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Novel Four Wheel Drive Propulsion System Control Using Backstepping Strategy

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Abstract

Recently the electrical machines are widely used in modern electric vehicle, by means new model of electric induction motors technologies are employed using in-wheel technology in on four wheels drive electric vehicle. This four wheels electric vehicle model use: static converter, modern battery storage system, in-wheel motors where the control of this multi motor system became very difficult. In this way we propose new control algorithm of one wheel motor based on backstepping control approach to control independently each in-wheel induction motors. The speed references of both of front and rear driving wheels is obtained using an electronic differential. It‘s permit the control independently, every driving wheel to turn at different speeds in any curve. This paper presents the study and the design of the backstepping control strategy of the electric vehicle driving wheel. Our model is simulated in MATLAB SIMULINK environment, the results obtained present the efficiency of the proposed control compared with classical types.

Keywords: electric vehicle; traction chain; driving wheels; Backstepping control; propulsion system.

1. Introduction

Researches on the power propulsion system of EVS have drawn significant attention in the automobile industry and among academics. EVs can be classified into various categories according to theirs configurations, functions or power sources. Pure EVs do not use petroleum, while hybrid cars take advantages of energy management between

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gas and electricity [1, 2]. Electric vehicle's drive system consists of motors and its controller, vehicle's controller, reducer and transmission device, wheels and so on [2]. There are three main drive modes: centralized drive, two-wheel independent drive, four-wheel independent drive. As the centralized drive can be realized by modifying a little, and it does not need to make too many changes in vehicle's structure and electronic control systems, the world's major automobile manufacturers are committed to the promotion of centralized drive electric vehicles. Every wheel is provided with a drive motor respectively, which is a novel research direction. Due to unique technical advantages and good application prospect, Four Wheels Drive 4WD EVs have attracted great attention worldwide [2, 7]. The advantages of four wheel drive electric vehicle are as follows: the simplified transmission system make vehicle lighter, which promotes the transmission efficiency. Secondly the regenerative braking system can be applied to each wheel and improve energy recovery efficiency, and also it is easy to implement electronic and initiative chassis. The basic vehicle configurations of this research has four directly driven wheel motors installed inside the driving wheels on a pure 4WEV. These wheel motors can be controlled independently and have so quick and accurate response to the command that the vehicle chassis control or motion control becomes more stable and robust, compared to indirectly driven EVs. Like most research on the torque distribution control of wheel motor, wheel motors [7, 8] proposed a dynamic optimal attractive force distribution control for an EV driven by four wheel motors, thereby improving vehicle handling and stability. In this paper, a backstepping controller for 4 wheels electric vehicle speed is proposed. The reminder of this paper is organized as follows. Section (2) reviews the brief description of the Electric traction chain. Section (3) shows the direct field-oriented control (FOC) of induction motor. Section (4) shows the development of backstepping controller design for Electric vehicle. Section (5) gives some simulation results of the different studied cases. Finally, the conclusion is drawn in section (6).

Nomenclature

IM	Induction motor.
FOC	field-oriented control.
EVs	Electric vehicles.
PWM	Pulse Modulation Width.
4WD	Four wheel drive.
EV	Electric vehicle
EVs	Electric Vehicles

2. Electric traction system of four wheel electric vehicle description:

Figure 1 presents the general diagram of one wheel of the electric vehicle globally system using an induction motor (IM) supplied by voltage inverter, the power sources is the lithium-ions battery [4, 8]. The globally traction chain of the 4WD electric vehicle is presented in Fig. 2. The speed references computation of driving wheels is made using an electronic differential [2, 7, 8, 10, 11, 12] as it shown in Fig. 3.

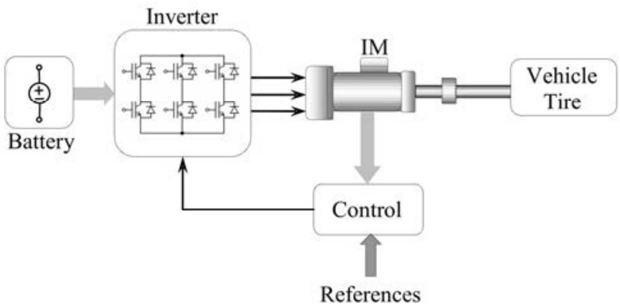

Fig. 1. Electrical traction chain for one wheel motor.

