

Speed Control Analysis of an Electric Vehicle by Using Fuzzy-PID Type 1 and Type 2

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Abstract—This paper investigates the speed control of an electric vehicle using three different control strategies: a classical PID controller, a type-1 fuzzy self-tuning PID controller, and a type-2 fuzzy self-tuning PID controller. A longitudinal dynamic model of the electric vehicle is developed in MATLAB/Simulink to evaluate and compare the performance of the proposed controllers under identical operating conditions. The fuzzy-based controllers adapt the PID gains online according to the speed error and its derivative, improving system robustness against nonlinearities and parameter uncertainties. Simulation results demonstrate that both fuzzy-PID controllers outperform the conventional PID in terms of overshoot reduction, settling time, and steady-state accuracy. Furthermore, the type-2 fuzzy-PID controller shows superior performance compared to the type-1 approach, particularly in handling higher levels of uncertainty. These results confirm the effectiveness of fuzzy logic-based adaptive control for electric vehicle speed regulation.

Keywords— *Speed Control, PID, Electrical vehicle, Fuzzy type 1, Fuzzy type 2.*

I. INTRODUCTION

The rapid advancement of electric vehicle (EV) technology has significantly increased the demand for efficient and reliable control strategies for propulsion systems. With the continuous development of power electronics, electric motors, and energy storage systems, EVs are becoming a key solution for sustainable transportation. In this context, precise speed control plays a crucial role in ensuring vehicle stability, passenger comfort, and overall system performance.

However, maintaining accurate speed regulation in electric vehicles remains a challenging task due to the presence of nonlinear dynamics, parameter uncertainties, and external disturbances such as road slope variations, aerodynamic drag, and changes in vehicle mass. These factors directly affect the dynamic behavior of the system, requiring advanced control techniques capable of providing fast response, minimal overshoot, and high steady-state accuracy.

Conventional control methods, particularly proportional-integral-derivative (PID) controllers, are widely used in industrial applications due to their simplicity, ease of implementation, and satisfactory performance under nominal conditions. In electric vehicle applications, PID controllers are

commonly employed to regulate motor speed based on the error between the reference and actual speed [1]. However, several studies have reported that fixed-gain PID controllers exhibit limited performance when dealing with nonlinear systems and varying operating conditions, leading to increased overshoot and longer settling times [1], [2].

To overcome these limitations, researchers have explored the integration of artificial intelligence techniques with classical control methods. For example, the work presented in [1] investigated the use of fuzzy-PID and ANFIS controllers for EV speed control, demonstrating improved dynamic response compared to conventional PID controllers. Similarly, the study in [5] proposed an ANFIS-based fractional-order PID controller, showing enhanced tracking performance and robustness against disturbances. In addition, optimization-based approaches such as the ACO-based fuzzy FOPID controller in [3] and PSO-based tuning methods in [8], [12] have been developed to improve controller performance through adaptive parameter adjustment.

Among intelligent control techniques, fuzzy logic controllers have gained significant attention due to their ability to handle system nonlinearities without requiring an accurate mathematical model. Type-1 fuzzy logic-based PID controllers have been successfully applied to improve

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transient response and reduce steady-state error in EV speed control systems [3], [11]. Nevertheless, their performance may still be limited when dealing with high levels of uncertainty.

To address this issue, type-2 fuzzy logic systems have been introduced as an extension of type-1 fuzzy logic by incorporating uncertainty directly into the membership functions. This additional degree of freedom allows type-2 fuzzy controllers to better manage parameter variations and external disturbances. Recent studies, such as [10], have demonstrated that type-2 fuzzy logic combined with intelligent learning techniques can significantly enhance control accuracy and robustness in electric vehicle applications.

In recent years, hybrid intelligent control approaches combining fuzzy logic, neural networks, and optimization algorithms have emerged as promising solutions for complex control problems. Methods such as ANFIS-PID and optimized fuzzy controllers have shown superior performance in terms of adaptability, convergence speed, and robustness compared to conventional control techniques [8], [9], [12]. These advancements highlight the importance of developing adaptive and intelligent control strategies for electric vehicle systems.

