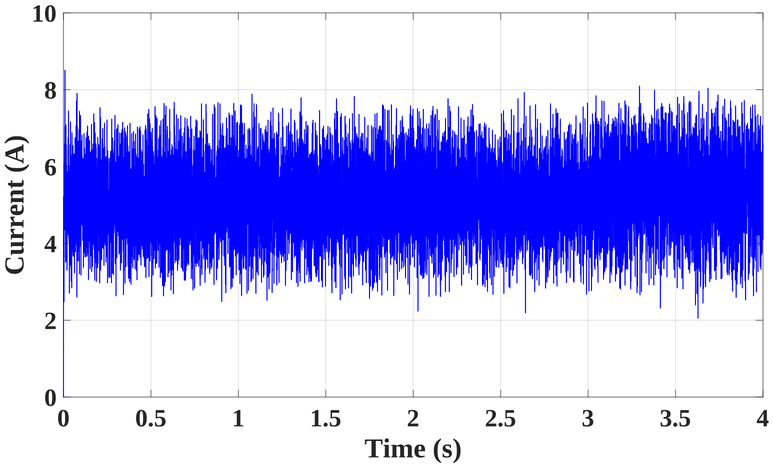


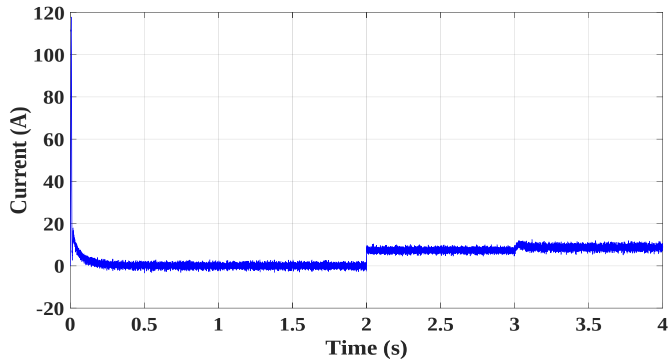
(a) Machine Speed



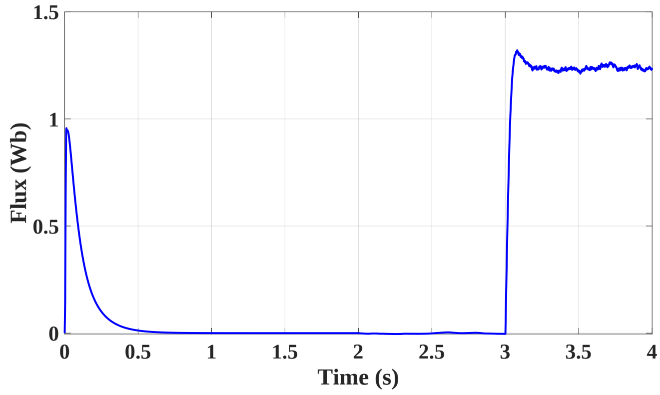
(b) Electromagnetic Torque



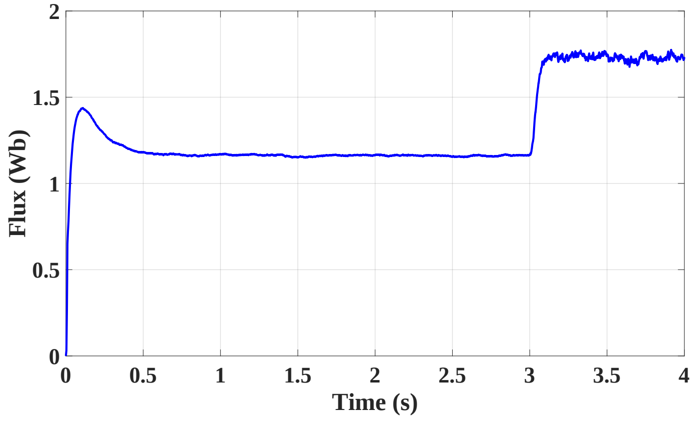
(c) Stator Current in the d-axis Reference Frame



(d) Stator Current in the q-axis Reference Frame



(e) Rotor Flux in the q-axis Reference Frame



(f) Rotor Flux in the d-axis Reference Frame

Fig. 8. Dynamic behavior of the system (MASP, Voltage Inverter) using RCLF regulators (Rr 200%).

9 CONCLUSION

The proposed adaptive control is with a reference model whose adaptation mechanism is in parallel with the RLF of the internal loop. The performance of the adaptive regulator by fuzzy logic has been tested. The results obtained by simulation show that RCLF is very robust with respect to disturbances due to variations of Rr. The speed response correctly follows the chosen reference model despite the presence of disturbances. The contribution of the proposed adaptive control for the speed control of an asynchronous machine is appreciable in terms of robustness to parametric variations such as rotor resistance. The implementation of this control has the advantage of not requiring rigorous identification of the rotor constant in a limited variation range. The correct choice of control parameters gives good performance.

