

Novel Propulsion System Applied for Four Wheels Electric Vehicle Using Hybrid Fuzzy Sliding Mode Controller

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Abstract: In this work an hybrid control schema of four wheels drive (4WD) propulsion system control is presented. This present paper introduces novel studies of hybrid sliding mode control applied on (4WD) four independent wheels electric vehicle systems, the proposed propulsion system consists of four Induction independent motors that ensure the driving of back and front driving wheels. The proposed control structure use an electronic differential for speeds reference computations of four wheels. This Novel four propulsion is studied and tested using hybrid Fuzzy-sliding mode control (FSMC) strategy for the electric vehicle driving wheels, to improve stability, in which the fuzzy logic system replace the discontinuous control action of the classical SMC law. Our electric vehicle sliding mode control's simulated in Matlab Simulink environment, the result obtained present satisfactory and show the efficiency of the proposed control comparing with classical PI controller with no overshoot, the rising time is perfected with good disturbances rejections.

Keywords: FSMC, SMC, PI,4WD, Electronic Differential.

1. Introduction

An electric automobile is car propelled by one or many electric motors, using electrical energy stored in batteries or another power source. Electric motors give an instant torque to the vehicle, creating an acceleration[1]. EV can be classified into various categories according to their configurations, functions of power sources. The first invented electric car is attributed to many people.[2,3] In 1828, Ányos Jedlik, a invented a small model car powered by his new motor[3]. In 1834, Vermont blacksmith built a similar contraption which operated on a short, circular, electrified track.[4]. In 1890 William Morrison present the first four-wheel electric road model in America to demonstrate his battery[5]. Four years ago Henry G. Morris and Pedro G. Salom in Philadelphia design a heavy four-wheel electric wagon similar to the Morrison car. It runs at 15 mph. They were designers of battery streetcars and saw potential in electrifying smaller road vehicles.[4,5] In 1899 to Fred J. Newman and Joseph Ledwinka build a four-wheel drive prototype in New Jersey.[5] A small number of Lohner-Porsche four-wheel drive version, were produced in 1900. The next few years' production included hybrid cars, some of which could reach top speeds of 35 mph.[5,7]. Ten years ago the first hybrid car was released. The hybrid was a commercial failure because of it's cost. Researches on the power propulsion system of EV have drawn significant attention in the automobile industry. Fuel cell development and power electronics essorts made four wheels drive in competitions. The basic vehicle configuration of this research has four directly driven wheel motors installed and operated inside the driving wheels on a pure EV[6,7,8]. 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[5,6,7]. Like most research on the torque distribution control of wheel motor, many researches were made on the electric vehicle linear speed control improvement, in this way we propose a novel demonstration on four wheels drive using an hybrid robust control based on fuzzy sliding mode controller FSMC for real estimation of driving force and optimal distribution current control for an EV driven by four wheel motors, thereby improving vehicle handling and stability[5,7,8]. The

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assumption of this work that four motors are not disturbed in the beginning of test that wheel motors were all identical with the same torque constant. In this paper, a fuzzy-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 and the fuzzy-sliding mode controller. Section 5 gives some simulation results carried on Matlab. Finally, the conclusion is drawn in section 6.

Nomenclature

Abbreviation

SMC

ED

FSMC

IFOC

IM

FLC

EV

4WD

PWM

DC

PI

Nomenclature

Sliding Mode Controller

Electronic Differential

Fuzzy-Sliding mode Control

Indirect Field Oriented Control

Induction Motor

Fuzzy Logic Controller

Electric Vehicle

Four Wheels Drive

Pulse Modulation Width

Direct Current

Proportional Integral

2. Four wheel electric vehicle modelling and description

The general schema of the four wheel drive propulsion system is shown on Figure 1, the following structure presents an multi motor system using four induction motors for motion (IM), each motor is connected to the wheel forming an in-wheel motor, this technology is widely used in electric traction to reduces motions losses, the in-wheel motor system is supplied by voltage inverter [7,8,9,10].

