

Fuzzy Logic Control for Enhanced 4WD Electric Vehicle Speed Control

Abdelhamid BOUREGBA¹, Aissa BENHAMMOU¹, Abdeldjabar HAZZAB², Samir HADJERI³

⁽¹⁾ SGRE laboratory, Tahri Mohamed University Bechar, Algeria

⁽²⁾ University of Quebec, Canada

⁽³⁾ University of Sidi Bel Abbès, Algeria

Email of corresponding author: Benhammou.aissa@univ-bechar.dz

Received: 28 November 2025

Accepted for publication: 15 December 2025

Published: 20 December 2025

Abstract—This study explains the implementation and design of a Fuzzy Logic Controller (FLC) for enhanced speed control in a four-wheel-drive (4WD) electric vehicle (EV). Traditional Proportional-Integral-Derivative (PID) controllers often struggle with the nonlinear dynamics, parameter variations, and external disturbances inherent in EV systems. To address these challenges, we propose an intelligent FLC that leverages heuristic knowledge to provide robust and adaptive control without requiring a precise mathematical model. The controller's performance is evaluated through simulation under various driving conditions, including different road surfaces and sudden load changes. Results demonstrate that the proposed FLC system achieves superior performance compared to a conventional PI controller, exhibiting significantly reduced rise and settling times, minimal overshoot, and enhanced stability, thereby ensuring improved traction, energy efficiency, and driving comfort.

Keywords— Electric vehicle, 4 wheel-drive, induction motor, Fuzzy Logic control, Exponential reaching law.

I. INTRODUCTION

Recently, the automotive sector has turned increasingly toward electric drives for vehicle propulsion, motivated by sustainability demands, the need to reduce emissions, and the pursuit of greater energy efficiency [1]. This evolution has fostered the advanced development of different categories of electric vehicles, including battery electric vehicles and hybrid electric vehicles, and fuel cell electric vehicles. Consequently, much research and innovation has focused on transmission technologies, particularly with regard to improving the performance, efficiency, and reliability of mobility systems. The performance of the vehicle is generally evaluated using parameters such as top speed, acceleration time, and gradeability. At the core of the electric propulsion system is the electric motor, a critical drivetrain component. In recent years, leading automotive manufacturers have broadly adopted induction motors (IMs) and permanent magnet motors (PMs) for electric vehicle applications, owing to their robustness, efficiency, and operational versatility [2].

In industry, induction motors are valued for electric vehicle systems due to their robustness, cost-effectiveness, and reliability, even under harsh operating conditions. In electric vehicles, speed control is essential for optimizing the performance, efficiency, and dynamic behavior of the traction system. As a fundamental element of the electric powertrain, speed regulation enables the vehicle to respond effectively to varying driving conditions—including rapid acceleration, braking, and changing road gradients—while ensuring smooth and precise motor operation [3].

Indeed, the induction motor (IM) features a strong coupling between flux and torque, which complicates its control, as changes in one variable directly influence the other. To tackle this challenge, numerous control strategies have been developed, ranging from conventional scalar control to vector-based approaches, most notably field-oriented control (FOC). Among these techniques, scalar control is distinguished by its simplicity and ease of implementation, making it an attractive solution that delivers adequate steady-state performance in induction motor drive applications. However, the limitations of scalar control become evident

under transient conditions, such as abrupt changes in load or speed. In contrast, vector control enables precise and decoupled regulation of flux and torque, ensuring smooth performance even during rapid variations in operating conditions. Nevertheless, this approach is highly sensitive to variations in machine parameters and requires an accurate motor model, precise measurements, and advanced control algorithms. This consequently increases the overall complexity of the system in terms of computational load, hardware requirements, and implementation effort [4]. For example, the adaptive neuro-fuzzy inference system (ANFIS) proposed by Benhammou et al. in [2] exhibited oscillatory behavior during low-speed operation, attributed to the adaptation requirements of the controllers.

However, the design of traditional controllers like PID often struggles with the nonlinear dynamics, parameter variations, and external disturbances inherent in electric vehicle systems. To overcome these limitations, intelligent control strategies have been developed to provide robust performance without requiring a precise mathematical model. One such method is Fuzzy Logic Control (FLC), which uses heuristic knowledge and a rule-based system to manage system complexities. This approach ensures system stability and robustness while providing a naturally smooth control action, thereby effectively eliminating the chattering phenomenon. This study primarily aims to investigate the application of a fuzzy logic controller (FLC) for speed regulation in a four-wheel drive EV (4WDEV). Designed for the outer speed control loop, the proposed FLC seeks to achieve high control performance, ensure system stability and robustness, and enhance the dynamic response of the EV [3]. A review of recent literature indicates that, in [8], a hybrid fuzzy sliding mode controller was developed. References [9–17] remain largely unchanged, as they provide background context on hybrid and intelligent control approaches. However, the concluding “Motivated by” section should be revised to better reflect the focus and contributions

of the present study.