Motivated by these developments, this paper presents a comparative study of three control strategies for electric vehicle speed regulation: a conventional PID controller, a type-1 fuzzy self-tuning PID controller, and a type-2 fuzzy self-tuning PID controller. The main contributions of this work can be summarized as follows:

- Development of a simplified longitudinal dynamic model of an electric vehicle in MATLAB/Simulink.
- Design and implementation of type-1 and type-2 fuzzy self-tuning PID controllers.
- Comparative analysis of the proposed controllers under identical operating conditions.
- Demonstration of the superior performance of type-2 fuzzy logic in handling uncertainties and improving dynamic response.

The remainder of this paper is organized as follows: Section II presents the electric vehicle model, Section III describes the control strategies, Section IV discusses the simulation results, and Section V concludes the paper.

II. A BASIC MODEL OF ELECTRIC VEHICLE

A simplified dynamic model of an electric vehicle is created and implemented in MATLAB/Simulink in order to evaluate the speed control performance of the suggested controllers. The model includes the traction force produced by the electric motor in addition to the primary resistive forces operating on the vehicle and depicts the longitudinal motion of the vehicle. The system response under various control strategies is assessed using the adopted parameters, which match those of a Tesla Model S.

A. Electric vehicle dynamic

The longitudinal behaviour of an electric vehicle is governed by the interaction between the traction force generated by the electric motor and the forces opposing vehicle motion. These opposing forces mainly arise from

aerodynamic effects, rolling resistance, and vehicle inertia. Together, they determine the acceleration and the speed response of the vehicle during different driving conditions [3][5].

At higher vehicle speeds, the aerodynamic drag (F_{aer}), a resistive force brought on by air interaction with the vehicle body, becomes more significant. The drag coefficient, air density, vehicle frontal area, and the square of the longitudinal velocity all affect this force [3][4] (Figure 1). The rolling resistance (F_r), on the other hand, results from tire deformation and contact with the road surface and remains approximately constant for a given vehicle mass and road condition [4] [5] (Figure 2).

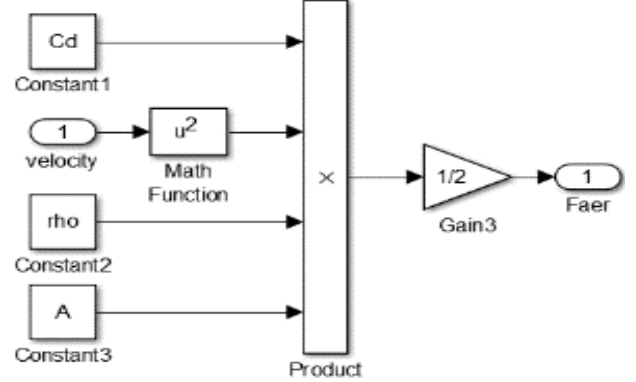


Fig. 1. Simulation of F_{aer} in matlab/Simulink

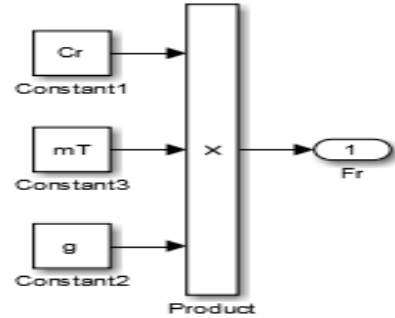


Fig. 2. Simulation of F_r in matlab/Simulink

The inertial resistance (F_{int}) appears when the vehicle undergoes acceleration or deceleration and is proportional to the total vehicle mass and longitudinal acceleration.

The combined effect of aerodynamic drag, rolling resistance, and inertial forces determines the overall resistive force acting on the vehicle (F_{mec}) [3], [5].

$$F_{mec} = F_{aer} + F_r + F_{int} \quad (1)$$

The traction force applied to the wheels (F_{mec}) is produced by the electric motor through the drivetrain system and depends on the motor torque (T), the gear ratio (G_r), the transmission efficiency (eff_{tr}), and the wheel radius (r) [3]. By applying Newton's second law, the vehicle acceleration can be derived from the difference between the traction force and the total resistive forces acting on the vehicle