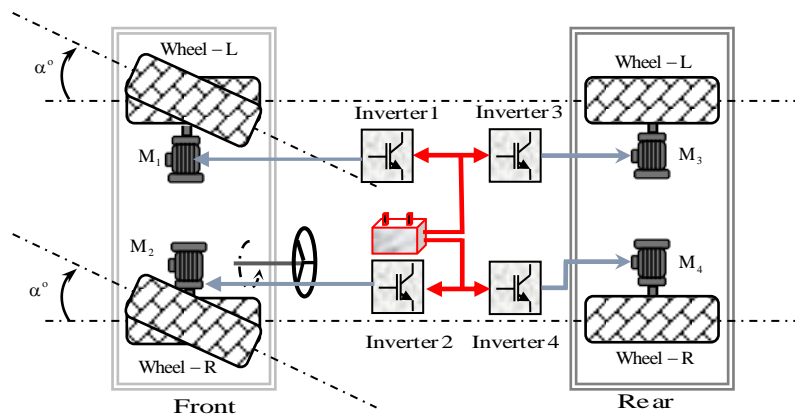


Figure 1. Electrical Propulsion system of four wheels electric vehicle system

The most power sources used in electric vehicle, is accumulators, in this work we use Lithium-Ion battery for it's high performance on charging-discharging and high autonomous [10]. In this electric traction system, the voltage DC-AC inverter is controlled using Pulse Modulation Width (PWM) technology to obtain three balanced alternating current phases with variable frequency from the current battery. 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 is presented in [11,12].

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

The logic S_i of the switches are obtained by comparing the control inverter signals with the modulation's signal.

A. Mechanical Load part of the used electric vehicle

The vehicle's load is characterized by three resistive torques [9,10,11,13,14]. These torques includes:

- The aerodynamics torque is:

$$T_{aero} = \frac{1}{2} \rho S T_x R_r^3 \omega_r^2 \quad (2)$$

- The slope torque is given as :

$$T_{slope} = Mg \cdot \sin \alpha \quad (3)$$

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

$$T_{max} = Mgf_r \cdot R_r \quad (4)$$

We obtain finally the total resistive torque:

$$T_v = T_{slope} + T_{tire} + T_{aero} \quad (5)$$

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.

3. The Indirect Field Oriented Control (IFOC)

The aim object of the vector control of induction motors is, to control independently the flux and he torque as DC machines [4,7,12,13,17]. In ideally field-oriented control, the rotor flux linkage axis is forced to align with the d -axes, and it follows that [4, 7, 17]:

$$\phi_{rq} = \frac{d\phi_{rq}}{dt} = 0 \quad (6)$$

$$\phi_{rd} = \phi_r = \text{cons} \tan t \quad (7)$$

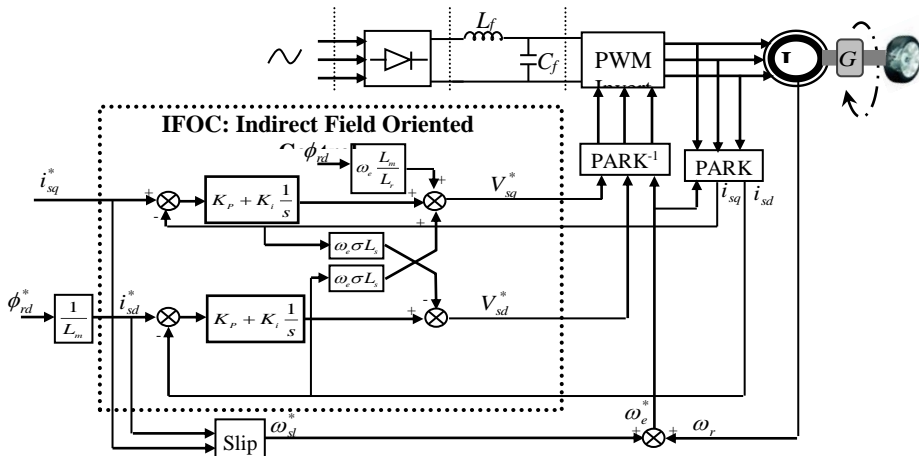


Figure 2. IFOC strategy for one wheel induction motor.