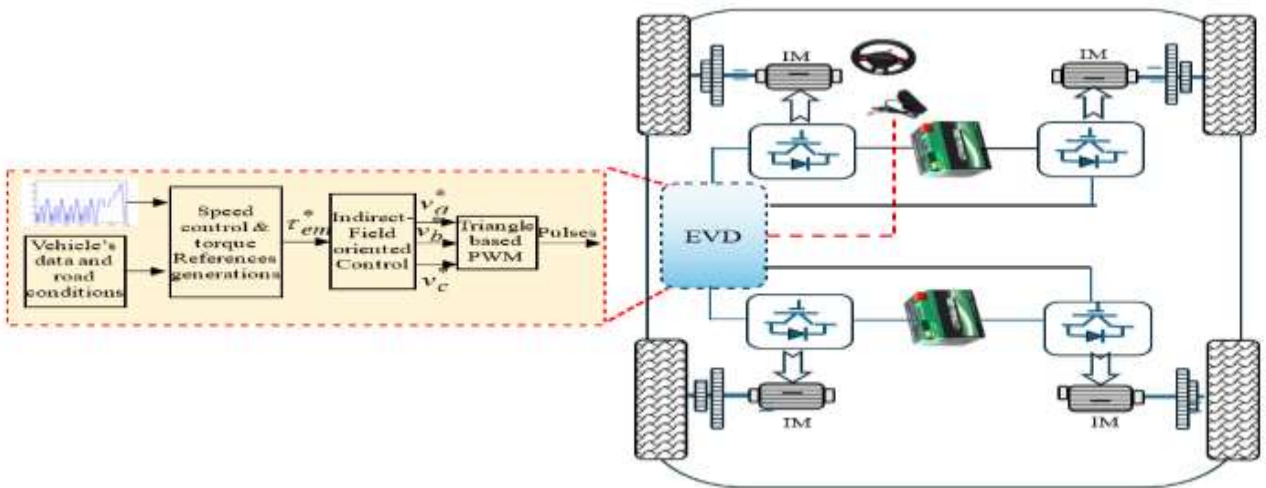
Inspired by the merits of the aforementioned studies, this work proposes a fuzzy logic controller (FLC) that directly computes the optimal control effort based on the speed error and its rate of change. The rule-based structure of the FLC is designed to ensure an adaptive and robust response under varying operating conditions and external load disturbances. This approach provides an effective solution that inherently eliminates the chattering phenomenon while generating a smooth control signal.

Overall, this study pursues three main objectives:

- Developing a mathematical design procedure for a speed controller based on indirect field-oriented control (FOC), specifically tailored for a four-wheel drive electric vehicle (4WDEV).
- Designing a fuzzy logic controller to replace traditional methods and overcome the chattering phenomenon.
- Developing a fuzzy logic system that considers both transient and steady-state behaviors to achieve robust system performance.

II. MODELLING OF EV DRIVING

Achieving effective speed control that tracks a predefined driving cycle requires a comprehensive vehicle model. In this configuration, the reference speed extracted from the driving cycle serves as the input to the control system, while the controller interfaces directly with the inverter. The inverter plays a critical role by converting electrical energy from the battery into appropriate control variables—namely, the reference rotational speed and electromagnetic torque for the IM. The induction motor then converts this electrical energy into mechanical energy to move the vehicle forward. Figure (1) depicts different components of the (EV) propulsion system, showing how these elements work together in an integrated fashion to ensure efficient and responsive vehicle performance [18].



The various components that constitute the EV propulsion system.

A. Ev Dynamic Model

Adopting a dynamic model plays a vital role in improving the efficiency of electric vehicles, because it facilitates the

evaluation of vehicle performance and the optimal design of the propulsion system under realistic operating conditions. Consider an electric vehicle of mass M_v moving at speed V

on a road inclined at an angle δ to the horizontal. A dynamic model can be formulated by treating the vehicle as a rigid body subjected to various longitudinal resistive forces. These forces correspond to aerodynamic drag, resulting from the movement of the vehicle, through air; rolling resistance, resulting from tire-road interaction; grade resistance, attributable to the road inclination; and inertial resistance, combined with changes in vehicle velocity. Collectively, these resistive forces define the total tractive effort required to propel the vehicle and directly influence energy consumption as well as the effectiveness of control strategies, as illustrated in Figure (2) [8].

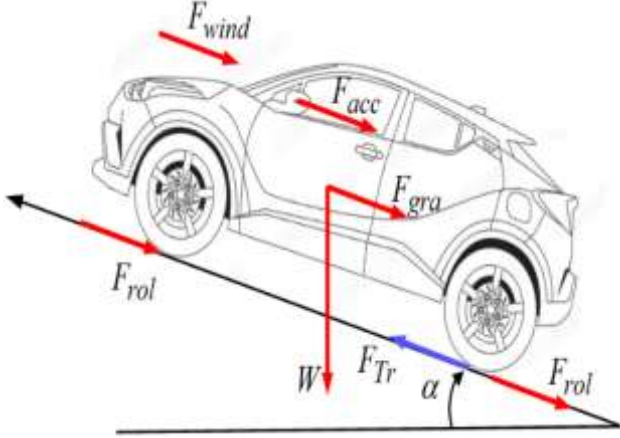


Fig. 1. Forces exerted on the four-wheel drive electric vehicle.

