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Sliding Mode Control for Four Wheels Electric Vehicle Drive

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Abstract

In this research a novel control schema of four wheels drive (4WD) propulsion system control is presented. The present paper introduces novel studies of sliding mode control applied on four independent wheels electric vehicle systems. The proposed propulsion system consists of four Induction Motors (IM) that ensure the driving of back and front driving wheels. This vehicle uses an electronic differential for speeds reference computations of four wheels. The electronic differential system ensures the robust control of the vehicle behaviour on the road; it also allows controlling, independently, every driving wheel to turn at different speeds in any curve. The result obtained is satisfactory for our electric vehicle sliding mode control's simulated in Matlab Simulink environment. It shows the efficiency of the proposed control comparing with classical PI controller with no overshoot. The rising time is perfected with good disturbances rejections.

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Keywords: 4WD; electric vehicle; induction motor; PI controller; sliding mode control.

1. Introduction

Electric vehicles (EVs) are developing fast during this decade due to drastic issues on the protection of environment and the shortage of energy sources. While commercial hybrid cars have been rapidly exposed on the market, fuel-cell-powered vehicles are also announced to appear in 5–10 years. 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 their configurations, functions or power sources. Pure EVs do not use petroleum, while hybrid cars take advantages of energy management between gas and electricity [1, 3]. Indirectly

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driven EVs are powered by electric motors through transmission and differential gears, while directly driven vehicles are propelled by in-wheel or, simply, wheel motors [2, 6]. The basic vehicle configuration of this research has four directly driven wheel motors installed and operated inside the driving wheels on a pure EV [3, 8, 9]. 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 [5, 6]. Like most research on the torque distribution control of wheel motor, wheel motors [3] proposed a dynamic optimal tactile force distribution control for an EV driven by four wheel motors, thereby improving vehicle handling and stability [5]. The researchers assumed that wheel motors were all identical with the same torque constant; neglecting motor dynamics the output torque was simply proportional to the input current with a prescribed torque constant. In this paper, a sliding mode decoupling controller for electric vehicle control is proposed. The reminder of this paper is organized as follows: Section 2 reviews the description of the principle components of Electric traction chain. Section 3 shows the indirect field-oriented control (IFOC) of induction motor. Section 4 shows the development of sliding mode controllers design for Electric vehicle. Section 5 gives some simulation results carried on Matlab Simulink software. Finally, the conclusion is drawn in Section 6.

Nomenclature

SMC	Sliding Mode Control
IFOC	Indirect Field Oriented Control
EVs	Electric vehicles.
PWM	Pulse Modulation Width
IM	Induction Motor

2. Electric traction system modelling and description

Fig.1 presents the general schema of four wheels electric vehicle using induction motor for motion (IM) supplied by voltage inverter [3, 5, 6, 9, 10].

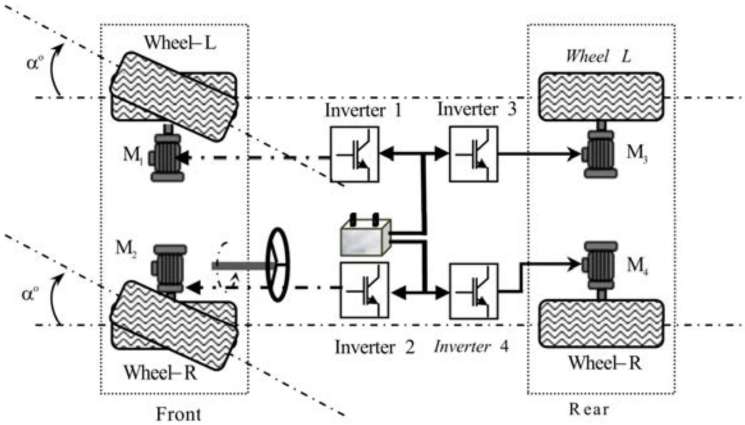

Fig.1. Electrical Propulsion system of four wheels electric vehicle chain.