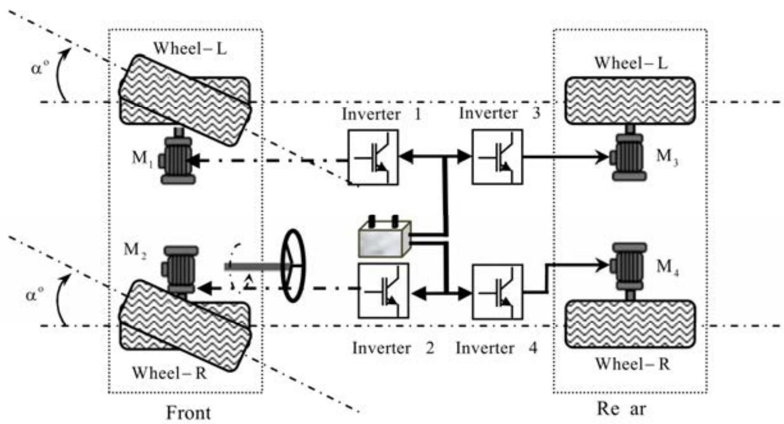

Fig. 2. Electric vehicle with Four-independent-wheels drive.

2.1. Propulsion Motor of four wheels drive electric vehicle

The propulsion motor used consist of three phase induction motor (IM) supplied by a voltage inverter controlled by Pulse Width Modulation (PWM) techniques. The dynamic model of three-phase, Y-connected induction motor can be expressed in the d-q synchronously rotating frame as [7, 9, 13, 15, 16,18]:

$$\begin{cases} \dfrac{di_{ds}}{dt} = \dfrac{1}{\sigma.L_s}.\left(-\left(R_s + \left(\dfrac{L_m}{L_r}\right)^2.R_r\right).i_{ds} + \sigma.L_s.\omega_e.i_{qs} + \dfrac{L_m.R_r}{L_r^2}.\varphi_{dr} + \dfrac{L_m}{L_r}.\varphi_{qr}.\omega_r + V_{ds}\right) \\ \dfrac{di_{qs}}{dt} = \dfrac{1}{\sigma.L_s}.\left(-\sigma.L_s.\omega_e.i_{ds} - \left(R_s + \left(\dfrac{L_m}{L_r}\right)^2.R_r\right).i_{qs} - \dfrac{L_m}{L_r}.\varphi_{dr}.\omega_r + \dfrac{L_m.R_r}{L_r^2}.\varphi_{qr} + V_{qs}\right) \\ \dfrac{d\varphi_{dr}}{dt} = \dfrac{L_m.R_r}{L_r}.i_{ds} - \dfrac{R_r}{L_r}.\varphi_{dr} + \left(\omega_e - \omega_r\right).\varphi_{dr} \\ \dfrac{d\varphi_{qr}}{dt} = \dfrac{L_m.R_r}{L_r}.i_{qs} - \left(\omega_e - \omega_r\right).\varphi_{dr} - \dfrac{R_r}{L_r}.\varphi_{qr} \\ \dfrac{d\omega_r}{dt} = \dfrac{3}{2}\dfrac{P^2.L_m}{L_r.J}.\left(i_{qs}.\varphi_{dr} - i_{ds}.\varphi_{qr}\right) - \dfrac{f_c}{J}.\omega_r - \dfrac{P}{J}.T_l \end{cases} \tag{1}$$

Where σ is the coefficient of dispersion and is given by (1):

$$\sigma = 1\,\frac{L_m^2}{L_s L_r} \tag{2}$$

L_s , L_r , L_m	stator, rotor and mutual inductances;
R_s , R_r	stator and rotor resistances;
ω_e, ω_r	electrical and rotor angular frequency;
ω_{sl}	slip frequency $\left(\omega_e - \omega_r\right)$;
τ_r	rotor time constant $\left(L_r / R_r\right)$;

P pole pairs.

