Vehicle Stability Improvement Based on Electronic Differential Using Sliding Mode Control

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Abstract: - This paper presents an electronic differential system for electric vehicle with two independent wheel drives using sliding mode control. When a vehicle drives along curved road lane, the speed of the inner wheel has to be different from that of the outer wheel in order to prevent the vehicle vibrating and traveling an unsteady path. Because each wheel of this electrical vehicle has independent driving force, an electrical differential system is required to replace a gear differential system. However, it is difficult to analyse the nonlinear behavior of the differential system in relation to the speed and steering angle, as well as vehicle structure. The proposed propulsion system consists of two permanent magnet synchronous machines that ensure the drive of the two back driving wheels. The proposed control structure called independent machines for speed control permits the achievement of an electronic differential. The electronic differential ensures the control of the vehicle behavior on the road. It also allows to control, independently, every driving wheel to turn at different speeds in any curve. Analysis and simulation results of this system are presented.

Key-Words: - Electric vehicle, sliding mode control, electronic differential, permanent magnet synchronous motor, mulimachine multiconverter system.

1 Introduction

Electric vehicle with in-wheel motors has remarkable advantage in the quick generation of precise torque on each driving wheel [1,2]. Some applications in the field of electrical drives require the use of several electric machines and as well as many static converters that have an important place among the electromechanic systems. These systems are called multi-converter multi-machine systems (MMS). [3]

A formalism has been developed in order to study systems composed of several electrical machines and/or power converters. It points out three energetic coupling inside the electromechanical conversion chains: electrical, magnetic and mechanical coupling. Adapted rules based on the inversion principle are suggested for the control of such systems. Energetic repartition criteria have to be defined to solve the coupling problems [4]. They are recognized through the existence of the coupling system type either of an electric nature, a magnetic and/or mechanical one used in several electric machines propulsing the vehicle. In such a control we model the coupling by using appropriate control structures including independent control, slave-master, by imposing criteria of energetic distribution in order to obtain a single machine or a single converter system. One of these control structures can be applied to the control of electric vehicle driving wheels.

2 Traction System Studied

The classical configuration of electric vehicle traction system is represented in Fig. 1. [5]

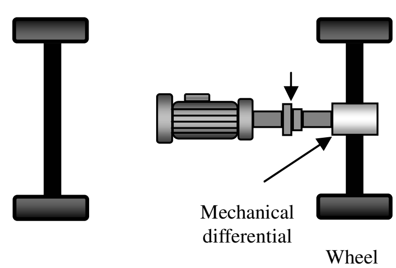


Fig. 1. Vehicle structure with one central motor.

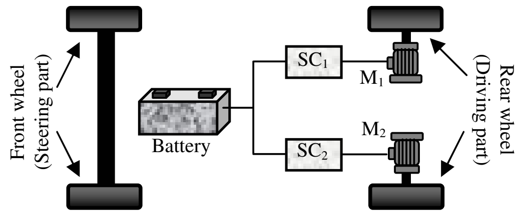


Fig. 2. Vehicle structure with two independent rear wheel drives.

Fig. 2, shows the structure of the electric vehicle, the rear two wheels are driven by two traction motors through reduction gears and drive shafts [6]. This figure represents the implemented vehicle configuration using two permanent magnet synchronous motor for two independent wheels.

The multi-machine systems are characterized by the coupling of different electromechanical conversion systems. The system represented by the Fig. 2 is characterised by only one coupling. It is illustrated by Fig. 3. In order to realize the electronic differential, the control structure "independent machines" is applied to the propulsion system of two driving wheels, by a speed control, Fig. 4.

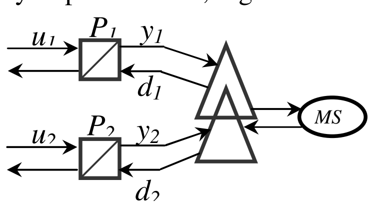


Fig. 3. Studied topology.

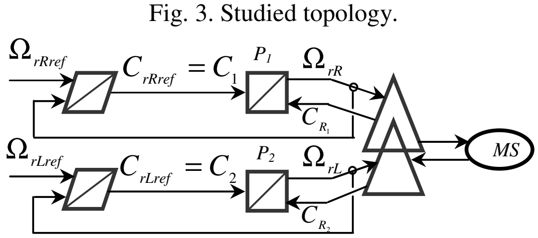


Fig. 4. Independent machine structure.