$$F_{mec} = \frac{T}{r} * G_r * eff_{tr} \quad (2)$$

$$a = (F_{mec} - F_{aer} - F_r)/m_T \quad (3)$$

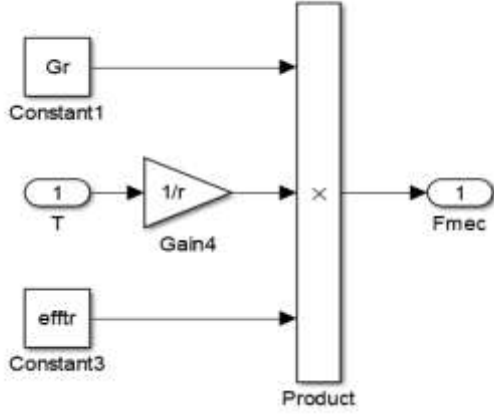


Fig. 3. Simulation of Fmec in matlab/Simulink

Based on these physical relationships, a simplified electric vehicle dynamic subsystem is implemented in MATLAB/Simulink. This model uses the motor torque as an input and provides the vehicle acceleration and the speed as outputs, allowing an effective evaluation of different speed control strategies under identical operating conditions.

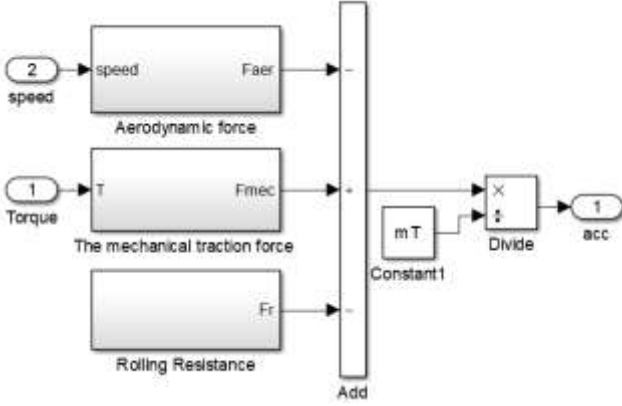


Fig. 4. Simulation of Faer in matlab/Simulink

B. Electric vehicle motor model

Due to the complexity associated with modelling a three-phase AC induction motor, a simplified brushed DC motor model is adopted to represent the traction motor behaviour while maintaining comparable dynamic characteristics. An overall efficiency factor is included to account for losses and ensure realistic performance.

The motor is modeled as a series R–L circuit with a back electromotive force (EMF). The electrical equation of the motor is given by [3]:

$$V(t) = i(t) \cdot R + L \cdot \frac{di(t)}{dt} + E(t) \quad (4)$$

Where $V(t)$ is the applied voltage, R and L are the armature resistance and inductance, respectively, and $E(t)$ is the back EMF.

The electromagnetic torque generated by the motor is proportional to the armature current and is expressed as [3]:

$$T(t) = K_T \cdot i(t) \quad (5)$$

Where K_T is the torque constant of the motor. The back EMF is related to the angular speed of the motor by:

$$E(t) = K_E \cdot w(t) \quad (6)$$

With K_E denoting the back EMF constant and $w(t)$ the motor angular speed.

The motor is implemented in MATLAB/Simulink using a transfer function block, where the input is the motor voltage and the output is the generated torque, by combining these equations and performing the Laplace transform. The motor's rotational speed is determined by integrating the vehicle acceleration through the drivetrain and wheel dynamics.

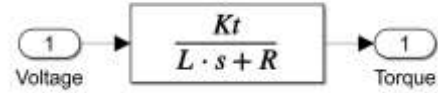


Fig. 5. Simulation of motor transfer function in matlab/Simulink

The numerical values of the vehicle and motor parameters used in this study are summarized in TABLE I

TABLE I. EV SPECIFICATION

ρ	1.225 Kg/m ³	efftr	0.7
A	2.3 m ²	R	5.3 mΩ
C_D	0.24	L	493 nH
C_r	0.02	K_e	0.12 v.s/rad
m_r	2300 kg	K_t	0.25 N.m/A
g	9.81 m/s ²	Gr	9.73
r	0.24 m		

The global Simulink model of the EV is represented in

III. SPEED CONTROLLER

The speed controller is critical to the operation of an electric vehicle since it directly affects the dynamic responsiveness, stability, and tracking accuracy of the propulsion system. In this paper, we analyze and compare three different control strategies: a type-1 fuzzy self-tuning PID controller (FL1-PID), a type-2 fuzzy self-tuning PID controller (FL2-PID), and a conventional proportional-integral-derivative (PID) controller. All controllers are designed to regulate the speed of the electric vehicle by decreasing the difference between the reference speed and the actual speed.