2.2. The 4WD electric vehicle Load's

The vehicle mechanical load is characterized by many resistive torques [4, 5, 14, 15, 17,18] such as :
The aerodynamics torque is :

$$T_{aero} = \frac{1}{2}\rho S.T_x.R_r^3.w_r^2 \tag{3}$$

The slope torque is:

$$T_{slope} = Mg.\sin\alpha \tag{4}$$

The maximal torque of the tire which can be opposed to the motion has the following expression:

$$T_{tire} = Mgf_r.R_r \tag{5}$$

The *total resistive torque:*

$$T_v = T_{slope} + T_{tire} + T_{aero} \tag{6}$$

The modeling of the traction system allows the implementation of some controls such as the vector control and the speed control in order to ensure the globally system stability [19, 20].

3. Vector control of one wheel induction motor

The main objective of the vector control of induction motors is to control independently the flux and he torque as DC machines [6]. In ideally field-oriented control, the rotor flux linkage axis is forced to align with the d-axes, and it follows that [3, 6, 10, 14]:

$$\varphi_{rq} = \frac{d\varphi_{rq}}{dt} = 0 \tag{7}$$

$$\varphi_{rd} = \varphi_r = cons\tan t \tag{8}$$

Consequently, the dynamic equations (1) yield:

$$\begin{cases} \dfrac{di_{ds}}{dt} = \left(\dfrac{R_s}{\sigma L_s} + \dfrac{1\sigma}{\sigma\tau_r}\right) i_{ds} + \omega_e i_{qs} + \dfrac{L_m}{\sigma L_s L_r \tau_r}\varphi_{rd} + \dfrac{1}{\sigma L_s} V_{ds} \\ \dfrac{di_{qs}}{dt} = \left(\dfrac{R_s}{\sigma L_s} + \dfrac{1\sigma}{\sigma\tau_r}\right) i_{qs}\ \omega_e i_{ds} + \dfrac{L_m}{\sigma L_s L_r \tau_r}\varphi_{rd} + \dfrac{1}{\sigma L_s} V_{ds} \\ \dfrac{d\varphi_r}{dt} = \dfrac{L_m}{\tau_r} i_{ds}\ \dfrac{1}{\tau_r}\varphi_{rd} \\ \dfrac{d\omega_r}{dt} = \dfrac{3}{2}\dfrac{P^2 L_m}{J L_r} i_{qs}\varphi_{rd}\ \dfrac{f_c}{J}\omega_r\ \dfrac{P}{J} T_l \end{cases} \tag{9}$$

4. The uses of Backstepping aproach on in-wheel induction motor

In this section we use the backstepping algorithm [3, 5, 6, 10, 12] to develop the speed control law of the induction motor. This speed will converge to the reference value from a wide set of initial conditions.

Step 1: Firstly we consider the tracking error of the direct current (φ_{dr}). A tracking error $z_1 = \varphi_{dr}^* - \varphi_{dr}$ is defined and the derivative becomes:

$$\dot{z}_1 = \frac{d\varphi_{dr}^*}{dt} - \frac{R_r}{L_r} \cdot \left(L_m \cdot i_{ds} - \varphi_{dr} \right) \tag{10}$$

To initiate backstepping, we propose i_{ds} as a first virtual control. the function stability is proposed as follow:

$$i_{ds}^* = \frac{\varphi_{dr}}{L_m} + c_1 \cdot \frac{\tau_r}{L_m} \cdot z_1 + \tau_r \cdot \frac{d\varphi_{dr}}{dt} \tag{11}$$

so we obtain: $$\dot{z}_1 = c_1 \cdot z_1 + \frac{1}{\tau_r} \cdot \left(i_{ds} - i_{ds}^* \right) \tag{12}$$

Due to the fact that i_{ds} is not a control input novel error variable $z_2 = i_{ds} - i_{ds}^*$ is defined

Step 2: The derivative of the error variable $z_2 = i_{ds} - i_{ds}^*$ is:

$$\begin{aligned}\dot{z}_2 = &-\frac{L_m}{\tau_r} \cdot \left(L_m \cdot i_{ds} - \varphi_{dr} \right) + c_1 \cdot \left(i_{ds} - \frac{\varphi_{dr}}{L_m} - \tau_r \cdot \frac{d\varphi_{dr}^*}{dt} \right) - \frac{\tau_r}{L_m} \cdot \frac{d^2\varphi_{dr}}{dt^2} + \frac{1}{\sigma \cdot L_s} \cdot V_{ds} \\ &- \frac{1}{\sigma \cdot L_s} \left(R_r \cdot i_{ds} - w_e \cdot \sigma \cdot L_s \cdot i_{qs} + \left(\frac{L_m}{L_r} \right)^2 \cdot R_r \cdot \left(i_{ds} - \frac{\hat{\varphi}_{dr}}{L_m} \right) \right) \\ &+ \frac{\left(\frac{L_m}{L_r} \right)^2 \cdot R_r}{\sigma \cdot L_s} \cdot \frac{\varphi_{dr}}{L_m} + w_r \cdot \frac{L_m}{\sigma \cdot L_s \cdot L_r} \cdot \varphi_{qr}\end{aligned} \tag{13}$$