Applying the result of (6) and (7), defined the indirect field-oriented control (IFOC), the torque equation become similar to the DC machine and can be given by:

$$T_e = \frac{3}{2} \frac{p \cdot L_m}{L_r} \cdot \phi_r \cdot i_{qs} \quad (8)$$

According to the obtained results given above, the IFOC [4, 7, 13] applied to an induction motor with current-regulated should be presented by the block diagram shown in the Figure 2. In this step we use the classical controller (PI) for IFOC tuning control parameter.

4. Sliding Mode Controller (SMC)

Sliding modes as phenomenon may appear in a dynamic system computing by ordinary differential equations with discontinuous right-hand sides. the function of control system state switches at high frequency, this motion is called sliding mode. It may be known in the simplest tracking relay system with the state variable $x(t)$ [15,16]:

$$\frac{\partial x}{\partial t} = f(x) + u \quad (9)$$

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 $e = r(t) - \frac{\partial x}{\partial t}$

; $r(t)$ is the reference input and u is given by:

$$u = \begin{cases} +u_0 & ; \text{if } e > 0 \\ -u_0 & ; \text{if } e < 0 \end{cases} \quad (10)$$

Or: $u = u_0 \text{sign}(e)$; u is constant. Figure 3 shows the relay control scheme:

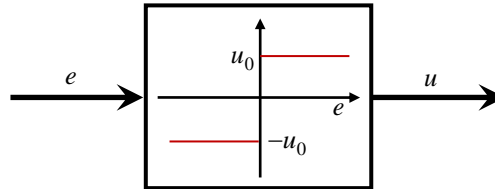


Figure 3. Relay control

The values of e and $\frac{\partial e}{\partial t} = \dot{e} = \dot{r} - f(x) - u_0 \text{sign}(e)$

According to Lyapunov criteria of the system's stability , if the system is stable if it does verify the following condition: $e \cdot \dot{e} < 0$

By means that we have the different signs if $u_0 > f_0 + \left| \dot{r} \right|$. And finally u_0 must be positive constant.

A. Design of sliding mode speed and current controller

The speed error of the system target is de fined by [15,16,17, 18]:

$$e = w_{ref} - w \quad (11)$$

$$\text{The derivative of the sliding surface can be given as: } \dot{s}(\omega) = \dot{\omega}_r^* - \dot{\omega}_r \quad (12)$$

From the equation (12) and equation cited in [4], we can obtain:

$$\dot{s}(\omega_m) = \dot{\omega}_m^* - \left(\frac{3}{2} \frac{P^2 L_m \phi_{dr}^*}{J L_r} i_{qs} - \frac{f_c}{J} \dot{\omega}_m - \frac{P}{J} T_l \right) \quad (13)$$

The current quadrate square control is given by:

$$i_{qs} = i_{qs}^{equ} + i_{qs}^n \quad (14)$$

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

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

Where ϕ is the boundary layer thickness. The discontinuous control action can be given as:

$$i_{qs}^n = k_{iqs} \cdot sat(s(\omega)/\phi_\omega) \quad (15)$$

k_{iqs} : Positive constant.

The current control is defined by:

$$i_{qs}^{equ} = \frac{2}{3} \frac{JL_r}{P^2 L_m \phi_{dr}^*} \left(\dot{\omega}_m^* + \frac{f_c}{J} \omega_m + \frac{P}{J} T_l \right) \quad (16)$$

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

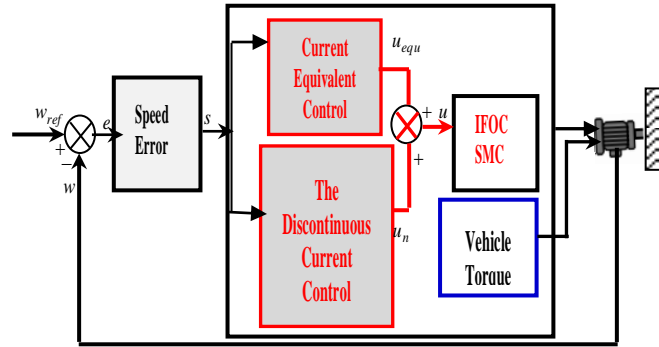


Figure 4. The SMC control strategy schema for One wheel electric vehicle

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 for each wheel where:

$$S_1 = i_{ds}^* - i_{ds} \quad (17)$$

$$S_2 = i_{qs}^* - i_{qs} \quad (18)$$

The derivate of S_1 can be given as:

$$\dot{S}_1 = \dot{i}_{ds}^* - \dot{i}_{ds}$$

from equation cited in [12] and (18) we can obtain :

$$\dot{S}_1 = \dot{i}_{ds}^* - \left[-\left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma \tau_r} \right) i_{ds} + \omega_e i_{qs} + \frac{L_m}{\sigma L_s L_r \tau_r} \phi_{rd} + \frac{1}{\sigma L_s} V_{ds} \right] \quad (19)$$