2.1 Independent machine control

This structure is composed of two machines controlled independently as two single machine structures. For every machine we can impose different speed reference ($\Omega_{rRref} \neq \Omega_{rLref}$) by using two static converters. These machines are uncoupled through the control structure and reject all disturbances like single machine control. The principle of this control is illustrated by Fig. 4.

An energetic macroscopic representation (EMR) of the propulsion system was proposed to obtain a global view of an electronic differential, Fig. 5.

This investigation proposes the control of the driving wheels speeds Ω_{ω_R} and Ω_{ω_L} by the "independents machines" control structure. This structure permits to impose two speed references $\Omega_{\omega\_R} \neq \Omega_{\omega\_L}$ (i.e in a curve), the applied torque on each wheel is different $T_{gear\_R} \neq T_{gear\_L}$, the two wheels control system does not receive the same torque reference. Thus, it is not possible to impose the same speed reference.

Fig. 6 shows the structure of electronic differential. The system uses the vehicle velocity and steering angle as input parameters and calculates the required inner and outer wheels speeds where the two rear wheels are controlled independently by two PMS motors. The inputs of the reference block are vehicle speed and steering angle, and the outputs are required rotation speeds of the inner and outer wheels, referred to as commanded speeds. According to the steering angle direction (left or right), the rotational speed of the inner wheel and outer wheel is allocated to the rotation speed of left wheel and right appropriately.

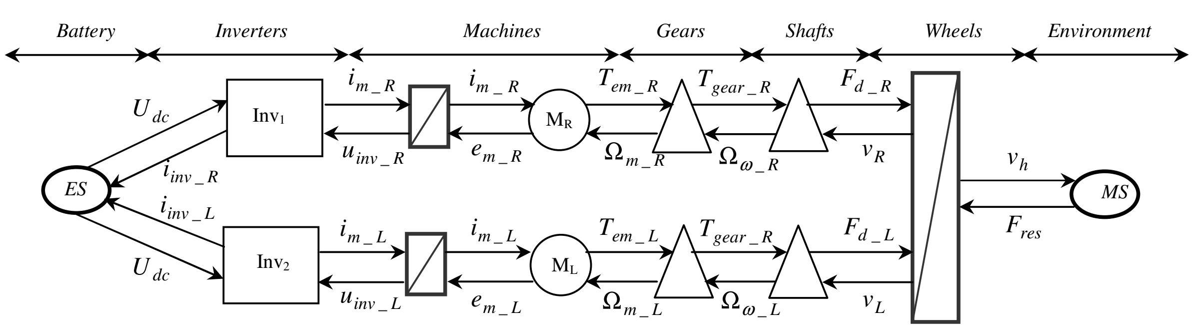


Fig. 5. EMR of the electronic differential system.