After the application of the second law of Newton, the obtained expression formulated as follows:

$$M_v \frac{d\vec{v}}{dt} = \sum \vec{F}_{ext} = \vec{F}_{Tr} + \vec{F}_{acc} + \vec{F}_{rol} + \vec{F}_{wind} + \vec{F}_{gra} \quad (1)$$

The projection of the law onto the horizontal axis leads to:

$$M_v \frac{dv}{dt} = \sum F_{ext} = F_{Tr_x} - (F_{acc_x} + F_{rol_x} + F_{wind_x} + F_{gra_x}) \quad (2)$$

Where:

$$F_{wind_x} = \frac{1}{2} \rho S C_x (v - v_0)^2 \quad (3)$$

$$F_{gra_x} = G_r M_v g \cos(\alpha) \quad (4)$$

$$W_x = M_v g \sin(\alpha) \quad (5)$$

$$F_{acc_x} = M_v \frac{dv}{dt} \quad (6)$$

Where F_{Tr} represents the total tractive force, F_{wind} the force of wind resistance. Let F_{rol} denote the rolling resistance force, F_{gra} the grade resistance force, and F_{acc} the acceleration resistance force. Furthermore, let C_{win} and C_{rol} represent the wind resistance coefficient and the rolling resistance coefficient, respectively, while m is the vehicle mass and g is the gravitational acceleration. The wheel radius, gear ratio, and vehicle velocity are denoted by w_r , G_r , and V_v , respectively.

$$\omega_r = G_r \frac{V_v}{R_{wheel}}, \text{ and } \omega_{wheel} = \frac{V_v}{R_{wheel}} \quad (7)$$

The motor load torque T_L can be formulated as function

of speed as follow:

$$T_L = \frac{1}{G_r} T_w = \frac{1}{G_r} (F_{wind} + F_{rol} + F_{acc} + F_{gra}) \quad (8)$$

B. Modelling And Field Oriented Control Of An Induction Motor

Within the d-q synchronous reference frame, the dynamic behavior of a three-phase Y-connected stator induction motor is governed by the following differential equations [19], [20].:

$$\frac{di_{ds}}{dt} = \frac{1}{\sigma L_s} (-R_{eq} i_{ds} + \sigma L_s \omega_s i_{qs} + \frac{L_m R_r}{L_r^2} \phi_{dr} + P \frac{L_m}{L_r} \phi_{qr} \omega_r + v_{ds}) \quad (9)$$

$$\frac{di_{qs}}{dt} = \frac{1}{\sigma L_s} (-\sigma L_s \omega_s i_{ds} - R_{eq} i_{qs} - P \frac{L_m}{L_r} \phi_{dr} \omega_r + \frac{L_m R_r}{L_r^2} \phi_{qr} + v_{qs}) \quad (10)$$

$$\frac{d\phi_{dr}}{dt} = \frac{L_m R_r}{L_r} i_{ds} - \frac{R_r}{L_r} \phi_{dr} + (\omega_s - P \omega_r) \phi_{qr} \quad (11)$$

$$\frac{d\phi_{qr}}{dt} = \frac{L_m R_r}{L_r} i_{qs} - (\omega_s - P \omega_r) \phi_{dr} - \frac{R_r}{L_r} \phi_{qr} \quad (12)$$

$$\frac{d\omega_r}{dt} = \frac{1}{J} \left(\frac{3 P L_m}{2 L_r} (i_{qs} \phi_{dr} - i_{ds} \phi_{qr}) - f_c \omega_r - T_l \right) \quad (13)$$

Let R_s , and R_r be the stator and rotor resistances per phase, respectively, and L_m the magnetizing inductance per phase.

The stator and rotor inductances per phase are denoted by L_s and L_r while ω_s and ω_r represent the synchronous frequency and the rotor frequency, respectively. P is the number of pole pairs. Additionally, $\tau_r = L_r / R_r$ is the rotor time constant, $\sigma = 1 - [L_m^2 / (L_s L_r)]$ the leakage coefficient, i_{ds} and i_{qs} the d-axis and q-axis stator currents, ϕ_{dr} and ϕ_{qr} the d-axis and q-axis rotor fluxes, and v_{ds} and v_{qs} the d-axis and q-axis stator voltages. The electromagnetic torque can then be expressed as shown in equation (14).

$$T_e = \frac{3 P L_m}{2 L_r} (i_{qs} \phi_{dr} - i_{ds} \phi_{qr}) \quad (14)$$

Under vector control, the dynamic behavior of an induction motor resembles that of a separately excited DC machine, since torque and flux can be regulated independently. Under ideal rotor-flux orientation, the quadrature component of the rotor flux becomes zero, which ensures complete decoupling between the torque and flux-producing components. ϕ_{qr} is set to equal zero, then we can write as given in (15) and (16):

$$\phi_{qr} = 0 \quad (15)$$

$$\phi_{dr} = \phi_r^N = \text{constant} \quad (16)$$

Where ϕ_r^N denotes the rated rotor flux value.

Consequently, the torque expression is simplified and takes a form analogous to that of a DC motor, as follows:

$$T_e = \frac{3PL_m}{2L_r} i_{qs} \varphi_{dr} \quad (17)$$

And the slip frequency, $\omega_{sl} = \omega_s - P\omega_r$, is computed by the following equation:

$$\omega_{sl} = \frac{1}{\tau_r} \frac{i_{qs}^*}{i_{ds}^*} \quad (18)$$

where superscript (*) represents reference values.