A. Proportional Integral Derivative (PID) Controller

The PID controller is one of the most often used feedback control techniques in industrial settings due to its simple design, ease of use, and sufficient robustness [1][2][7]. The PID controller is widely used in electric vehicle speed control to regulate the traction motor speed by generating an appropriate control signal depending on the speed error.

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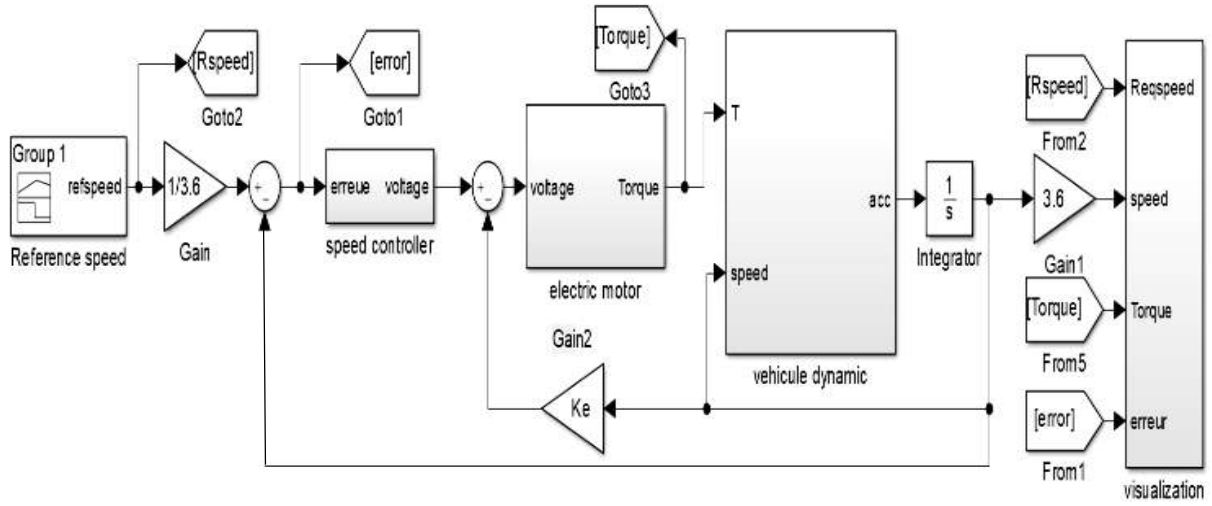


Fig. 6. MATLAB/Simulink implementation of the electric vehicle longitudinal dynamics mode

Three components contribute to the control action of a PID controller. The proportional term, which produces an output proportionate to the instantaneous error between the reference speed and the measured speed, offers a prompt response. The integral term accounts for the accumulation of prior errors and is mainly responsible for eliminating steady-state error. The derivative term minimizes overshoot and improves system damping by forecasting the error's future behavior by accounting for its rate of change.

In the Laplace domain, the PID controller's transfer function can be written as [7]:

$$U(s) = K_p + \frac{K_i}{s} + K_d * s \quad (10)$$

where the proportional, integral, and derivative gains are shown by the symbols (K_p), (K_i), and (K_d), respectively. To guarantee a reliable response and provide a baseline for comparison with fuzzy-based controllers, the PID parameters in this study are chosen as ($K_p = 100$), ($K_i = 2$), and ($K_d = 0.05$).

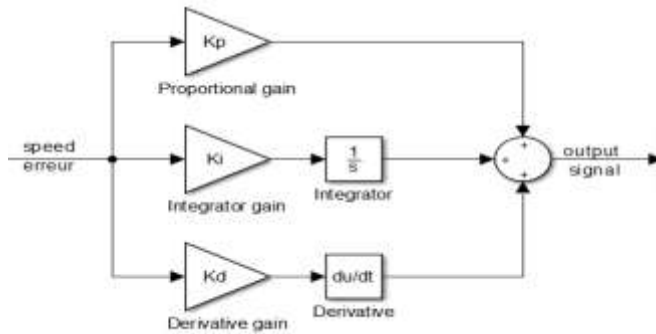


Fig. 7. The block diagram of PID controller

B. Fuzzy Logic type 1 Controller (FL1- PID)

In this study, type-1 fuzzy logic is used to improve the performance of the traditional PID controller by allowing adaptive tweaking of its parameters under time-varying and nonlinear operating situations. The fuzzy logic approach improves the flexibility and robustness of the controller by adjusting the PID parameters online based on the speed error's instantaneous behavior rather than depending on preset gains [3], [6].

