SERBIAN JOURNAL OF ELECTRICAL ENGINEERING
Vol. 9, No. 2, June 2012, 279-291

UDK: 621.3.027.412 ; 629.113.65-46 **DOI: 10.2298/SJEE1202279G**

A Novel Multi-Drive Electric Vehicle System Control Based on Multi-Input Multi-Output PID Controller

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Abstract: In-wheel-motor drive electric vehicle (EV) is an innovative configuration of the modern EV, in which each wheel is driven individually by an electric motor. The classical traction motor control called the Independent Machine Control Structure (IMCS) using a PID speed controller presents major inconveniences in modern EV safety, when the proposed control can not ensure stability of the EV with differing road topology and variations of speed. A new approach is proposed for a control of a two-in-wheel-motor drive EV, called the Maximum Control Structure MCS. This is based on a multivariable PID (MIMO-PID) strategy, which is employed to estimate the linear speed error of each of the two back driving wheels, when the error of each wheel is taken into account in the other speed control computations. Simulation results show that the new control system presents increased safety for the EVs compared with the IMCS strategy and can maintain the error slip rate within the optimal range, ensuring the stability of the vehicle either in a straight or a curved line.

Keywords: Electric vehicles (EVs), Maximum Control Structure (MCS), Multivariable PID.

1 Introduction

Many attempts have been made to reduce Electric Vehicle (EV) body mass, including structure and form optimisation or by adopting aluminium materials [l]. Due to the improvement of both motor design and control technology, modern configurations can include motorised wheels, which means motors are fitted into the wheels of EVs [2]. The EV offers one of the best solutions for improving air quality while reducing the reliance on fossil fuels to power vehicles. The usual configuration of EVs presents only one traction-motor driving two wheels, using a differential gear. However, the over all mass of an EV is considerably increased by the mass of the batteries. Considering that the torque/rotation-speed curve of an electric motor is almost perfectly adapted to the resistance-torque/speed curve of an electric vehicle, the conventional heavy

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gearbox can be replaced by an electronic differential (ED),which is the most common solution for speed reference computation in the double-driven EV. With this approach, not only is the overall mass is reduced but the performance of the EV is also significantly improved due to the fast response time of the electric motors. The ED can control the speed each wheel in order to satisfy the motion requirements when the EV encounters different conditions, such as a curvilinear trajectory or a lane change.

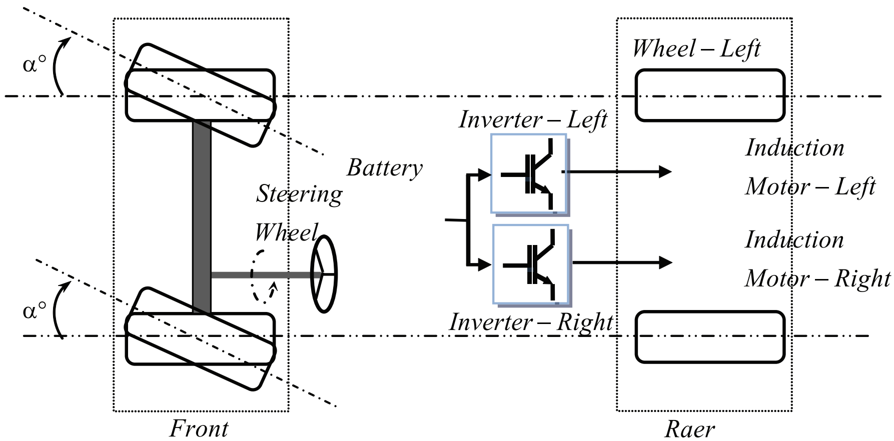

Fig. 1 – *Electric vehicle with two-independent-wheel drive.*

However, the algorithm of the ED is complicated because of the non-linearity of the vehicle dynamics. On the one hand, the ED system must guarantee that the double-driven wheels rotate at exactly the same speed when the EV drives in a straight line, whereas it must adjust the torque generated from the motors, to prevent the wheels from slipping, when the steering angle is not equal to zero, or the adhesion coefficients are different. Therefore, the complexity of the control system has become one of the primary obstacles in the development of a double-driven EV. Most existing studies have used the Ackermann and Jean model to solve the differential problem [2, 3].