The battery used in this paper is Lithium-Ion battery accumulator, a simplified version of the complex battery model reported in [11]. In this electric traction system, we use Pulse Modulation Width (PWM) techniques to obtain three balanced alternating current phases with variable frequency from the current battery:

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \frac{U_{dc}}{2} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \tag{1}$$

The logic S_i of the switches is obtained by comparing the control inverter signals with the modulation's signal.The employed motor is a three phase Induction Motor type (IM). A model based on circuit equivalent equations is generally sufficient in order to make control synthesis [4, 9, 10, 11]. The speeds references of four driving wheels are computed using an electronic differential [3, 5, 6, 8, 14].

2.1. Mechanical load of the studied four wheels electric vehicle

The vehicle's considered mechanical load is characterized by three resistive torques [4, 9, 10, 11] that includes:

1. The aerodynamics torque: $T_{aero} = 1/2\,\rho S.T_x.R_r^3.w_r^2$ (2)
2. The slope torque is given as : $T_{slope} = Mg.\sin\alpha$ (3)
3. The maximal torque of the tire which can be opposed to the motion has the following expression:
   $T_{\max} = Mgf_r.R_r$ (4)

We obtain finally the total resistive torque: $T_v = T_{slope} + T_{tire} + T_{aero}$ (5)

The modelling 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 [16, 17].

3. The vector control (IFOC)

The main objective of the vector control of induction motors is, to control independently the flux and the torque as DC machines. This is done by using a *d-q* rotating reference frame synchronously with the rotor flux space vector [4, 7, 12, 13, 15]. According to the above analysis, the indirect field-oriented control (IFOC) [4, 7, 13] of induction motor with current-regulated PWM inverter control system is presented by the block diagram shown in the Fig.2 we use the classical regulator for IFOC tuning control parameter.

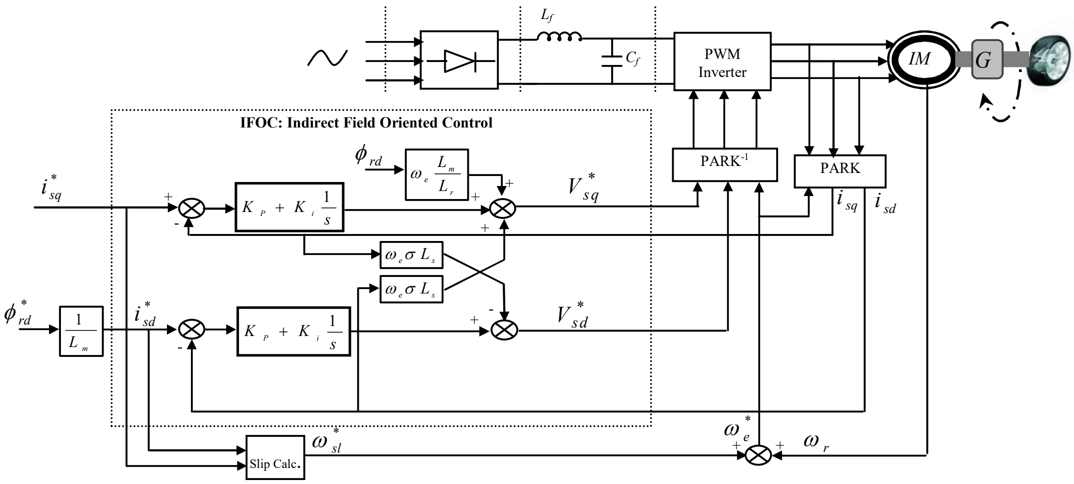

Fig. 2. IFOC strategy for one wheel induction motor

4. Sliding Mode Control (SMC)

Sliding modes control is phenomenon that may appear in a dynamic system governed by ordinary differential equations with discontinuous right-hand sides. It may happen that the control as a function of the system state switches at high frequency, and this motion is called sliding mode. It may be enforced in the simplest tracking relay system with the state variable [4, 7, 12, 13, 15, 11, 16, 18]:

$$x(t)\ \frac{\partial x}{\partial t} = f(x) + u \tag{6}$$

With the bounded function $f(x)$ Sliding Mode Control (SMC) $|f(x)| < f_0$; f_0 is constant and the control as a relay function of the tracking error $e = r(t) - \partial x/\partial t$; $r(t)$ is the reference input, and u is given by:

$$u = \begin{cases} +u_0 & ;if \quad e > 0 \\ -u_0 & ;if \quad e < 0 \end{cases} \tag{7}$$

Or: $u = u_0 sign(e)$; where u is constant. Fig.3 shows the relay control scheme:

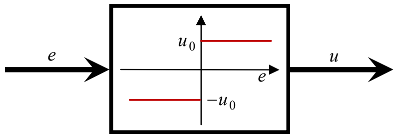

Fig.3. Relay control.