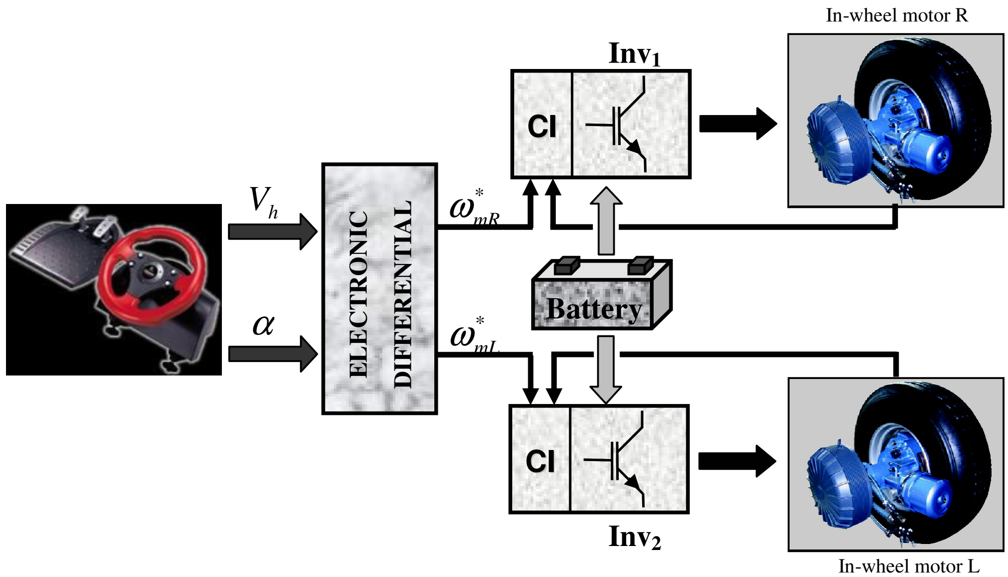


Fig. 6. The driving wheels control system.

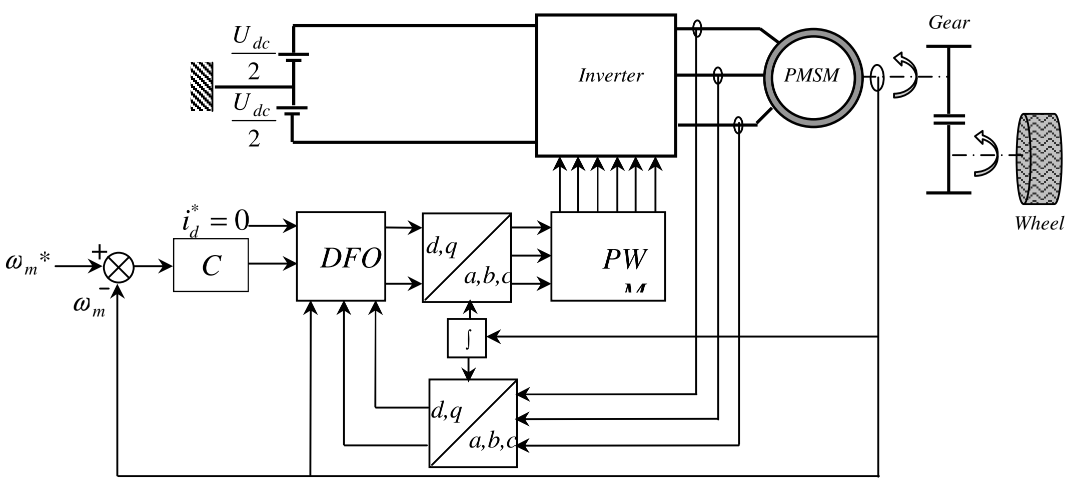


Fig. 8. Block-diagram of an electric drive system for PMS motors.

The power structure in this paper is composed of two permanent magnet synchronous motors which are supplied by two three-phase inverters and driving the two rear wheels of a vehicle trough gearboxes, Fig. 7.

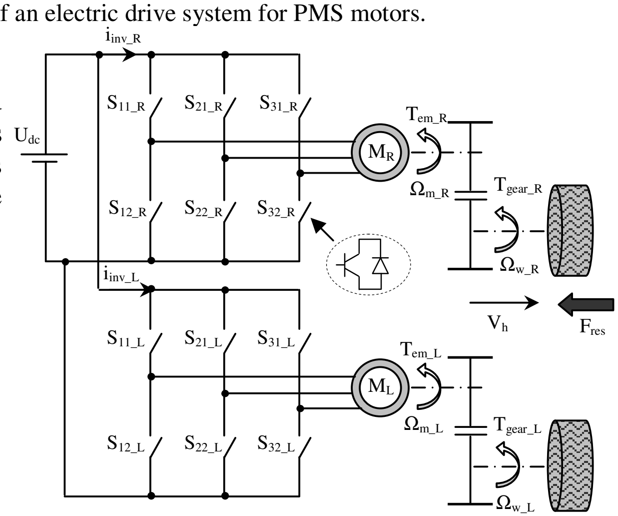


Fig. 7. Components of studied system.

3 Vector Control

Fig. 8 gives the vector control scheme of a permanent magnets synchronous motor. It represents the speed control system with i_d and i_q current controls.

In order to simplify the control algorithm and improve the control loop robustness, instead of using classical control, we use sliding mode control.