However, this model has the disadvantage of ignoring the influence of centrifugal and centripetal force when the vehicle is driven on a curved surface. In addition, the load transfer and effects of the tyres are not considered. Therefore, this steady state analysis is not adequate when the vehicle navigates complex roads such as those with different road surface conditions or with turns. In this paper, a novel control method based on a Multi-Input Multi-output PID controller is proposed to overcome the problems of the ED. Modelling and simulation are carried out using the Matlab/Simulink tool to investigate the performance of the proposed system and the simulation results are shown to be satisfactory.

2 Configuration of the Wheel-Drive EV

The vehicle considered in this simulated analysis is a two-rear-wheel drive urban electric vehicle (Fig. 1). Two induction motors are coupled in each of the rear wheels [4]. The energy source of the electric motors comes from the Li-ions batteries placed under the seats [2, 3].

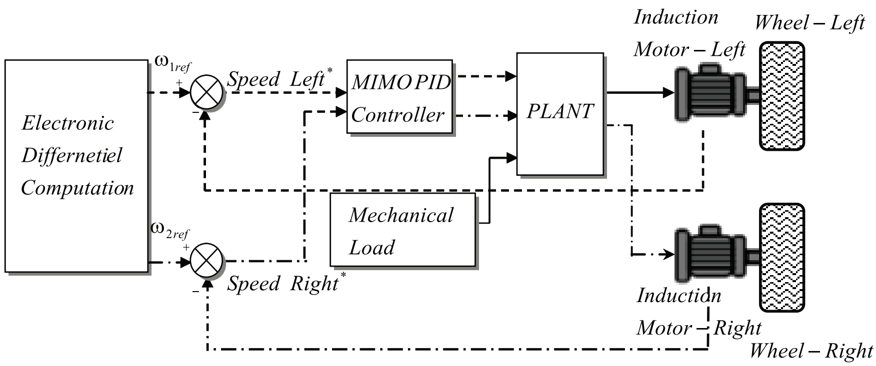

Fig. 2 – *Propulsion and* EV *system's control.*

3 Electric Vehicle Mechanical Load

The vehicle mechanical load is characterised by many torques, which are considered resistives [5, 6]. The different torques include:

– The vehicle inertial torque defined by the following relationship:

$$T_{in} = J_v \frac{\mathrm{d}w_v}{\mathrm{d}t}; \tag{1}$$

– The aerodynamics torque is:

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

– The slope torque is:

$$T_{slope} = Mg\sin\alpha; \tag{3}$$

– The tyre torque is obtained by:

$$T_{tire} = Mg f_{rr}. \tag{4}$$

Finally, we obtain the global resistive torque:

$$T_V = T_{aero} + T_{slope} + T_{tire}. \tag{5}$$

4 Multivariable PID (MIMO-PID) Controller Structure for Two-Wheel-Drive EV Systems

Generally, a standard PID controller structure is known as the "three-terms" controller [7, 8, 9,11]. The classical PID control law of the left motor is given by:

$$u_1(t) = K_{p1}\varepsilon_1(t) + K_{d1}\frac{\mathrm{d}\varepsilon 1(t)}{\mathrm{d}t} + \frac{1}{K_{i1}}\int \varepsilon_1(t)\,\mathrm{d}t\,. \tag{6}$$

When the classical PID control law of the right motor is given by:

$$u_2(t) = K_{p2}\varepsilon_2(t) + K_{d2}\frac{\mathrm{d}\varepsilon_2(t)}{\mathrm{d}t} + \frac{1}{K_{i_2}}\int \varepsilon_2(t)\,\mathrm{d}t\,. \tag{7}$$

The multivariable PID (MIMO-PID) controller of the twin motors is given by the following formula:

$$u_i(t) = \left[K_{pi}\right]\varepsilon_i(t) + \left[K_{di}\right]\frac{\mathrm{d}\varepsilon_i(t)}{\mathrm{d}t} + \left[K_{ii}\right]\int \varepsilon_i(t)\,\mathrm{d}t\,, \tag{8}$$

where $\varepsilon_1(t)$ and $\varepsilon_2(t)$ are the speed error of the left and right wheel motors and $i = 1,2$, as is shown in Fig. 2. The three terms K_{pi}, K_{ii} and K_{di} define:

*The proportional term: providing an overall control action proportional to the error signal through the all pass gain factor [9 – 11].