Stages of fuzzification, rule inference, and defuzzification make up the fl2-PID's structure. The fuzzy logic system enables the controller to react efficiently to both steady-state and transient conditions by using the vehicle speed error and the derivative of the speed error as input variables. To guarantee seamless control action over the whole operating range, five language phrases are used to define each input [6].

Three separate fuzzy logic blocks are used in the suggested setup to produce the tuning signals for the derivative, integral, and proportional gains. Continuous modification of the controller parameters during vehicle operation is made possible by the output linguistic variables, which indicate incremental adjustments performed to the PID gains. To ensure quick real-time implementation and minimize computational complexity, a Sugeno-type inference mechanism is used [3].

The type-1 fuzzy self-tuning PID controller outperforms the classical PID controller in terms of transient responsiveness and steady-state error by dynamically modifying the PID gains in accordance with the fuzzy rule base displayed in Table II. In electric vehicle applications, this adaptive method improves speed tracking performance and offers more resilience to system uncertainties [3], [6].

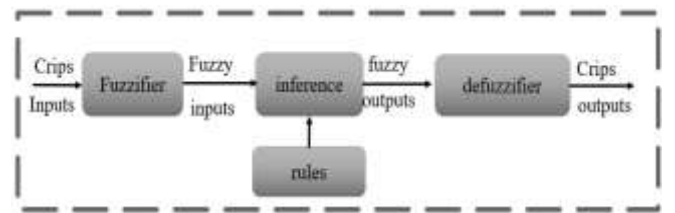


Fig. 8. Block diagram for Fuzzy type 1 controller

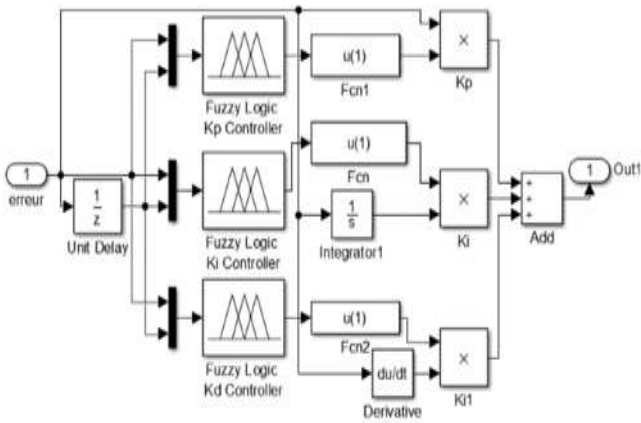


Fig. 9. Structure of FL1- PID Controller block in matlab simulink

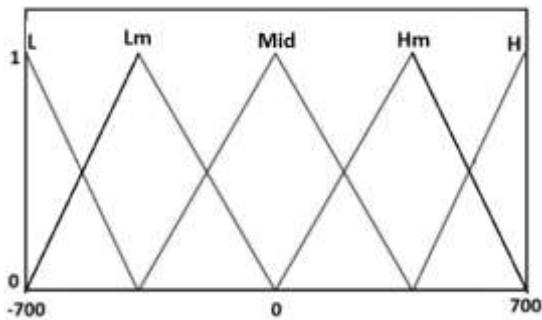


Fig. 10. Membership functions of the type-1 fuzzy logic system inputs used for PID tuning

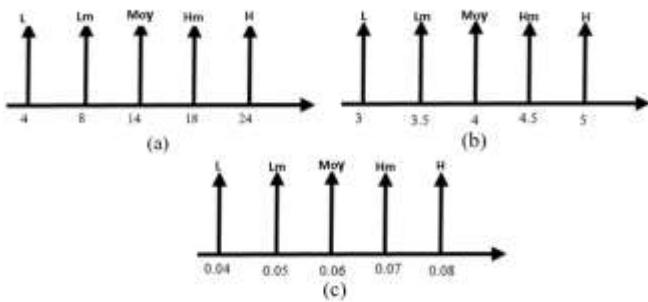


Fig. 11. Membership function for the output of FL1-PID: (a) Kp, (b) Ki, (c) Kd

TABLE II. THE FUZZY RULES BASE OF FL1-PID

De \ e	L	Lm	Mid	Hm	H
L	L	L	L	Lm	Moy
Lm	L	L	Lm	Moy	Hm
Mid	L	Lm	Moy	Hm	H
Hm	Lm	Moy	Hm	H	H
H	Moy	Hm	H	H	H