III. THE ELECTRONIC DIFFERENTIAL PRINCIPLE

The electronic differential system (EDS) employed in four-wheel-independent electric vehicles represents an advanced control architecture. In the proposed scheme (Fig. 3), each wheel—front left, front right, rear left, and rear right—is individually driven by its own independently controlled in-wheel motor. Induction machines are selected as traction motors owing to their favorable characteristics, including high efficiency, high torque density, low acoustic noise, and broad compatibility with electric vehicle traction requirements [21–26].

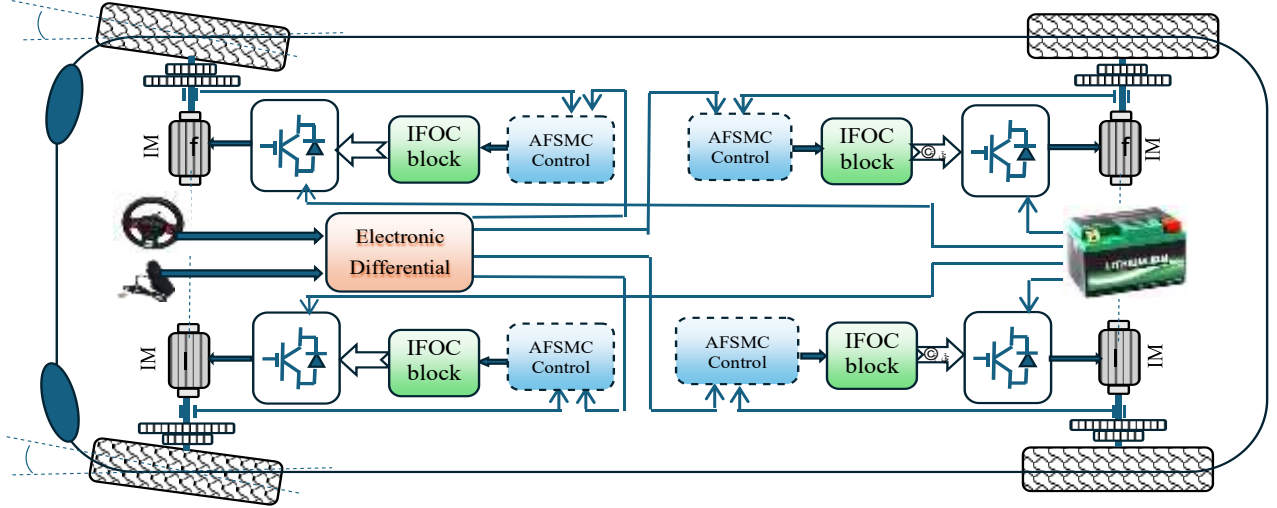


Fig. 2. The EV4WD under study

The reference speed for the four driving wheels is defined as follows:

$$\omega_{lr}^* = \omega_{veh} \frac{\sqrt{1 + \left(\cos(\delta) - \frac{d_\omega}{2L_\omega}\right)^2}}{\sqrt{1 + (\cos(\delta))^2}} \quad (32)$$

$$\omega_{rr}^* = \omega_{veh} \frac{\sqrt{1 + \left(\cos(\delta) + \frac{d_\omega}{2L_\omega}\right)^2}}{\sqrt{1 + (\cos(\delta))^2}} \quad (33)$$

$$\omega_{lf}^* = \omega_{veh} \left(1 - \frac{d_\omega \tan(\delta)}{2L_\omega}\right) \quad (34)$$

$$\omega_{rf}^* = \omega_{veh} \left(1 + \frac{d_\omega \tan(\delta)}{2L_\omega}\right) \quad (35)$$

Where (*) denotes a reference quantity: ω_{lr} is the left rear wheel speed, ω_{rr} is the right rear wheel speed, ω_{lf} is the left front wheel speed, and ω_{rf} is the right front wheel speed. ω_{veh} represents the vehicle speed, while d_ω and L_ω denote the track width between the left and right wheels and the wheelbase between the front and rear axles, respectively.

IV. SIMULATION RESULTS

To thoroughly evaluate the proposed FLC-based control

strategy, two distinct test scenarios were simulated in MATLAB/Simulink. These test cases were designed to assess the controller's performance under varying dynamic operating conditions. The corresponding vehicle parameters and system specifications are summarized in Tables 1 and 2.

TABLE I. NOMINAL IM PARAMETERS VALUES [8]

Parameter	Value
Rated Power P_n	37 Kw
Line-Line voltage V_n	400 V
Rated current I_n	64 A
Rated Speed ω_n	2960 rpm
Number of pole pairs P	1
Stator resistance R_s	85.1 mΩ
Rotor resistance R_r	65.8 mΩ
Stator Inductance L_s	31.4 Mh
Rotor Inductance L_r	31.4 Mh
Magnetizing Inductance L_m	29.1 mH
Inertia Moment of motor J	0.23 kg/m ²
Friction coefficient f_c	0.0095 Nm.s/rad