*The integral term: reducing steady state errors through low-frequency compensation by an integrator.

*The derivative term: improving transient response through high-frequency compensation by a differentiator. In our simulations, the computation of the MIMO PID parameters is based on our experiences in EV control. Therefore, there are no specific methods to the MIMO PID computations because our controllers have two important considerations: the speed references (acceleration, brake) and the road topology (slope, curve) and each motor has to considerate the error speed of the other. Our MIMO PID parameters are given as follows:

MIMO PID	Lef Wheel	Right Wheels
K_P	1200	1200
K_d	2500	2500
K_i	400	400

5 Electronic Differential

The main purpose of the electronic differential (ED) is to substitute the mechanical differential in multi-drive systems, providing the required torque for each driving wheel and allowing different wheel speeds. Each drive-wheel's linear speed is given by [2,4,5, 6,12]:

$$V_1 = w_v\left(R - d/2\right), \tag{9}$$

$$V_2 = w_v\left(R + d/2\right), \tag{10}$$

where $R = L/\tan\delta$ and δ is the steering angle, when this angle is zero the vehicle is travelling on a stright path, and *d* is the width of the car. The angular speeds in curved roads are:

$$w_1 = \frac{L-(d/2)\tan\delta}{L} w_v, \tag{11}$$

$$w_2 = \frac{L+(d/2)\tan\delta}{L} w_v, \tag{12}$$

where L is the length of the car and w_V is the center of turn angular speed expressed by:

$$w_V = \frac{w_1 + w_2}{2}, \tag{13}$$

where $w_{1\text{ref}}$ and $w_{2\text{ref}}$ are the output electronic differential speed references submitted for the wheels.

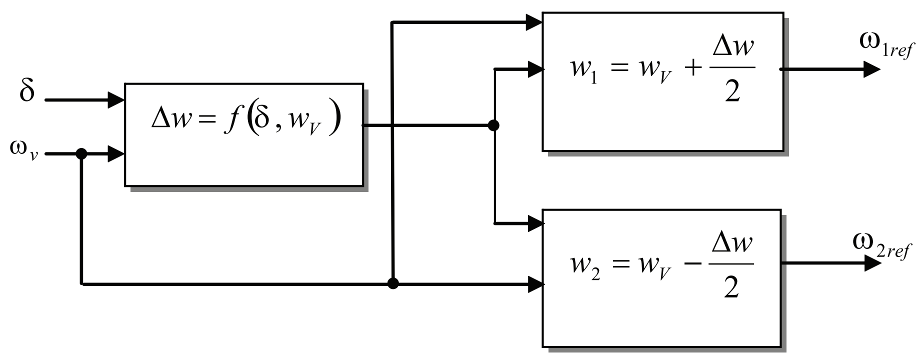

Fig. 3 – *The electronic differential of the* EV.

Table 1
Electric vehicle Parameters.

T_e	Motor traction torque	247 Nm
J_e	Moment on inertia of the drive train	7.07 kgm^2
R_w	Wheel radius	0.36 m
a	Total gear ratio	10.0
η	Total transmission efficiency	93 %
M	Vehicle mass	3904 kg
f_e	Bearing friction coefficient	0.001
K_d	Aerodynamic coefficient	0.46
A	Vehicle frontal area	3.48 m^2
f_v	Vehicle friction coefficient	0.01
α	Grade angle of the road	rad
L_w	Distance between two wheels and axles	2.5 m
d_w	Distance between the back and the front wheels	1.5 m

Table 2
Induction Motors Parameters.