3.1 Sliding Mode Control

The PMSM equations are as follows:

$$\frac{di_d}{dt} = f_1 + \frac{1}{L_d} v_d \tag{1.a}$$

$$\frac{di_q}{dt} = f_2 + \frac{1}{L_q} v_q \tag{1.b}$$

$$\frac{d\omega_m}{dt} = f_3 \tag{1.c}$$

where

$$f_1 = -\frac{R_s}{L_d} i_d + \frac{L_q}{L_d} \omega_m i_q \tag{2.a}$$

$$f_2 = -\frac{R_s}{L_q} i_q - \frac{L_d}{L_q} \omega_m i_d - \frac{\Phi_f}{L_q} \omega_m \tag{2.b}$$

$$f_3 = \frac{p^2}{J} \left[\left(L_d - L_q \right) i_d + \Phi_f \right] i_q - \frac{p}{J} T_r - \frac{f}{J} \omega_m \tag{2.c}$$

- *Speed and current sliding mode controller*

Using the non-linear PMSM model of equations (1), it is possible to design both a speed and a current sliding mode controller [7,8]. Let us define the sliding surface

$$S_{c1} = S_{c1}(\omega_m) = \lambda_\omega (\omega_m^* - \omega_m) + \frac{d}{dt} (\omega_m^* - \omega_m) \tag{3.a}$$

$$S_{c2} = S_{c2}(i_d) = (i_d^* - i_d) \tag{3.b}$$

where $\lambda_\omega \succ 0$, ω_m^* and i_d^*, are the speed reference and the reference stator current, respectively.

To determine the control law that is expected to steer the sliding function (3) to zero in finite time, one has to consider the dynamics of $S_c = [S_{c1} \quad S_{c2}]^T$, described by:

$$\dot{S}_c = A + BV_s \tag{4}$$

where

$$A = \begin{bmatrix} \ddot{\omega}_m^* + \lambda_\omega \dot{\omega}_m^* - a f_1 - b f_2 - c f_3 \\ \dot{i}_d^* - f_1 \end{bmatrix};$$

$$B = \begin{bmatrix} -\frac{b}{L_q} & -\frac{a}{L_d} \\ 0 & -\frac{1}{L_d} \end{bmatrix};$$

$$a = \frac{p^2}{J} \left(L_d - L_q \right) i_q ; \quad b = \frac{p^2}{J} \left[\left(L_d - L_q \right) i_d + \Phi_f \right];$$

$$c = \lambda_\omega - \frac{f}{J}$$

In the Lyaponov method of stability it is used to ensure that S_c is attractive and invariant, the following condition has to be satisfied

$$S_c^T . \dot{S}_c \prec 0 \tag{5}$$

So, it is possible to choose the switching control law for stator voltages as follows:

$$\begin{bmatrix} v_q \\ v_d \end{bmatrix} = -B^{-1} F - B^{-1} \begin{bmatrix} K_\omega & 0 \\ 0 & K_{i_d} \end{bmatrix} \begin{bmatrix} sign(S_{c1}) \\ sign(S_{c2}) \end{bmatrix} \tag{6}$$

where $K_\omega \succ 0$, $K_{i_d} \succ 0$

The sliding mode causes drastic changes of the control variable introducing high frequency disturbances. To reduces the chattering phenomenon, a saturation function $sat(S_c)$ instead of the switching one $sign(S_c)$ has been introduced:

$$sat(S_{ci}) = \begin{cases} \frac{S_{ci}}{\delta_i} & if \quad |(S_{ci})| \le \delta_i \\ sign(S_{ci}) & if \quad |(S_{ci})| \succ \delta_i \end{cases} \tag{7}$$

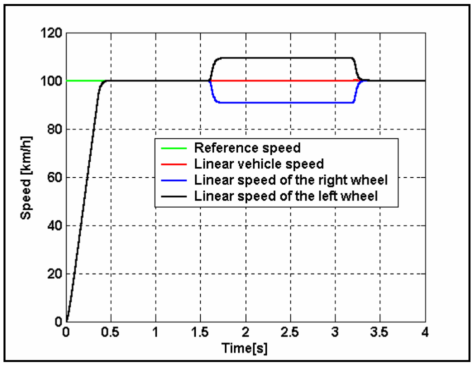
where $\delta_i \succ 0$ for $i = 1,2$ with $\delta_1 = \delta_\omega$ and $\delta_2 = \delta_{i_d}$