C. Fuzzy Logic type 2 Controller (fl2-PID)

Type-2 fuzzy logic control is used to strengthen the speed controller's adaptability in situations when the electric vehicle system displays nonlinear behavior and elevated levels of uncertainty. Because type-2 fuzzy systems explicitly account for uncertainty in the membership functions, they are more

resilient than type-1 fuzzy logic to changes in parameters and external disturbances [6], [7].

The framework of the proposed FL2-PID consists of four phases: fuzzification, rule inference, type-reduction, and defuzzification. The additional type-reduction phase, which transforms type-2 fuzzy outputs into equivalent type-1 sets prior to generating the final control action, enables more reliable gain adjustment under unpredictable operating conditions [6].

In this study, the inputs for the fuzzy system are selected to be the vehicle speed error and its derivative. To enable smooth and continuous controller parameter adaptation, these variables are described by five triangle membership functions. The fuzzy logic system's outputs, the PID gains (Kp, Ki, and Kd), are modified online using the preset fuzzy rule base shown in Table III [6], [7].

By continuously modifying the PID gains in response to real-time speed variations, the type-2 fuzzy controller enhances tracking accuracy and system stability. Because of its adaptive behavior, the proposed controller performs better than the regular PID controller and the type-1 fuzzy self-tuning PID controller in terms of handling uncertainty [6].

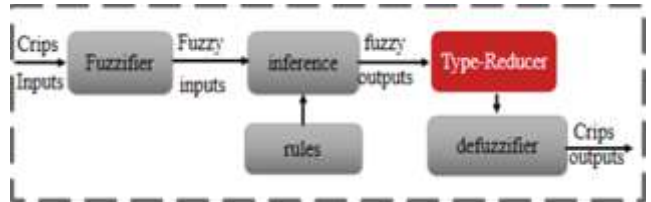


Fig. 12. Block diagram for Fuzzy type 2 controller

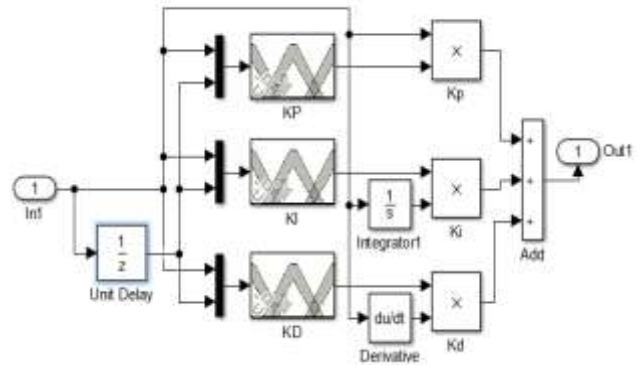


Fig. 13. Structure of fl2- PID Controller block in matlab simulink

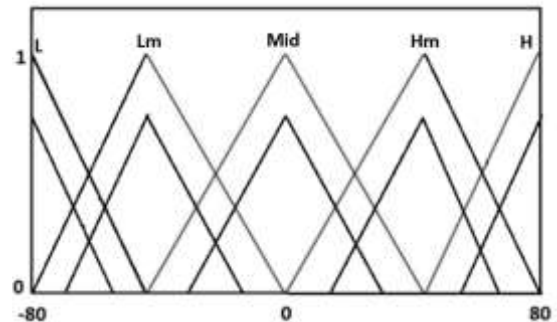


Fig. 14. Membership functions for the inputs e and de of fl2-PID

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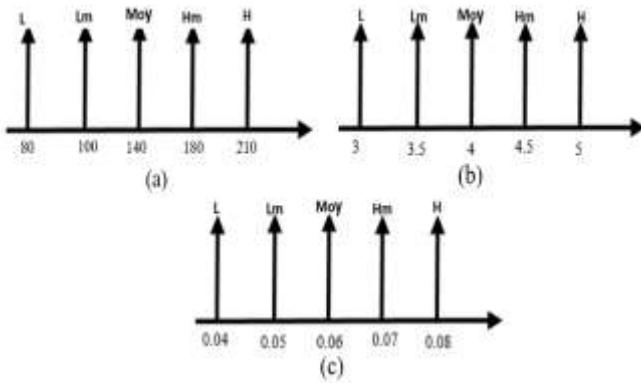