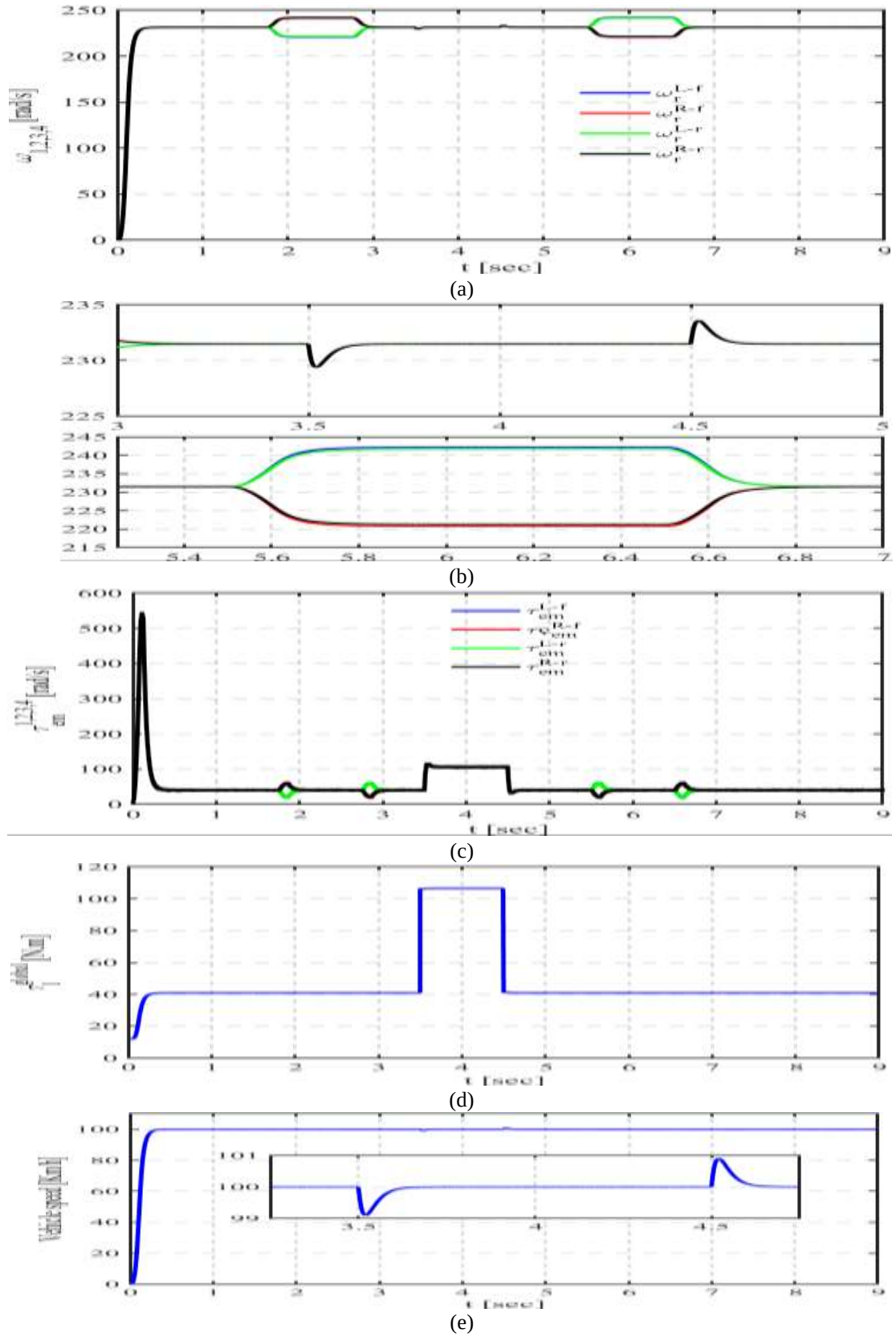


Fig. 3. EV behaviour, (a) EV wheels speed [rpm]; (b) ZOOM of speed; (c) Wheels' electromagnetic torque [N.m]; (d) Load torque [Nm]; and (e) EV speed.

TABLE II. EV MECHANICAL AND AERODYNAMIC PARAMETERS [8]

Parameter	Value
m	150 kg
A	1.8 m ²
R	0.3 m
μ_{rr1}	0.0055
μ_{rr2}	0.056
Cad	0.19
G	104
η_g	0.95
T	57.2 Nm
v_0	4.155 m/s
g	9.81 m/s ²
ρ	0.23 kg/m ³

A. Case 01

The proposed FLC technique for the 4WDEV traction system is validated by subjecting the system to reference speed variations combined with realistic driving maneuvers. In this test scenario, two distinct steering inputs are applied by the driver, corresponding to two successive turns.

At $t = 8$ s, the first maneuver (Phase 01) initiates with a left turn, followed by a right turn at $t = 28$ s. Figure (4) illustrates the linear velocity of each wheel throughout the turning sequences while the vehicle maintains a constant speed. The steering angle δ imposed by the driver is initially applied to the front wheels.

As a result, the electric drive system (EDS) dynamically regulates the individual speeds of the four induction motors. When executing a right turn, the EDS reduces the speed of the inner (right-side) wheels while simultaneously increasing that of the outer (left-side) wheels, thereby ensuring optimal torque distribution and cornering stability. During Phase 01, the front-left and rear-left wheels revolve at higher speeds than their right-side counterparts, reflecting the system's adaptive behavior. The second phase displays analogous behavior with interchanged wheel speed roles. Figure (4a) distinctly captures this speed differentiation among the four wheels during cornering, confirming the accurate real-time performance of the proposed FLC-based EDS strategy.