R_r	Rotor winding resistance (per phase)	0.003 Ω
R_s	Stator winding resistance (per phase)	0.0044 Ω
L_s	Stator leakage inductance (per phase)	16.1 μH
L_m	Magnetising inductance (per phase)	482 μH
L_r	Rotor leakage inductance (per phase)	12.9 μH
f_c	Friction coefficient	0.0014
P	Number of poles	4
V_h	Vehicle linear speed	60 km/h

6 Simulation Results

In order to characterise the driving wheel system's behaviour, simulations were carried using the model of Fig. 2. They show vehicle speed variation for PID and MIMO-PID controllers in the following road trajectory:

– Curved road at right side at 2 s and left side's at 5 s with speed of 60 km/h under slope at 3 s and inverse slope's road at 5 s. Simulation were carried on Matlab Simulink and we obtained the following results:

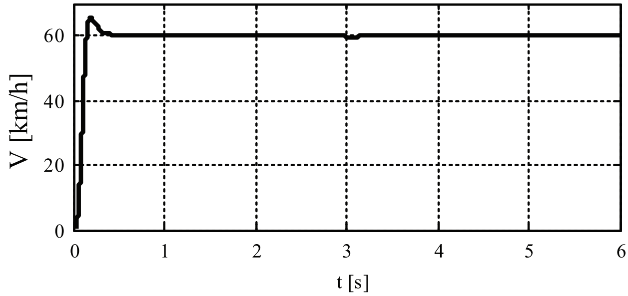

Fig. 4– PID *vehicle linear speed variation*.

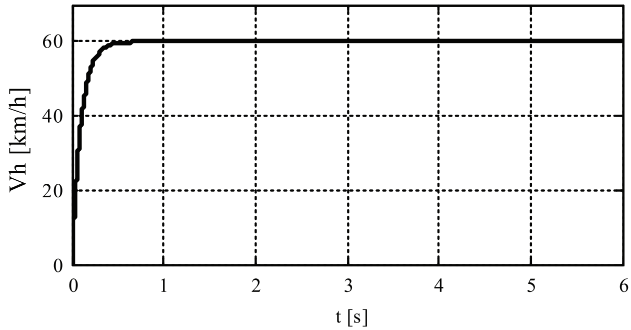

Fig. 5 – MIMO-PID *vehicle linear speed*.

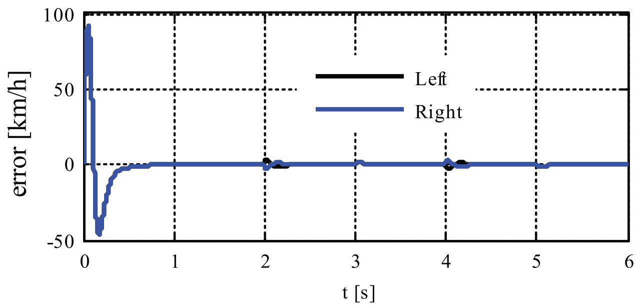

Fig. 6 – PID *vehicle speed error variation.*

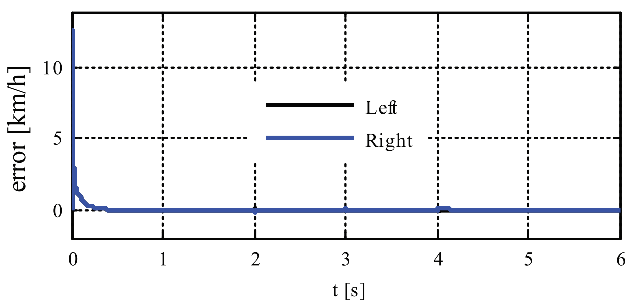

Fig. 7 – MIMO-PID *vehicle speed error variation*.

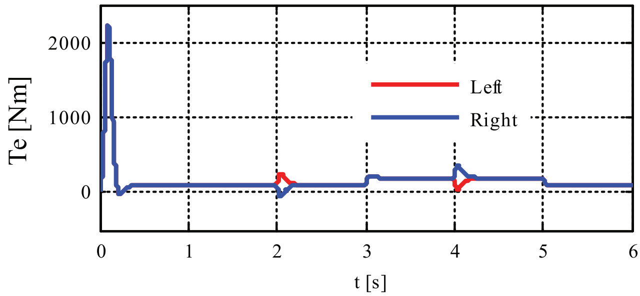

Fig. 8 – PID *vehicle traction motors torque variation*.