The values of e and $\partial e/\partial t = \dot{e} = \dot{r} - f(x) - u_0 sign(e)$, according to Lyapunov stability criteria, the system's stable if it does verify the following condition: $e.\dot{e} < 0$, by means that we have the different signs if $u_0 > f_0 + |\dot{r}|$, and finally u_0 must be positive constant.

4.1. Design of sliding mode speed and current controller

The speed error is de fined by [4, 12, 13, 15, 11]: $e = w_{ref} - w$ (8)

The derivative of the sliding surface can be given as: $\dot{s}(\omega) = \dot{\omega}_r^* - \dot{\omega}_r$ (9)

From equation cited in [4], we can obtain:

$$\dot{s}(\omega_m) = \dot{\omega}_m^* - \left(\frac{3}{2} \frac{P^2 L_m \varphi_{dr}^*}{J L_r} . i_{qs} - \frac{f_c}{J} \dot{\omega}_m - \frac{P}{J} T_l \right) \tag{10}$$

The current control is given by: $i_{qs} = i_{qs}^{equ} + i_{qs}^{n}$ (11)

To avoid the chattering phenomenon produced by the $Signs$ function we use the Saturation function Sat in the discontinuous control defined as follow:

$$sat\left(\frac{S}{\varphi}\right) = \begin{cases} \dfrac{S}{\varphi} & ; \quad if \quad \left|\dfrac{S}{\varphi}\right| < 1 \\ Sign\left(\dfrac{S}{\varphi}\right) & ; \quad if \quad \left|\dfrac{S}{\varphi}\right| > 1 \end{cases}$$

The discontinuous control action can be given as: $i_{qs}^{n} = k_{iqs} \cdot sat(s(\omega)/\phi_\omega)$ (12)

k_{iqs} : Positive constant. The curent control is defined by: $i_{qs}^{equ} = \dfrac{2}{3} \dfrac{J L_r}{P^2 L_m \varphi_{dr}^*} \left(\dot{\omega}_m^* + \dfrac{f_c}{J} \omega_m + \dfrac{P}{J} T_l \right)$ (13)

The Fig.4 shows the SMC control strategy scheme for one wheel electric traction chain.

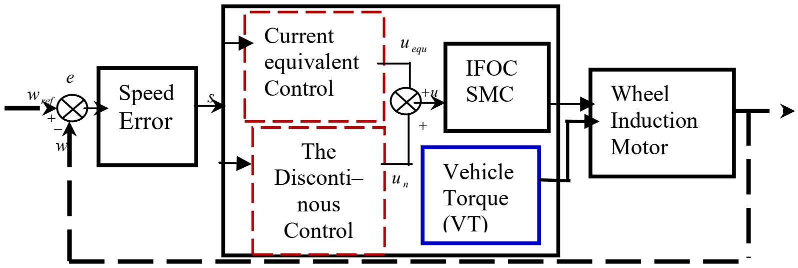

Fig. 4. The SMC control strategy schema for one wheel electric vehicle.