4 Simulation Results

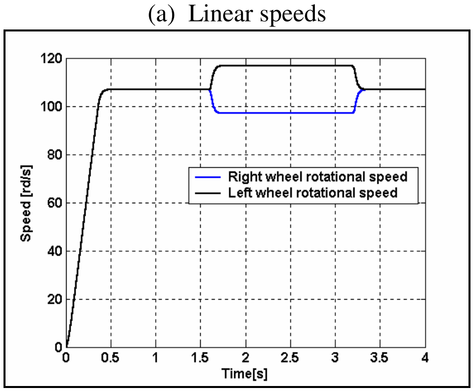
1 Case of curved way

Case1: Curved road at right side with speed of $100 km/h$

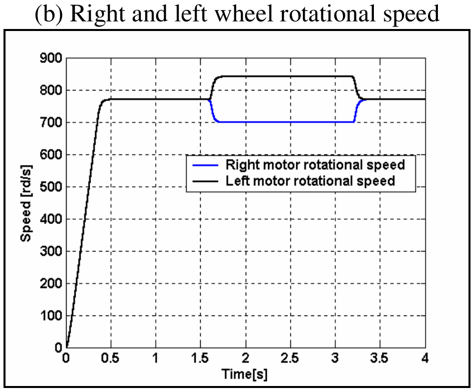
The vehicle is driving on a curved road on the right side with $100 km/h$ speed. The assumption is that the two motors are not disturbed. In this case the driving wheels follow different paths, and they turn in the same direction but with different speeds. The electronic differential acts on the two motor speeds by decreasing the speed of the driving wheel on the right side situated inside the curve, and on the other hand by increasing the wheel motor speed in the external side of the curve. The behaviour of these speeds is given by Fig. 9(a) and 9(b).



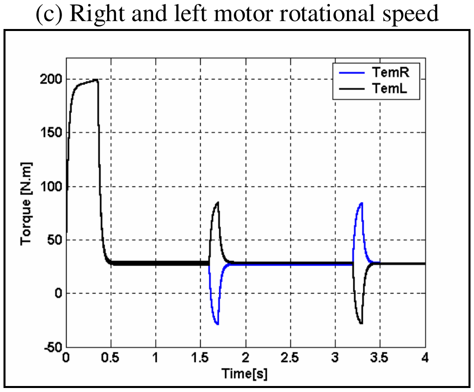
(a) Linear speeds



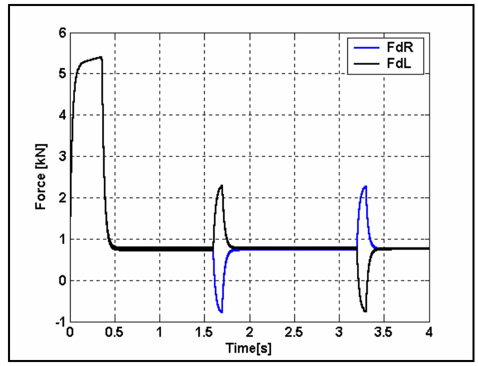
(b) Right and left wheel rotational speed



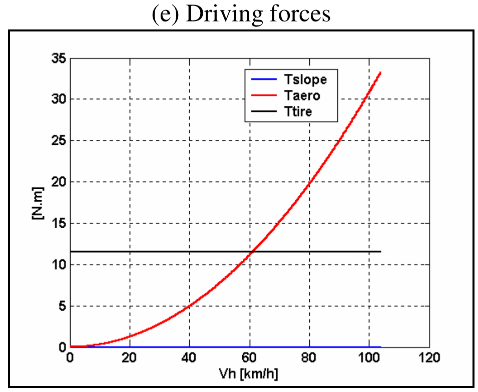
(c) Right and left motor rotational speed