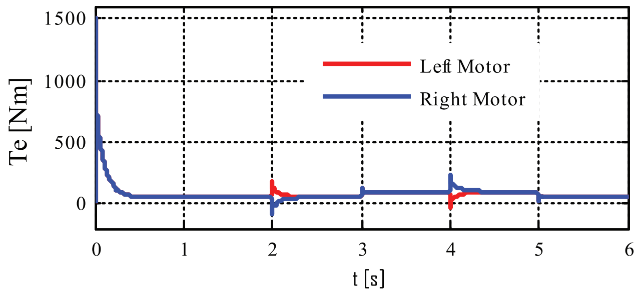

Fig. 9 – MIMO-PID *vehicle traction motors torque variation.*

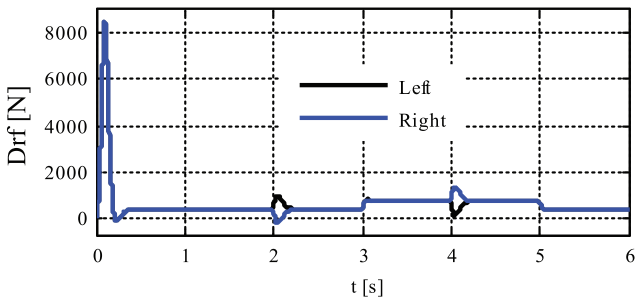

Fig. 10 – PID *vehicle driving forces variations*.