For the IFOC tuning parameters we need two surfaces S_1 and S_2 the first for the i_{ds} regulator and the second for i_{qs} regulator respectively where:

$$s_1 = i_{ds}^* - i_{ds} \tag{14}$$

$$s_2 = i_{qs}^* - i_{qs} \tag{15}$$

The derivate of S_1 can be given as: $\dot{s}_1 = \dot{i}_{ds}^* - \dot{i}_{ds}$. From equation cited in [4] and (15) we can obtain :

$$\dot{s}_1 = \dot{i}_{ds}^* - \left[-\left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma \tau_r} \right) i_{ds} + \omega_e i_{qs} + \frac{L_m}{\sigma L_s L_r \tau_r} \varphi_{rd} + \frac{1}{\sigma L_s} V_{ds} \right]$$

The virtual voltage controller V_{ds} is given by: $V_{ds} = V_{ds}^{equ} + V_{ds}^{n}$ (16)

The voltage discontinuous control V_{ds}^n is defined as: $V_{ds}^n = k_1 \cdot sat(s_1/\phi_1)$ (17)

According to lyapunov stability criteria [12, 13, 15] our speed loop system's sable if: $s_1 \dot{s}_1 < 0$ by means that K_1 is positive constant. The equivalent control V_{ds}^{equ} is given as:

$$V_{ds}^{equ} = \sigma.L_s \left(\dot{i}_{ds}^* + \frac{1}{\sigma.L_s} \left(R_s + R_r . \left(\frac{L_m}{L_r} \right)^2 \right) .i_{ds} - w_s .i_{qs} - \frac{L_m . R_r}{\sigma.L_s L_r^2} \varphi_r^* \right) \tag{18}$$

The derivate of S_2 can be given as: $\dot{s}_2 = \dot{i}_{qs}^* - \dot{i}_{qs}$, From equation cited in [4] and (16) we can obtain:

$$\dot{s}_2 = \dot{i}_{qs}^* - \left[-\left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma \tau_r} \right) i_{qs} - \omega_e i_{ds} + \frac{L_m}{\sigma L_s L_r \tau_r} \varphi_{rd} + \frac{1}{\sigma L_s} V_{qs} \right]$$

The voltage controller V_{qs} is given by: $V_{qs} = V_{qs}^{equ} + V_{qs}^{n}$ (19)

The V_{qs}^{equ} equivalent control defined as:

$$V_{qs}^{equ} = \sigma.L_s .[i^*_{qs} + \omega_s .i_{ds} + \frac{1}{\sigma.L_s} \left(R_s + R_r \left(\frac{L_m}{L_r} \right)^2 \right) .i_{qs} + \frac{L_m}{\sigma L_s L_r} \varphi_r^* \omega_m] \tag{20}$$

The voltage discontinuous control V_{ds}^{n} is defined as: $V_{qs}^{n} = k_2 \cdot sat\left(s_2/\phi_2\right)$ (21)

For the same reason condition of K_1 : K_2 are positives constant.

5. Simulation Results

In order to characterize the driving wheel system behavior, simulations were carried on Matlab using the model of Fig.5.

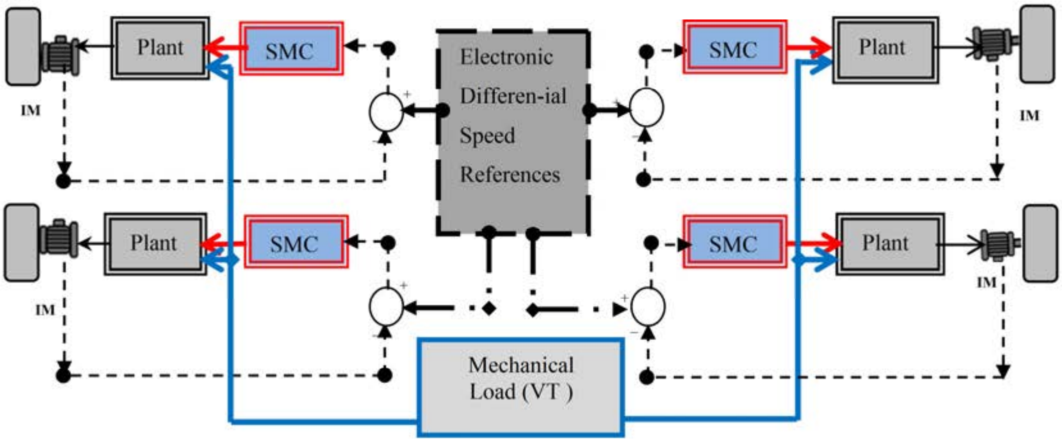

Fig. 5. Four wheels electric vehicle simulated model.