Fig. 15. Membership function for the output of f12-PID (a) Kp (b) Ki (c) Kd.

TABLE III. THE FUZZY RULES BASE OF FL2-PID

De e	H	Lm	Mid	Hm	H
L	L	L	L	Lm	Moy
Lm	L	L	Lm	Moy	Hm
Mid	L	Lm	Moy	Hm	H
Hm	Lm	Moy	Hm	H	H
H	Moy	Hm	H	H	H

IV. SIMULATION RESULTS

The efficiency of the proposed control systems was assessed using MATLAB/Simulink simulations on the developed electric vehicle model. The FL1-PID, FL2-PID, and conventional PID controllers were evaluated under identical operating conditions to ensure a fair and comparable comparison. Performance was assessed using key performance parameters, including steady-state speed error, settling time, overshoot, and rising time.

The speed response generated by the conventional PID controller, which is displayed in Fig. 16, demonstrates that despite the controller's ability to track the reference speed, there is a noticeable overshoot and a somewhat lengthy settling period. These results imply that fixed PID parameters may not be sufficient to guarantee optimal performance when operating conditions vary.

The response of the electric car using the f11-PID is displayed in Fig. 17. Compared to the traditional PID controller, the adaptive tuning mechanism improves the dynamic responsiveness by reducing overshoot and settling time. This improvement illustrates the benefit of continuously

adjusting the PID gains in accordance with the instantaneous speed error and its rate of change.

Figure 18 shows the speed response that the f12-PID achieved. In comparison to the FL1-PID and PID controllers, the results show an extra improvement in performance. Faster reference speed tracking, decreased overshoot, and increased steady-state precision are all achieved. This behavior shows how well type-2 fuzzy logic manages higher levels of uncertainty and nonlinear effects in speed control systems for EVs.

The obtained results are consistent with recent studies reported in the literature, where intelligent controllers such as fuzzy-PID and ANFIS-based approaches significantly outperform conventional PID controllers in terms of dynamic response and robustness [5], [9], [11]. In particular, the superior performance of the FL2-PID controller aligns with findings in [10], which highlight the effectiveness of type-2 fuzzy logic in handling uncertainty and nonlinear behavior in electric vehicle systems.

A comparative evaluation of the three controllers is summarized in Table IV.

TABLE IV. COMPARISON OF PID, FL1-PID, AND FL2-PID CONTROLLERS

Criterion	PID	FL1-PID	FL2-PID
Rise Time	Moderate	Fast	Fast
Overshoot	High	Moderate	Very Low
Settling Time	Long	Medium	Short
Steady-State Error	Small	Very Small	Very Small (best)
Stability	Moderate	Good	Very High
Robustness to Uncertainty	Low	Medium	High
Overall Performance	Fair	Good	Excellent

From Table IV, it is clear that the FL1-PID controller improves the system performance compared to the classical PID by reducing overshoot and improving response speed. However, the FL2-PID controller provides the best overall performance, achieving minimal overshoot, faster settling time, and superior stability.

The improved performance of fuzzy-based controllers is mainly due to their ability to adapt PID parameters in real time according to system conditions. In particular, the FL2-PID controller effectively handles system uncertainties by incorporating type-2 fuzzy logic, resulting in enhanced robustness and smoother dynamic behavior.

These results confirm that intelligent control strategies significantly improve electric vehicle speed regulation, with the FL2-PID controller being the most efficient among the tested approaches.