The virtual voltage controller V_{ds} is given by:

$$V_{ds} = V_{ds}^{equ} + V_{ds}^n \quad (20)$$

The voltage discontinuous control V_{ds}^n is defined as:

$$V_{ds}^n = k_1 \cdot \text{sat}(s_1/\phi_1) \quad (21)$$

According to Lyapunov stability criteria [15,16] our speed loop system's stable if: $\dot{s}_1 \leq 0$ by means that K_1 is positive constant.

The equivalent control V_{ds}^{equ} is given as:

$$V_{ds}^{equ} = \sigma \cdot L_s \left(\dot{i}_{ds}^* + \frac{1}{\sigma \cdot L_s} \left(R_s + R_r \left(\frac{L_m}{L_r} \right)^2 \right) i_{ds} - \omega_s i_{qs} - \frac{L_m \cdot R_r}{\sigma \cdot L_s L_r^2} \phi_r^* \right) \quad (22)$$

The derivate of S_2 can be given as: $\dot{s}_2 = \dot{i}_{qs}^* - \dot{i}_{qs}$, From equation cited in [12] and (19) we can obtain:

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

The voltage controller V_{qs} is given by:

$$V_{qs} = V_{qs}^{equ} + V_{qs}^n \quad (23)$$

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

$$V_{qs}^{equ} = \sigma \cdot L_s \cdot [\dot{i}_{qs}^* + \omega_s i_{ds} + \frac{1}{\sigma \cdot L_s} \left(R_s + R_r \left(\frac{L_m}{L_r} \right)^2 \right) i_{qs} + \frac{L_m}{\sigma L_s L_r} \phi_r^* \omega_m] \quad (24)$$

The voltage discontinuous control V_{ds}^n is defined as:

$$V_{qs}^n = k_2 \cdot \text{sat}(s_2/\phi_2) \quad (25)$$

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

B. Fuzzy-sliding mode control (FSMC) for one wheel

The disadvantage of SMC is the chattering phenomenon of the discontinuous control signal, the chattering is aggravated by small time delays in the system. In order to eliminate the chattering phenomenon, different schemes have been proposed in the literature [15, 17]. In this section, a Fuzzy-Sliding mode controller is developed, in which a fuzzy inference mechanism is used to generate the equivalent control law parameters by means that the employed fuzzy logic controller replace the discontinuous control in the SMC schema. The proposed hybrid fuzzy-sliding mode controller scheme for EV speed control is shown in Figure 5. The fuzzy logic controllers replace the inequalities given in (15) which determine the parameters of the equivalent control action. We show that a particular fuzzy controller is an extension of an SMC with a boundary layer [16,18]. The proposed fuzzy controller in this paper is constructed from the following IFTHEN rules which are the most adapted with this kind of hybrid robust control problem:

BN : Big Negative	Bigger
MN : Medium Negative	Big
ZE : Zero	Medium
MP : Medium Positive	Small
BP : Big Positive	Smaller

The Figure 5 shows the Fuzzy Sliding Mode Control (FSMC) control strategy scheme for the electric traction chain.

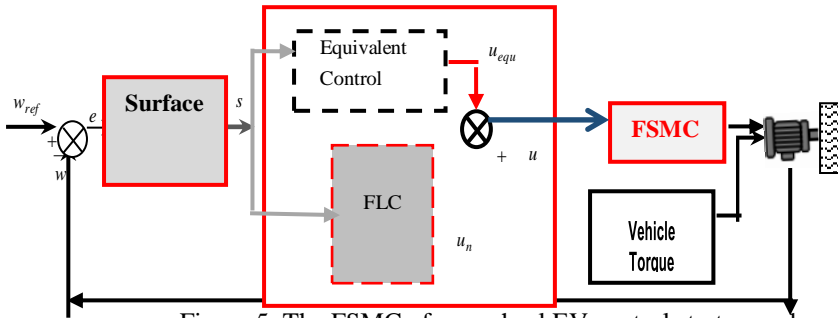


Figure 5. The FSMC of one wheel EV control strategy scheme.