They show vehicle speed variation for PI and the Sliding mode controllers for the same linear speed of 60km/h and under the same conditions. For the test, the vehicle change linear speed from 60 to 80 km/h at time 2 sec and enter curded road at right side at 3 sec and another curve at left side at 4 sec and four motors are not distrusted in the beginning as assumptions.

According to the obtained results we can say that in classical PI controller the globally vehicle resistive torque became 175 NM, when the vehicle resistive torque is only 52.2 NM. In Sliding mode controller in the same conditions, by means 175/52.2 = 3.35 ,the vehicle stability became very difficult especially in the speed variation at time (2 Sec). In this critical situation the vehicle risk to lose the global stability before the beginning of the two curves (at 3 and 4 Sec respectively), by means the aerodynamic torque in PI cases became very important and equal 3.35 of aerodynamic torque in SMC cases, the travelled distance in PI case's is only 352 meters when the travelled distance in SMC cases became 400 meters with gain of 50 meters and that's justify the efficiency of control algorithm and improve the control loop robustness, instead of using classical control, we use the sliding mode the torque load changes in two cases (PI and SMC).

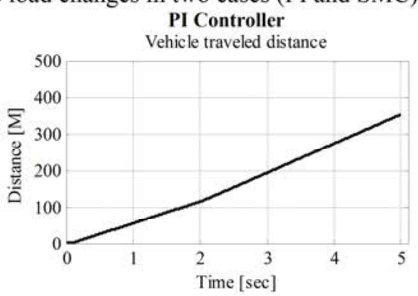

Fig. 6.Vehicle travelled distance in PI case's.

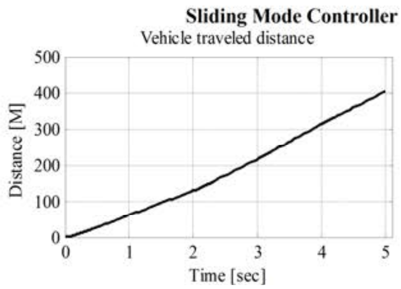

Fig. 7. Vehicle travelled distance in SMC case's.

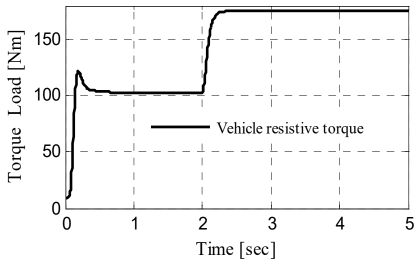

Fig. 8. Vehicle Resistive torque in PI case's.

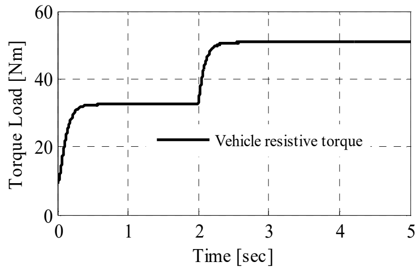

Fig. 9. Vehicle Resistive torque in SMC case's.

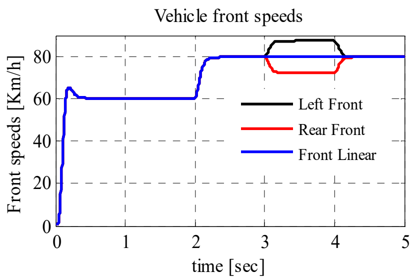

Fig. 10. Vehicle Front speeds in PI case's.

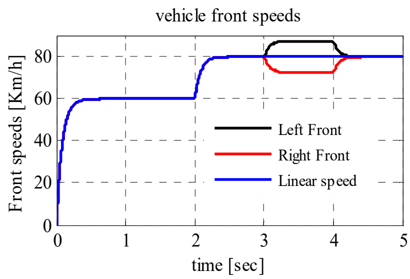

Fig. 11. Vehicle Front speeds in SMC case's.