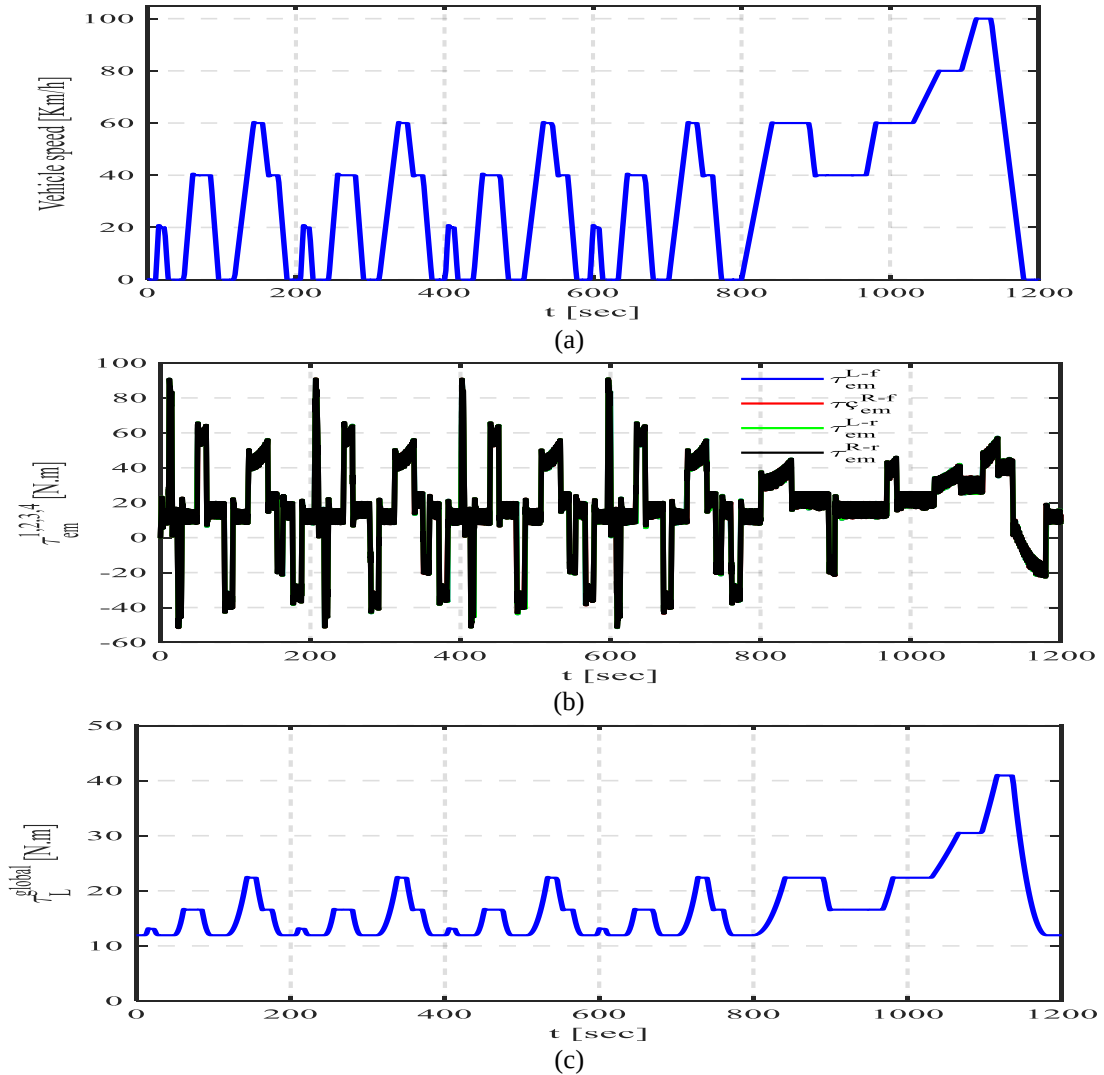


Fig. 4. EV scenario, (a) European Driving Cycle (EDC) Speed Profile Applied to the 4WD Electric Vehicle; (b) Electromagnetic Torque Response Under the Proposed Control Strategy; (c) Load Torque Variation Corresponding to Realistic Driving Conditions.

B. Case 02

In this study, the dynamic response of the EV propulsion system is examined under the standardized New European Driving Cycle (NEDC), which comprises urban (ECE-15) and extra-urban (EUDC) phases, providing a thorough framework for evaluating energy consumption, motor performance, and overall system efficiency. The simulation investigates the current drawn by the electric motor from the power source across all cycle operating modes, namely acceleration, cruising, and deceleration (regenerative braking). During acceleration phases, high torque demand leads to increased current consumption. In cruising conditions, the emphasis is on maintaining steady-state operation with minimal current fluctuations, while during deceleration, the regenerative braking capability and energy recovery are evaluated.

Examining current profiles yields valuable insights into motor efficiency, power electronic losses, and overall energy consumption, while also revealing opportunities to optimize control strategies—such as field-oriented control (FOC)—with the aim of reducing energy losses and extending battery life. Furthermore, the simulated current waveforms are compared against ideal theoretical models to identify deviations stemming from nonlinear motor behavior, switching harmonics, and load variations. These findings provide a deeper understanding of real-world energy usage and validate the effectiveness of the proposed fuzzy logic control strategy in reducing peak current demand while maintaining robust and stable vehicle performance throughout the NEDC cycle.