REFERENCES

[1] J. Satué, F. Barrero, J. M. Martínez-Heredia, and F. Colodro, "Concurrent AI tuning of a double-loop controller for multi-phase drives," *Machines*, vol. **12**, no. 12, Art. no. 899, (2024).
[2] D. Kumar, "Modern-day multiphase multi-level DC-AC inverter for advanced electric drives," *International Journal for Research in Applied Science & Engineering Technology (IJRASET)*, (2025).
[3] T. Nouaoui, A. Dendouga, and A. Bendaikha, "Speed control of PMSM using a fuzzy logic controller with deformed MFS tuned by a novel hybrid meta-heuristic algorithm". *Electrical Engineering*, vol. **106**, pp. 6927–6939, (2024). https://doi.org/10.1007/s00202-024-02404-w.
[4] Y. Liu et al., "A stable fuzzy-based computational model and control for induction motors," *Computational Modeling in Engineering & Sciences*, vol. **138**, no. 1, pp. 793–812, (2024). https://doi.org/10.32604/cmes.2023.028175.
[5] Z. Yang, X. Yan, W. Ouyang, H. Bai, and J. Xiao, "Multi-Parameter Fuzzy-Based Neural Network Sensorless PMSM Iterative Learning Control Algorithm for Vibration Suppression of Ship Rim-Driven Thruster," *Journal of Marine Science and Engineering*, vol. **12**, no. 3, Art. no. 396, (2024).
[6] J. Wang and D. F. Yu, "Fuzzy controller-based predictive speed control of a permanent magnet synchronous motor," *Proceedings of the Indian National Science Academy*, vol. **89**, pp. 811–824, (2023).
[7] H. Zou and M. Wang, "Enhanced sliding-mode control for tracking control of uncertain fractional-order nonlinear systems based on fuzzy logic systems," Appl. Sci., vol. **15**, no. 9, p. 4686, (2025).
[8] H. Al-Naemi and M. A. Khan, "Design of a robust hybrid fuzzy super-twisting speed controller for induction motor vector control systems," Neural Comput. Appl., vol. **34**, pp. 19863–19876, (2022).
[9] K. A. Abdelrahman et al., "Fault-tolerant fuzzy logic control of a six-phase induction generator," Energies, vol. **15**, no. 4, p. 1301, (2022).
[10] M. Ibrahim, A. Allag, and M. Menacer, "A comprehensive review on predictive control strategies of multiphase machines," Energies, vol. **15**, no. 21, p. 8046, (2022).
[11] J. Li et al., "A review on nonlinear control techniques for permanent magnet synchronous motor drives," Mathematics, vol. **11**, no. 7, p. 1525, (2023).
[12] S. Karan, A. Alam, and A. Thakur, "Hybrid control using fuzzy logic and adaptive space vector modulation for reduction of torque ripples in PM-BLDC motor drive" J. Eng. Appl. Sci., vol. **70**, art. 66, Jun. (2023). https://doi.org/10.1186/s44147-023-00238-0.

[13] T. Pani et al., “Predictive current control strategies for multiphase machines: A review,” IEEE Trans. Ind. Electron., vol. **70**, no. 4, pp. 3370–3382, Apr. (2023).
[14] S. Sahoo et al., “Finite control set model predictive control of multiphase drives: Challenges and recent advancements,” IEEE Access, vol. **10**, pp. 55360–55375, (2022).
[15] L. Yin, B. Wu, and Y. He, “Robust gain-scheduled LPV control for PMSM with nonlinearities and time-varying parameters,” Int. J. Control Autom. Syst., vol. **20**, no. 1, pp. 122–132, Jan. (2022).
[16] A. M. Ouhrouche and R. Ghorbani, “Observer-based robust LQR control of a Z-source inverter fed induction motor drive,” Int. J. Control, vol. **95**, no. 6, pp. 1489–1498, (2022).
[17] C. Wang, Z. Zhang, and L. Zhang, “A comparative study on disturbance rejection control strategies for PMSM drives,” Energies, vol. **16**, no. 3, p. 1333, (2023). https://doi.org//10.1109/ACCESS.2021.3110259.
[18] Z. Zhu et al., “Reinforcement learning control strategies for AC motor drives: A review,” IEEE Trans. Ind. Informat., vol. **20**, no. 2, pp. 1234–1247, Feb. (2024).
[19] O. Amieur and H. Mohellebi, “An Asynchronous Motor’s Design and Control for Electric Vehicles (Conception et Commande d’un Moteur Asynchrone Destiné au Véhicule Électrique),” ResearchGate, (2015). http://doi.org//10.13140/RG.2.2.29404.16000.
[20] M. Habibullah, T. Debanath, and M. S. H. Sabbir, “Fault tolerant control of five-phase induction motor drive,” in Induction Motors — Recent Advances, New Perspectives and Applications, IntechOpen, (2023), http://doi.org//10.5772/intechopen.1001586.