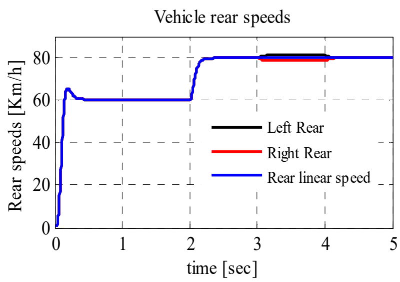

Fig. 12. Vehicle Rear speeds in PI case's.

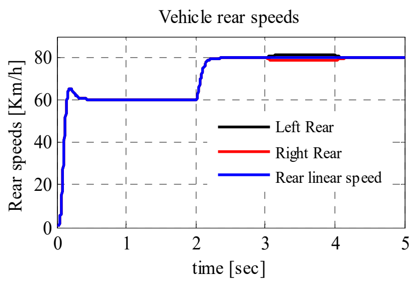

Fig. 13. Vehicle Rear speeds in SMC case's.

In this paper appears clearly the advantage of the SMC control such as its robustness, its capacity to maintain ideal trajectories for four wheel control independently and ensure good disturbances rejections with no overshoot and stability of vehicle perfected ensured with the speed variation and less error speed. To compare the effect of in two cases, the Table1 summaries the obtained results given bellow:

Table 1: Performances of the PI & SMC controllers in the speed loop response.

Results	Torque load (Nm)	Overtaking (exist)	Travelled distance (Meter)	Time of curved road
PI	175	yes	395,5	At 3 Sec (right side) and 4 Sec (left side)
SMC	52,2	0	352	At 3 Sec (right side) and 4 Sec (left side)

To show more and more performances of the proposed control, Figs 14 and 15 gives the driving forces variations of the front and rears driving wheels, and Figs 16 and 17 show the electromagnetic torques variations of the front and rear driving wheels.

6. Conclusions

The research proposed in this paper has demonstrate the possibility of an improved four wheel vehicle stability which uses four independent drive wheels for motion by using the sliding mode control.

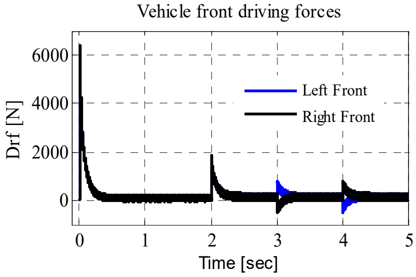

Fig. 14. Vehicle front driving forces.

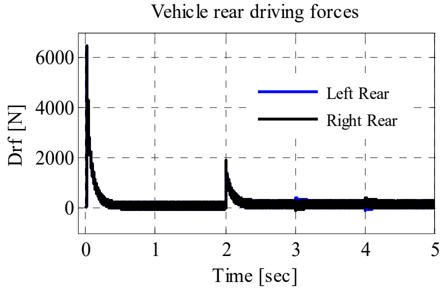

Fig. 15. Vehicle rear driving forces

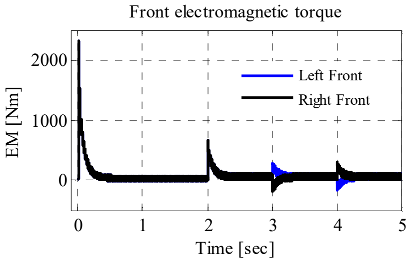

Fig. 16. Vehicle front driving forces.

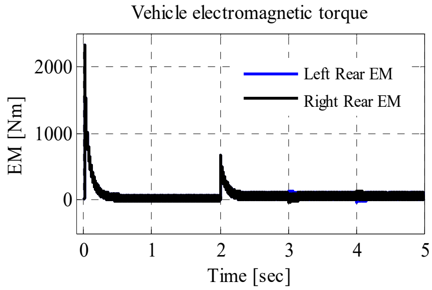

Fig. 17. Vehicle rear driving forces

The studied four wheels independent wheel control approach structure applied to the electric chain system using the sliding mode speed control ensure the driving on slope with high safety conditions. The results obtained by Matlab simulation proves that this structure permits the realization of robust control loop speed based on Lyapunov switching surface with a good dynamic performances of electric vehicle. The proposed sliding mode model controls the driving wheels speeds with high accuracy in flat roads or curved ones in each case. The slope's road does not affect the performances of the driving motor wheels stability comparing with the PI classical controller.

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