Figure (5) illustrates the EV operating scenario over a 1200 s duration, with Figure (5a) depicting the vehicle speed profile, Figure (5b) presenting the electromagnetic torque of each wheel, and Figure (5c) showing the load torque variation under realistic driving conditions. The simulation results reveal that the proposed approach surpasses the reference method across several key performance indicators. Unlike conventional PI control strategies, which offer limited robustness and are prone to performance degradation under varying operating conditions, the fuzzy logic controller (FLC) leverages an intelligent decision-making mechanism that considerably enhances system response, leading to superior robustness and improved tracking accuracy.

Beyond that, the proposed strategy exhibits remarkable adaptability to complex driving conditions, including slope variations, curved trajectories, and the NEDC cycle, while achieving enhanced energy efficiency and more effective motor current regulation. Taken together, the results unambiguously underscore the theoretical and practical advantages of the FLC-based approach, positioning it as a strong contender for advanced EV motion control systems.

V. CONCLUSIONS.

This paper presents a novel fuzzy logic controller (FLC) aimed at enhancing speed tracking performance for a four-wheel-drive electric vehicle (4WD-EV). The developed control strategy demonstrates superior stability across diverse driving scenarios, including sharp turns and uneven slopes, while contributing to improved energy efficiency. By

effectively minimizing torque and flux ripples particularly during startup phases the controller significantly reduces energy losses and extends the vehicle's driving range, which is critical in electric vehicles where energy optimization directly affects driving autonomy.

High-fidelity MATLAB/Simulink simulations were conducted to validate the effectiveness of the proposed FLC structure, with its performance compared against that of a conventional PI controller. The simulation results reveal a faster dynamic response in torque and flux, and improved speed tracking accuracy. Moreover, the fuzzy logic controller mechanism enhances robustness by effectively compensating for load variations and external disturbances, ensuring consistent performance under realistic driving conditions.

REFERENCES

- [1] A. Kimouche, M. R. Mekideche, M. Chebout, and H. Allag, "Influence of permanent magnet parameters on the performances of claw pole machines used in hybrid vehicles," *Electrical Engineering & Electromechanics*, no. 4, Art. no. 4, Jun. 2024, pp. 3-8. doi: 10.20998/2074-272X.2024.4.01.
- [2] Benhammou, H. Tedjini, Y. Guettaf, M.A. Soumeur, M.A. Hartani, O. Hafsi, A. Benabdelkader, "Exploitation of vehicle's kinetic energy in power management of tow -wheel drive electric vehicles based on ANFIS DTC-SVM comparative study," *International Journal of Hydrogen Energy*, vol. 46, no. 54, pp. 27758–27769, Aug. 2021, doi: 10.1016/j.ijhydene.2021.06.023.
- [3] L. Djafer, R. Taleb, F. Mehedi, A. Aissa Bokhtache, T. Bessaad, F. Chabni, H. Saidi, "Electric drive vehicle based on sliding mode control technique using a 21-level asymmetrical inverter under different operating conditions," *Electrical Engineering & Electromechanics*, no. 3, May 2025, pp. 31-36 doi: 10.20998/2074-272X.2025.3.05.
- [4] K. Abed and H. K. E. Zine, "Intelligent fuzzy back-stepping observer design based induction motor robust nonlinear sensorless control," *Electrical Engineering & Electromechanics*, no. 2, Feb. 2024, pp. 10-15, doi: 10.20998/2074-272X.2024.2.02.
- [5] O. Oualah, D. Kerdoun, and A. Boumassata, "Comparative study between sliding mode control and the vector control of a brushless doubly fed reluctance generator based on wind energy conversion systems," *Electrical Engineering & Electromechanics*, no.1, Feb. 2022, pp. 51-58, doi: 10.20998/2074-272X.2022.1.07.
- [6] O. Oualah, D. Kerdoun, and A. Boumassata, "Super-twisting sliding mode control for brushless doubly fed reluctance generator based on wind energy conversion system," *Electrical Engineering & Electromechanics*, no. 2, Mar. 2023, pp. 86-92. doi: 10.20998/2074-272X.2023.2.13.
- [7] D. Sakri, H. Laib, S. E. Farhi, and N. Golea, "Sliding mode approach for control and observation of a three phase AC-DC pulse-width modulation rectifier," *Electrical Engineering & Electromechanics*, no. 2, Mar. 2023, pp.49-56. doi: 10.20998/2074-272X.2023.2.08.
- [8] D. Cherifi and Y. Miloud, "Hybrid Control Using Adaptive Fuzzy Sliding Mode Control of Doubly Fed Induction Generator for Wind Energy Conversion System," *Periodica Polytechnica Electrical Engineering and Computer Science*, vol. 64, no. 4, Art. no. 4, Sep. 2020, doi: 10.3311/PPee.15508.
- [9] F. F. M. El-Sousy, M. M. Amin, and O. A. Mohammed, "Robust Adaptive Neural Network Tracking Control With Optimized Super-Twisting Sliding-Mode Technique for Induction Motor Drive System," *IEEE Transactions on Industry Applications*, vol. 58, no. 3, pp. 4134–4157, May 2022, doi: 10.1109/TIA.2022.3160136.
- [10] D. Cherifi and Y. Miloud, "Hybrid Control Using Adaptive Fuzzy Sliding Mode Control of Doubly Fed Induction Generator for Wind Energy Conversion System," *Periodica Polytechnica Electrical Engineering and Computer Science*, vol. 64, no. 4, Art. no. 4, Sep. 2020, doi: 10.3311/PPee.15508.
- [11] A. Benhammou, M. A. Hartani, H. Tedjini, H. Rezk, and M. Al-Dhaifallah, "Improvement of Autonomy, Efficiency, and Stress of Fuel