Viewing φ_{dr} and φ_{ar} as unknown disturbances we apply nonlinear damping [5, 6, 11] to design the control function:

$$\begin{aligned}\frac{1}{\sigma \cdot L_s} \cdot V_{sd} = &\frac{1}{\sigma \cdot L_s} \left(R_s \cdot i_{ds} - w_e \cdot \sigma \cdot L_s \cdot i_{qs} + \left(\frac{L_m}{L_r} \right)^2 \cdot R_r \cdot \left(i_{ds} - \frac{\hat{\varphi}_{dr}}{L_m} \right) \right) \\ &\cdot \left(\frac{1}{\tau_r} - c_1 \right) \cdot \left(i_{ds} - \frac{\hat{\varphi}_{dr}}{L_m} \right) + c_1 \frac{\tau_r}{L_m} \cdot \frac{d\varphi_{dr}^*}{dt} + \frac{\tau_r}{L_m} \cdot \frac{d^2\varphi_{dr}^*}{dt^2} \\ &- c_2 \cdot z_2 - \frac{1}{\tau_r} \cdot z_1 - d_2 \cdot \left\{ \left(\frac{\left(L_m / L_e \right)^2 R_r}{\sigma L_s} \right)^2 + \left(w_r \cdot \frac{(1-\sigma)}{\sigma} \right)^2 \right\} \cdot z_2\end{aligned} \tag{14}$$

We define:

$$\varphi_1 = \frac{\left(L_m/L_r\right)^2 \cdot R_r}{\sigma \cdot L_s}, \qquad \varphi_2 = w_r \cdot \frac{L_m^2/L_r}{\sigma \cdot L_s} \qquad \text{and} \qquad \varphi^2 = \varphi_1^2 + \varphi_2^2 .$$

Step 3: We find the torque tracking error. The tracking error is maintain for $\varphi_{dr} \neq 0$ defined as:

$$z_3 = i_{qs} - \frac{T_e^*}{\left(P \cdot \frac{L_m}{L_r} \cdot \varphi_{dr}\right)} \tag{15}$$

φ_{dr} and φ_{ar} as unknown disturbances we apply nonlinear damping [5, 6, 10, 11, 12] to design the control function:

$$\begin{aligned} \frac{1}{\sigma \cdot L_s} \cdot V_{qs} = & \frac{1}{\sigma \cdot L_s} \cdot \Big(R_s \cdot i_{qs} - w_e \cdot \sigma \cdot L_s \cdot i_{qs} + \left(L_m/L_r\right)^2 \cdot R_r \cdot i_{qs} \\ & + w_r \cdot (1-\sigma) \cdot L_s \cdot \frac{\hat{\varphi}_{dr}}{L_m} \Big) - \frac{2 \cdot L_r \cdot T_e^*}{3 \cdot P \cdot \varphi_{dr}} \cdot \frac{1}{T_r} \cdot \left(i_{ds} - \frac{\hat{\varphi}_{dr}}{L_m} \right) + \frac{2 \cdot L_r}{3 \cdot P \cdot L_m \cdot \hat{\varphi}_{dr}} \cdot \frac{dT_e^*}{dt} \\ & - c_3 \cdot z_3 - d_3 \cdot \left\{ \left(\frac{\left(L_m/L_r\right)^2 \cdot R_r}{\sigma \cdot L_s} \right)^2 + \left(w_r \cdot \frac{(1-\sigma)}{\sigma} \right)^2 \right\} \cdot z_3 \end{aligned} \tag{16}$$