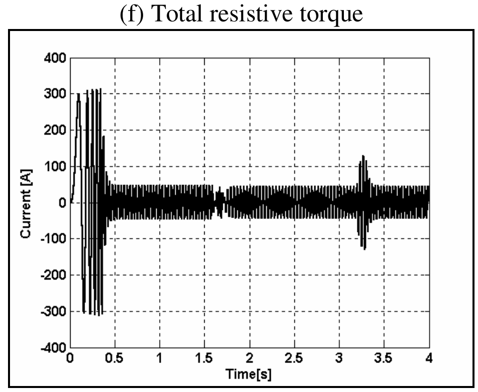
(d) Electromagnetic torques



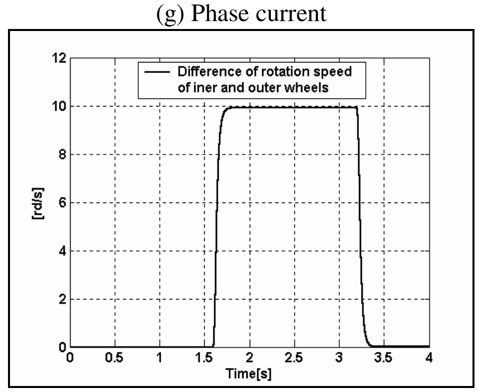
(e) Driving forces



(f) Total resistive torque



(g) Phase current

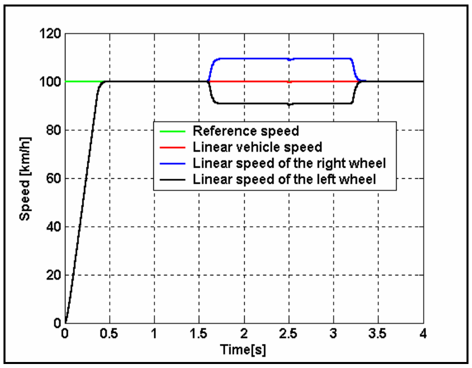


(d) Difference of rotation speed

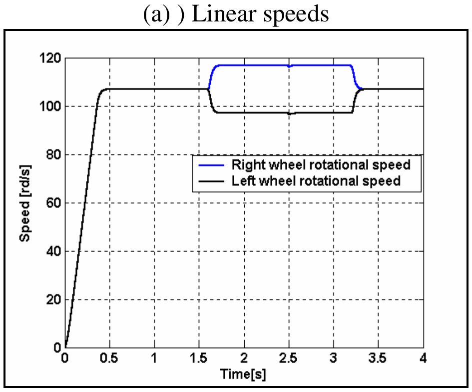
Fig. 9. Simulation results of case 1

Case 2: Curved road with 10% slope with right turn.

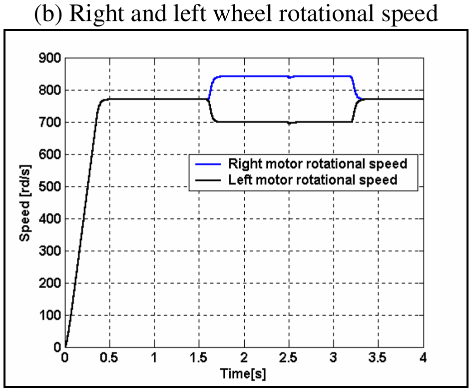
This test shows the influence of the road slope on the vehicle moving in curved road. Figure 10 shows the effect of the slope and the curved road on the motor parameters. The driving wheels speeds are controlled and the errors created by the disturbances are quickly compensated.



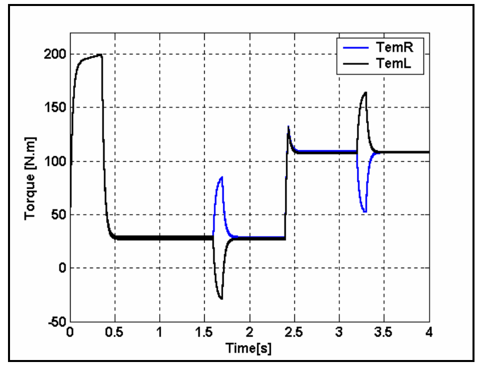
(a)) Linear speeds



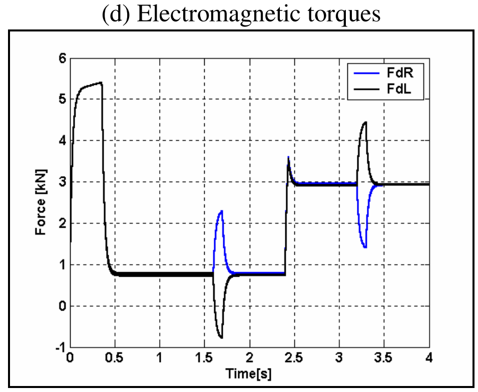
(b) Right and left wheel rotational speed