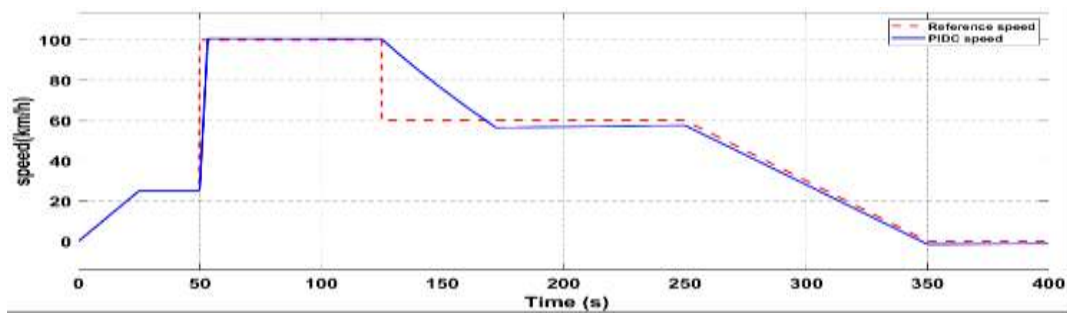


Fig. 16. Vehicle speed response using the conventional PID controller.

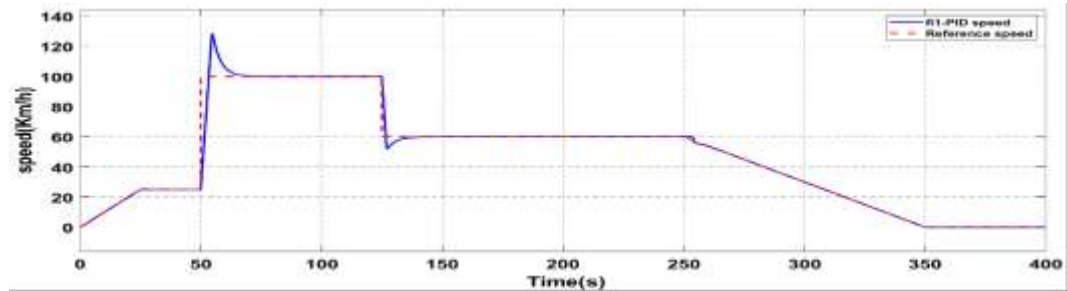


Fig. 17. Speed response of the EV with the fl1-PID

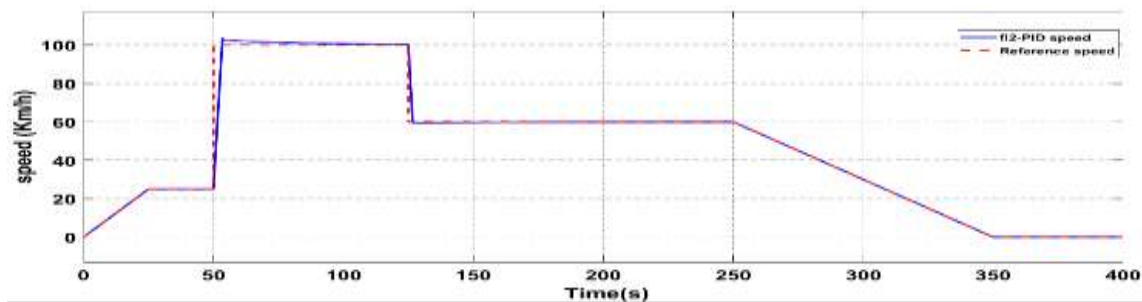


Fig. 18. Speed response of the EV with the fl2-PID

V. CONCLUSION

This study used a simple dynamic model constructed in MATLAB/Simulink to compare three speed control options for an electric car. The effectiveness of two intelligent self-tuning techniques based on type-1 and type-2 fuzzy logic was compared to that of a traditional PID controller.

According to simulation studies, the classical PID controller's fixed gain structure restricts its performance under different operating conditions, even though it offers respectable speed regulation. The benefit of adaptive control strategies in addressing system nonlinearities was demonstrated by the better transient responsiveness and decreased overshoot that resulted from the online tuning of PID gains using type-1 fuzzy logic.

The fl2-PID performed the best overall among the techniques that were studied. Its improved steady-state accuracy, less overshoot, and accelerated response were all results of its better capacity to handle uncertainty and dynamic changes. These results demonstrate that type-2 fuzzy logic is a reliable and efficient solution for situations involving electric vehicle speed control. Future research might concentrate on applying the suggested methodology to real-time experimental implementation and more intricate vehicle models.

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