4.1. Linear Speed control of Electric Vehicle Induction and stator quadratic current estimation

To control speed of the vehicle motorization, we consider i_{qs}^* as the control law, so tracking error is defined as:

$$z_0 = \omega_r^* \ \omega_r \tag{17}$$

So, it's derivate is given as: $\dot{z}_0 = \dot{\omega}_r^* - \dot{\omega}_r$ (18)

$$\dot{z}_0 = \dot{\omega}_r^* - \left[\frac{3}{2} \frac{P^2 \cdot L_m}{L_r \cdot J} \cdot i_{qs} \cdot \varphi_{dr} - \frac{f_c}{J} \cdot \omega_r - \frac{P}{J} \cdot T_l \right] \tag{19}$$

The control law obtained as:

$$i_{qs}^* = \frac{2}{3} \frac{L_r \cdot f_c}{P^2 \cdot L_m \cdot \varphi_{dr}} \cdot \omega_r + c_0 \frac{2 \cdot L_r \cdot J}{3 \cdot P^2 \cdot L_m \cdot \varphi_{dr}} z_0 + \frac{2}{3} \frac{L_r}{P \cdot L_m} \cdot T_l \tag{20}$$

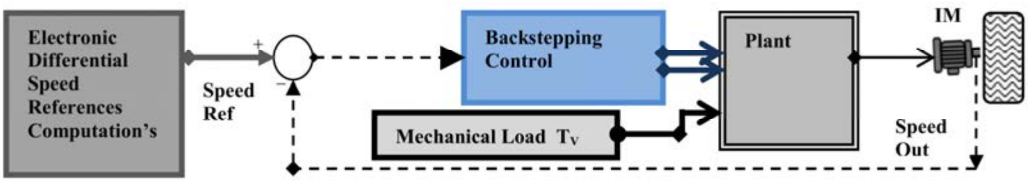

Fig.3. Speed Backsteeping Control Schema of One wheel Electric Vehicle.

5. Simulations Results

In order to show the driving wheel system performances, simulations were carried using the model of figure 2 and 3. They show vehicle speed variation for backstepping and classical PI controllers in the following road trajectory:

- Curved road at right side at 3 sec then left side's at 4 sec, the vehicle move in slope (mountain) road at 2 sec with speed of 70km/h. Simulation were carried on Matlab Simulink for both of classical PI control and robust backstepping control, we obtain the following results:

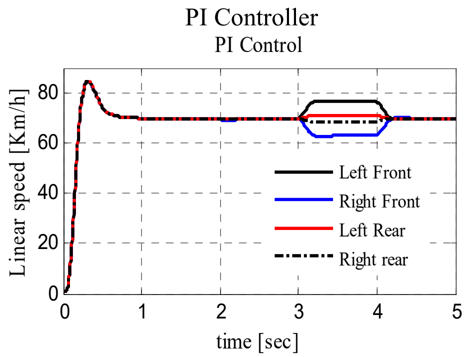

Fig.4. Four wheels electric Vehicle linear speed (PI).

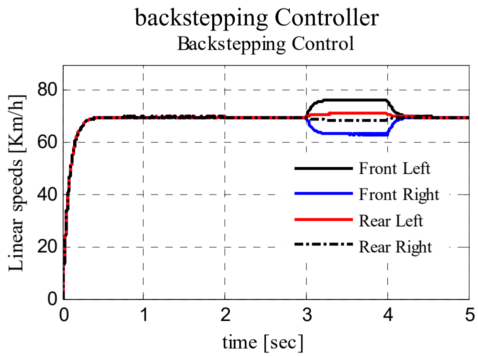

Fig.5. Four wheels electric Vehicle linear speed (backstepping).

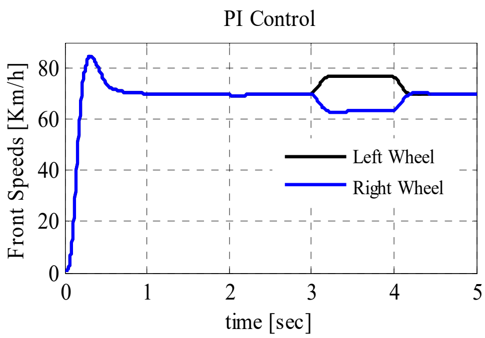

Fig.6. Vehicle Front linear speeds (PI).