We take five fuzzy subsets, BN, MN, ZE, MP and BP, are defined for s , s_1 and s_2 ; the fuzzy inference mechanism contains five rules for the Fuzzy Logic Controller (FLC) output. The resulting fuzzy inference rules for the output variable u_n as follows:

Rule 1: IF s , s_1 and s_2 is BN THEN u_n is Bigger

Rule 2: IF s , s_1 and s_2 is MN THEN u_n is Big

Rule 3: IF s , s_1 and s_2 is ZE THEN u_n is Medium

Rule 4: IF s , s_1 and s_2 is MP THEN u_n is Small

Rule 5: IF s , s_1 and s_2 is BP THEN u_n is Smaller

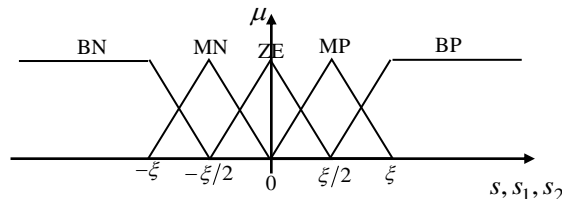


Figure 6. The inputs s , s_1 and s_2 membership functions of the Discontinuous control

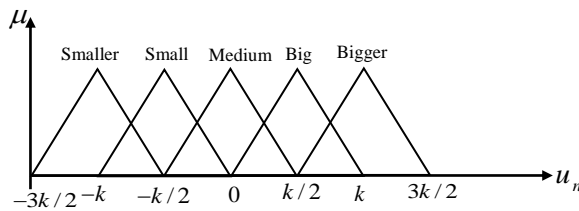


Figure 7. The output membership function of the discontinuous control.

Where S_1 , S_2 , S_3 present the sliding surface of speed error ws , i_{qs} , i_{ds} respectively. The membership functions of input and output fuzzy sets are depicted in Figures 6 and 7. In this study, the triangular membership functions and center average defuzzification method are adopted for their efficiency in solving the chattering problem, they are computationally simple, intuitively plausible, and most frequently used in the opening literatures[15,16,17,18].

5. Simulation Results

The globally scheme of the four driving wheels using control FSMC is presented by Figure 8. The reference blocks must provide the speed references of each motor taking into account all obtained information's from the different sensors such as motors and according to the real driver

decision (break , acceleration) [8,9,10]. So the electronic differential present an actuator for four wheels in front and rear and acts immediately and compute the novel references speeds given for each wheel taking into account the road curve angle the linear speed input. In order to show the propulsion system behaviour by applying hybrid control FSMC, simulations were carried on Matlab using the model of Figure 8. The specified trajectory is chosen as follow:

First the vehicle is moving on straight road, the linear speed is changed from 60 km/h to 90 km/h at time of 2sec, then the vehicle is moving curved road at right side at time of 3 sec , then the slope road of 10 % at 3.5 sec, finally the another curve at left side at time of 4 sec. the results obtained given as follow in the tables 1,2,3:

- In the linear speed characteristics:

Table 1. Comparative studies on linear speeds results

Controller	Speed range (60-90)	Speed error	overshoot	Rising time	Autonomous (meters)	Ability to follow the ED	Ability to drive during curve
PI	60-90	exist	16 %	0.7	381.8	no	no
SMC	60-90	no	no	0.85	417.5	yes	yes
FSMC	60-90	no	no	0.8	427.5	yes	yes

- Mechanical load characteristics:

Table 2. Comparative studies on mechanical load results

Controller	Vehicle torque (Nm)	Aerodynamic torque (Nm)	Aerodynamic torque change	Ability to overcome the slope
PI	312.2	210.8	0.003919	difficult
SMC	155.5	53.9	0.001287	easy
FSMC	154	48.49	0.0002847	Very easy

- Propulsion system and developed effort analysis:

Table 3. Comparative studies on developed effort analysis

Controller	Estimated driving force	Estimated torque	Estimated current	Stability to drive during curve and slope
PI	1201	312.4	239.3	bad
SMC	596.6	155.5	119.7	good
FSMC	593.4	154.3	118.2	Very good

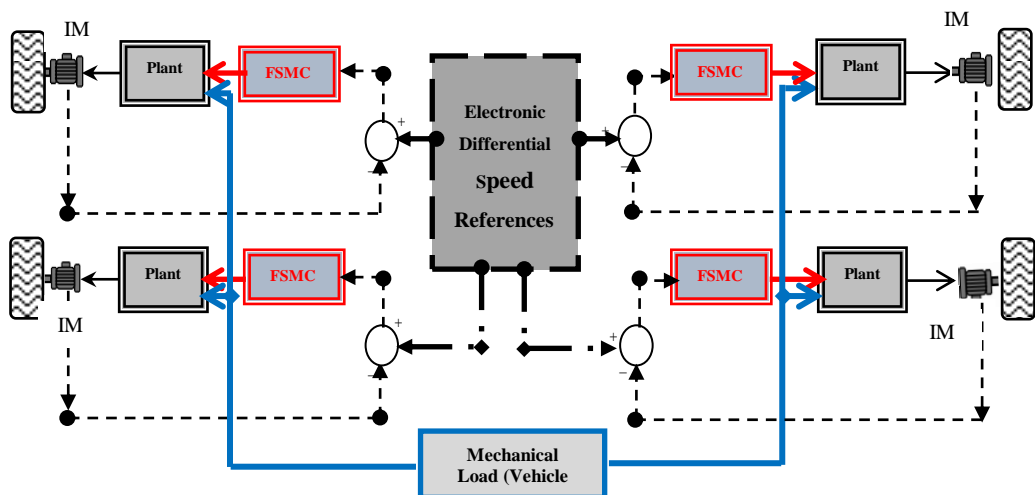


Figure 8. Four wheels electric vehicle simulated model

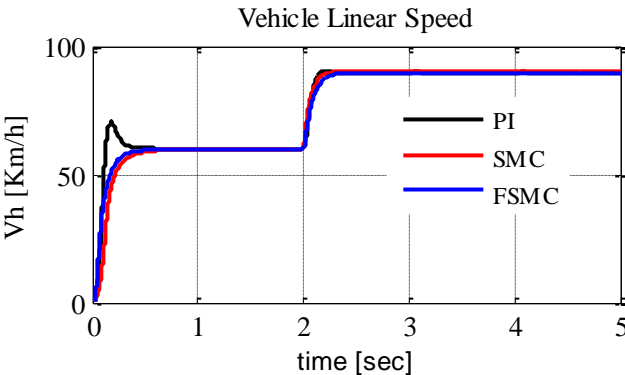


Figure 9. Vehicle linear speed comparative studies

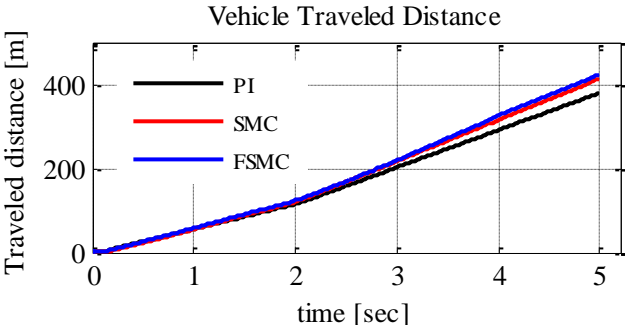


Figure 10. Vehicle travelled distance

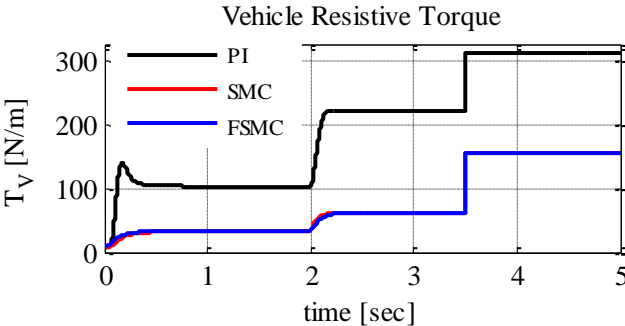


Figure 11. Vehicle resistive torque

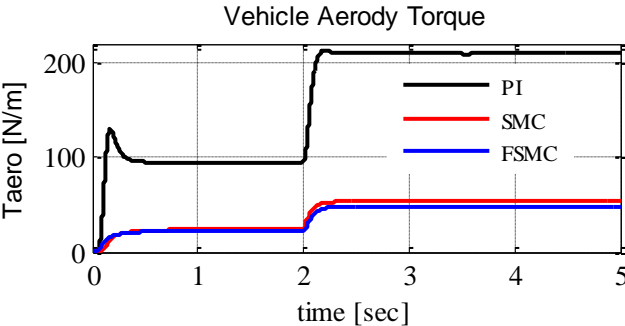


Figure 12. Vehicle aerodynamic torque

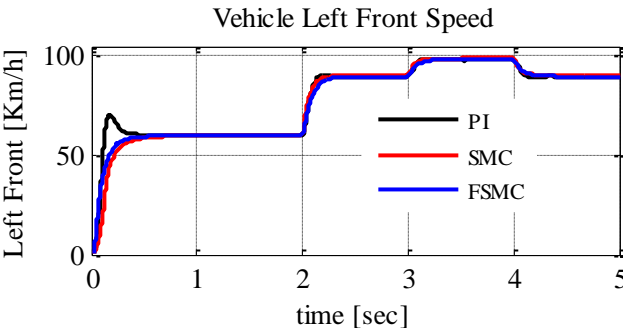


Figure 13. Vehicle left front speeds compare

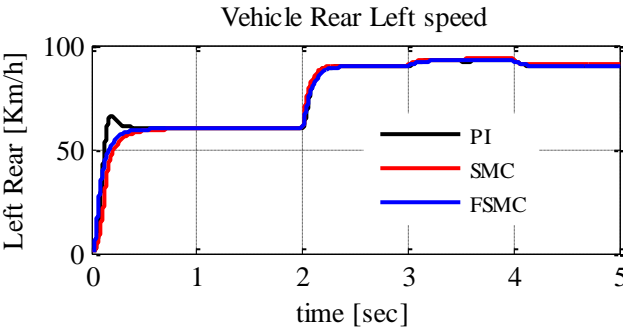


Figure 14. Vehicle left rear speeds compare

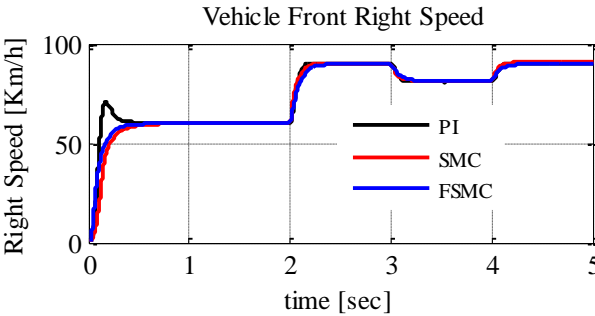


Figure 15. Vehicle front right speeds compare

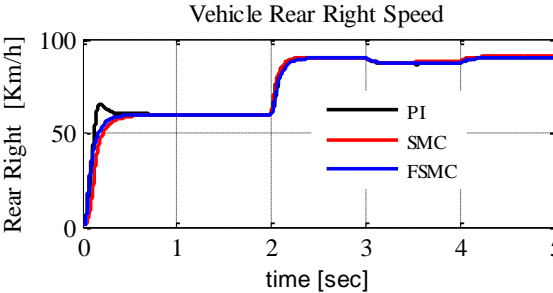


Figure 16. Vehicle right rear speeds compare

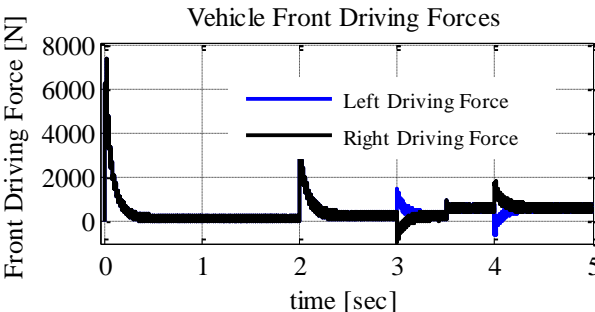


Figure 17. Vehicle front driving force

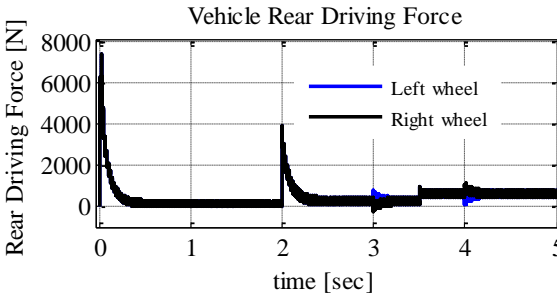


Figure 18. Vehicle rear driving force

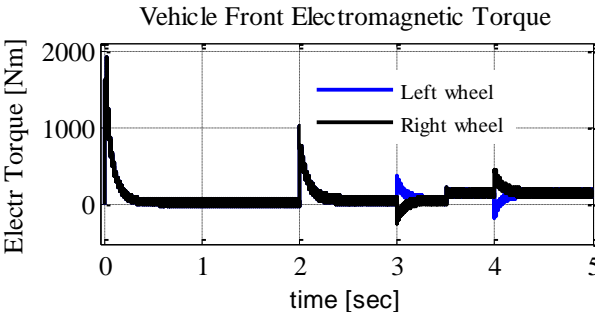


Figure 19. Vehicle front electromagnetic torque

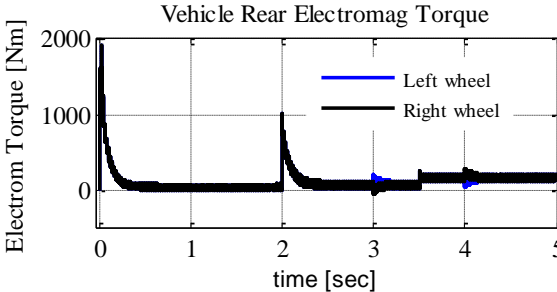