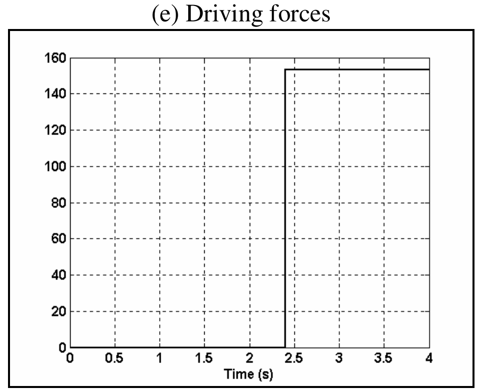
(c) Right and left motor rotational speed



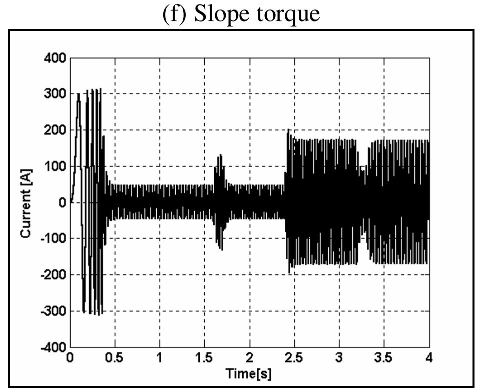
(d) Electromagnetic torques



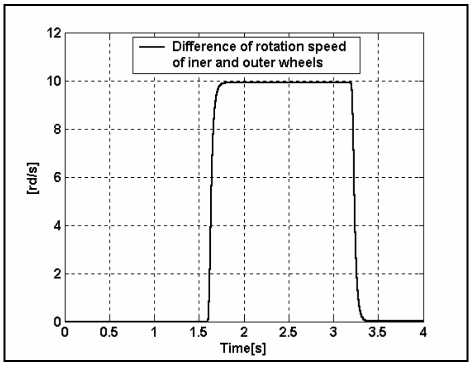
(e) Driving forces



(f) Slope torque



(g) Phase current



(h) Difference of rotation speed

Fig. 10. Simulation results of case 2

5 Conclusion

In the field of electric drives with variable speed, an application of an electric vehicle controlled by an electronic differential is presented. This paper proposes an "independent machine" control structure applied to a propulsion system by a speed control. The results obtained by simulation show that this structure permits the realization of an electronic differential and ensures good dynamic and static performances. The electronic differential controls the driving wheels speeds with high accuracy either in flat roads or curved ones. The disturbances do not affect the performances of the driving motors.

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ABREVIATIONS

DFOC : Direct Field Oriented Control
EC : Electrical Coupling
EM : Electrical Machine
EMR : Energetic Macroscopic Representation
ES : Electrical Source
EV : Electric Vehicle
MMS : Multi-machine Multi-converter System
MS : Mechanical Source
PMSM: Permanent Magnet Synchronous Machine
PWM : Pulse With Modulation

Nomenclature

L_d, L_q: d and q axis inductance
i_d , i_q : d and q axis currents
v_d , v_q: d and q axis voltage
R_s : Resistance
p : Pole pairs
θ : Electric position
Φ_f : Permanent magnet flux
J : Rotor inertia
J_v : Vehicle inertia
C_{em} : Electromgnetic torque
C_r : Load torque
M : Vehicle mass
R_r : Wheel raduis
N_{red} : Report of speed gear
η : Transmission efficiency

l_w : Distance between two wheels and axes
d_w : Distance between the back and the front wheel
ρ : Air density
S : Front area of vehicle
C_x : Aerodynamic coefficient
g : Acceleration of gravity
f_r : Friction coefficient
α : Angle of the slope
v_h : Linear speed of vehicle
U_{dc} : Battery voltage