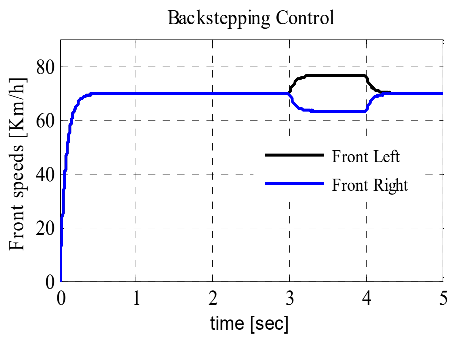

Fig.7. Front wheels linear speeds (backstepping).

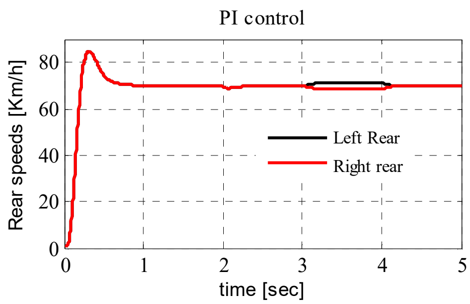

Fig.8. Vehicle Rear linear speeds (PI).

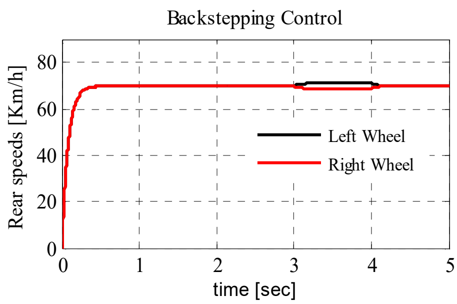

Fig.9. Rear wheels linear speeds (backstepping).

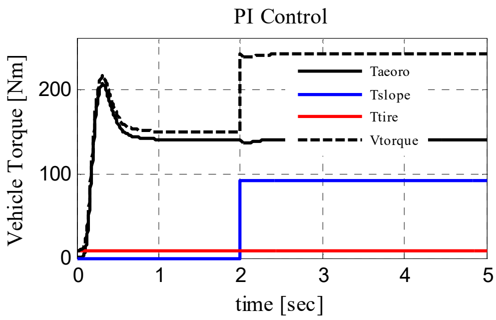

Fig.10. Vehicle resistive torques (PI).

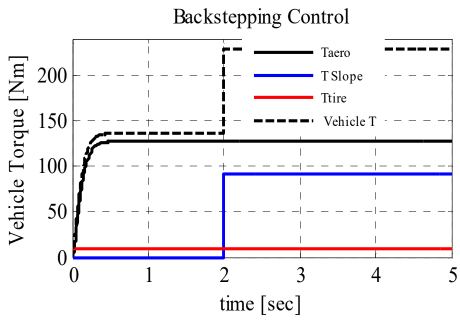

Fig.11.Vehicle resistive torques (backstepping).

According to the obtained results it's appear clearly the efficiency of the backstepping control compared with classical PI one, for example when we look for figures 4 and 5 it's easy to say that the bakcstepping control give more robustness for the electric vehicle and more and more safety to the globally system with good rising time and no overshoot and with easy and good driving on slope road. As it shown also in figures 6 and 7 the slope road affect the dynamic performances in classical PI controller and the vehicle driver have many difficulties to stabilize the vehicle moving on slope (at time 2 sec) or in curved road at time (3 and 4 sec) and the vehicle risk to exit the curved road, the impact of slope and the globally vehicle torque is clearly justified in figures 10 and 11.

As general idea on the presented control, the results presented with the backstepping control applied on four wheels drives moving in different regions road's present satisfactory and we say that the four have more and more stability with the proposed control.

6. Conclusions

The present work shows the efficiency of the non linear control such as the backstepping in the field of electric drives with variable speed. An application of the electric vehicle controlled by an electronic differential is presented. The research outlined in this paper has demonstrated the feasibility of an improved vehicle stability which utilizes two independent back drive wheels for motion by using the backstepping control. This paper proposes an "independent machine's" control structure applied to a propulsion system by the backstepping speed control law. The results obtained by simulation show that this structure permits the realization of an robust control based on Lyapunov feedback control which ensures good dynamic and static performances, however a good rising time, good disturbance rejection's response with no over shoot. The proposed backstepping model controls the driving wheels speeds with high accuracy either in flat roads or curved ones and gives more and more safety to the electric vehicle drive in any slope and the disturbances do not affect the performances of the driving motors, the exciting result obtained by the feedback control is the absence of the overshoot and the tracking error.

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