Figure 20. Vehicle rear electromagnetic torque

According to the obtained results as it shown an detailed in tables (1,2,3) and Figures from 9-20 we can say that in FSMC the driver can drive in easy way and safety comparing with SMC case , the stability is difficult in PI classical control and the losses in power and speeds clearly appear in this case with huge overshoot and the vehicle can't pass the slope in safety way and the

driving became very dangerous , the ED can provide all the vehicle needs and can do an economic distribution of speed and driving force and torque in FSMC , but the ability to follow the speed references in PI one is not possible , the aerodynamic torque is very important in PI compared with SMC and FSMC it have the value of 210 Nm compared with 48 Nm in FSMC and 53.9 Nm in SMC case , this value can be explained by that the frontal surface used in FSMC is the most biggest compared with SMC and FSMC it's appear clearly in aerodynamic torque changes ,the current estimated in PI case is very valuable compared of SMC an FSMC ,it's take a number of 239,3 A when the current demand for the same trajectory is only 118.2 A , at the driving force level for PI the driving force equal the double developed in FSMC case and SMC , so the driving of four wheels electric vehicle which utilize four independent induction motor for motion is very easy in FSMC case comparing with SMC and PI at any trajectory ,that make this all road electric vehicle very demanded at the industry stage and driver can drive the vehicle with security and safety .

6. Conclusion

The aim object of this work is the application of robust hybrid control on modern four wheel electric vehicle using an electronic differential , the results obtained have presented clearly that this type of propulsion system can be improved in the twin of autonomous and stability using the proposed control schema and comparing this choice with the SMC controller ,the assumption of this work is the four motor are not distrusted and the globally system use the independent machine structure as multi motor schema ,after the chattering phenomena which produce loss of energy and heat of cables inside the vehicle simulation where carried to compare the SMC and FSMC behavior and to ensure the driving on the chosen road trajectory with high safety conditions .The results obtained by Matlab simulation proves that this structure permits the realization of robust control and accuracy , the results obtained prove good performances of FSMC and make the driving easy of the four wheels drives and give good attention for industrials to applied this approach on multi motor vehicles.

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