- Cell Hybrid Electric Vehicle System Using Robust Controller,” *Sustainability*, vol. 15, no. 7, Jan. 2023, doi: 10.3390/su15075657.
- [12] J. Guo, K. Li, J. Fan, Y. Luo, and J. Wang, “Neural-Fuzzy-Based Adaptive Sliding Mode Automatic Steering Control of Vision-based Unmanned Electric Vehicles,” *Chinese Journal of Mechanical Engineering*, vol. 34, no. 1, p. 88, Sep. 2021, doi: 10.1186/s10033-021-00597-w.
- [13] Guo Qing Geng, Peng Cheng, Li Qin Sun, Xing Xu, and Fanqi Shen, “A Study on Lateral Stability Control of Distributed Drive Electric Vehicle Based on Fuzzy Adaptive Sliding Mode Control,” *International Journal of Automotive Technology*, vol. 25, no. 6, pp. 1415–1429.
- [14] B. Mohammed, F. Bounaama, S. Bennaceur, B. Aissa, and M. Soumeur, “A Particle Swarm Optimization Based Fuzzy Flcpi-Pso Controller for Quadcopter System,” *Communications - Scientific letters of the University of Zilina*, vol. 26, issue 3, Apr. 2024, doi: 10.26552/com.C.2024.027.
- [15] T. Huang, X. Gao, and T. Li, “Adaptive Fuzzy Attitude Sliding Mode Control for a Quadrotor Unmanned Aerial Vehicle,” *Int. J. Fuzzy Syst.*, vol. 26, no. 2, Mar. 2024, pp. 686–701, doi: 10.1007/s40815-023-01628-5.
- [16] Q. Shi, M. Wang, Z. He, C. Yao, Y. Wei, and L. He, “A Fuzzy-based Sliding Mode Control Approach for Acceleration Slip Regulation of Battery Electric Vehicle,” *Chinese Journal of Mechanical Engineering*, vol. 35, no. 72, Jun. 2022, doi: 10.1186/s10033-022-00729-w.
- [17] T. A. Nguyen, “A novel approach with a fuzzy sliding mode proportional integral control algorithm tuned by fuzzy method (FSMPIF),” *Sci Rep*, vol. 13, 7327, May 2023, doi: 10.1038/s41598-023-34455-7.
- [18] A. Haddoun, M. E. H. Benbouzid, D. Diallo, R. Abdessemed, J. Ghouili, and K. Srairi, “Modeling, analysis, and neural network control of an EV electrical differential,” *IEEE Transactions on industrial electronics*, vol. 55, no. 6, pp. 2286–2294, 2008.
- [19] L. Baghli, “Contribution to Induction Machine Control: Using Fuzzy Logic, Neural Networks and Genetic Algorithms,” *Henri Poincare University, Phd Thesis*, 1999.
- [20] V. I. Utkin, “Sliding mode control design principles and applications to electric drives,” *IEEE transactions on industrial electronics*, vol. 40, no. 1, pp. 23–36, 2002.
- [21] M. A. Hartani, A. Benhammou, and A. Laidi, “Performance Evaluation of PI and ST-SMC Controllers in Low Voltage/Power DC-Microgrids,” chapter in book: “Advances in Robust Control and Applications” edited by Mahmut Reyhanoglu, intechopen, 2025. DOI: 10.5772/intechopen.1006834
- [22] R.-J. Wai, “Adaptive sliding-mode control for induction servomotor drive,” *IEE Proceedings-Electric Power Applications*, vol. 147, no. 6, pp. 553–562, 2000.
- [23] K. Makhloufi, I. K. Bousserhane, and S. A. Zegnoun, “Adaptive fuzzy sliding mode controller design for PMLSM position control,” *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 12, no. 2, Jun. 2021, pp. 674–684, doi: 10.11591/ijpeds.v12.i2.pp674-684.
- [24] Q. Nguyen-Vinh and T. Pham-Tran-Bich, “Sliding mode control of induction motor with fuzzy logic observer,” *Electrical Engineering*, vol. 105, no. 5, pp. 2769–2780, 2023.
- [25] A. Nurettin and N. İnanc, “Design of a robust hybrid fuzzy super-twisting speed controller for induction motor vector control systems,” *Neural Comput & Applic*, vol. 34, no. 22, pp. 19863–19876, Nov. 2022, doi: 10.1007/s00521-022-07519-4.
- [26] A. Ghezouani, G. Brahim, N. Nouria, O. Abdelkhalek, and J. Ghouili, “Comparative Study of PI and Fuzzy Logic Based Speed Controllers of an EV with Four In-Wheel Induction Motors Drive,” *Journal of Automation, Mobile Robotics and Intelligent Systems*, vol. 12, N°. 3, Dec. 2018, pp. 43–54, doi: 10.14313/JAMRIS_3-2018/17.