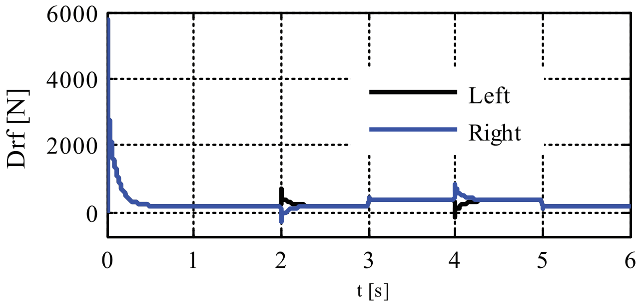

Fig. 11 – MIMO-PID *vehicle driving forces.*

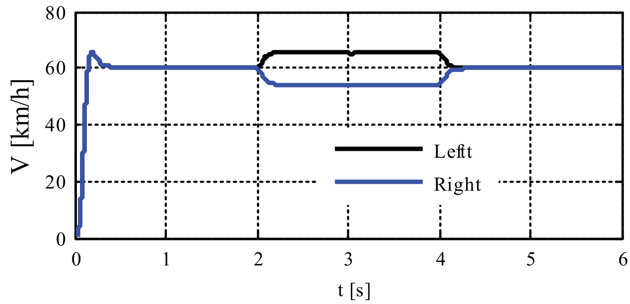

Fig. 12 – PID *right and left wheels speed variations.*

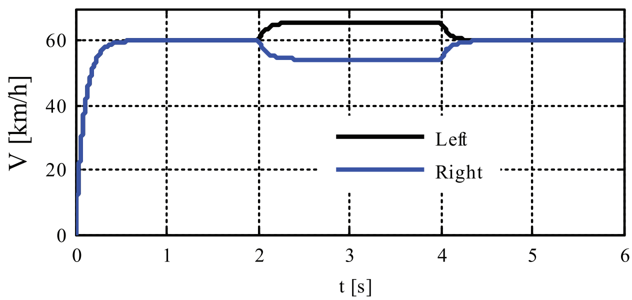

Fig. 13 – MIMO-PID *right and left wheels speed variations.*

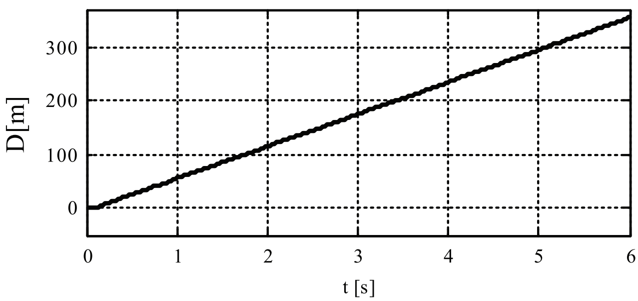

Fig. 14 – PID *vehicle travelled distance variations.*

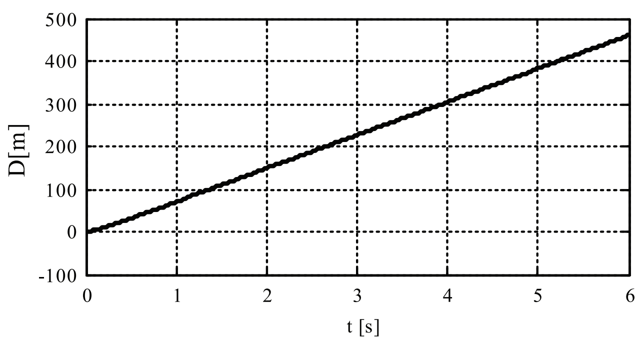

Fig. 15 – MIMO-PID *vehicle travelled distance.*

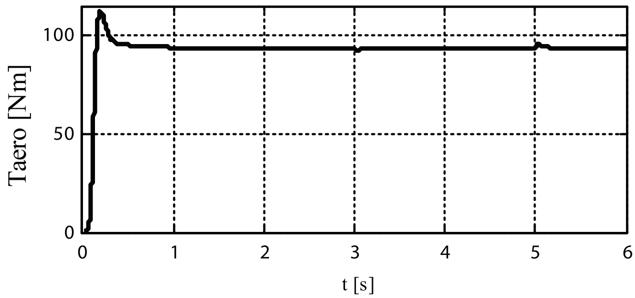

Fig. 16 –PID *vehicle aerodynamic torque variations.*

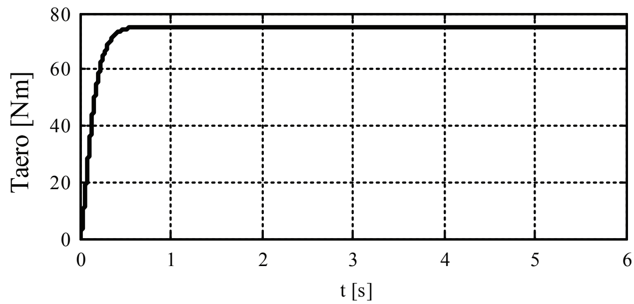

Fig. 17 – MIMO-PID *vehicle aerodynamic torque variations.*

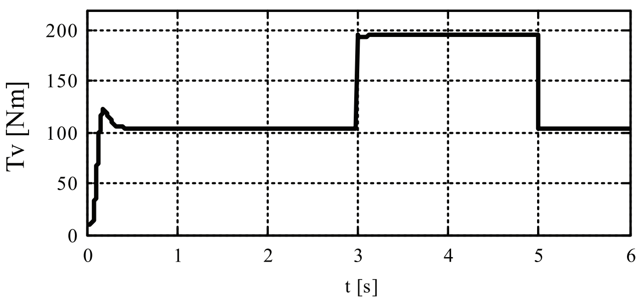

Fig. 18 – PID *vehicle load torque variations.*

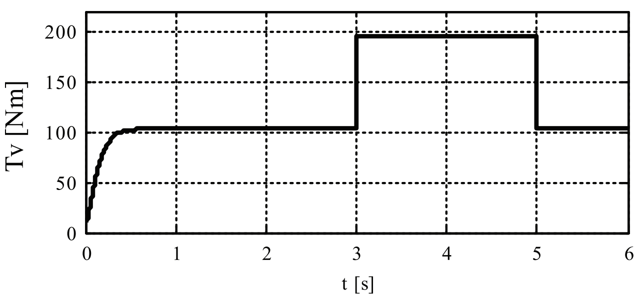

Fig. 19 – MIMO-PID *vehicle load torque variations.*

To compare the effects of disturbances on the vehicle's speed, Figs. 4 and 5 show the system response in the two cases of the two types of controls (MIMO-PID the PID classical control).

– A 10% sloped road at 60km/h speed at time 3 and 5 s:

In this test, the system is submitted to the same speed steps. The speed of the driving wheels always stays the same and the road slope does not affect the control of the wheel, as shown in Figs. 4 and 5. Therefore, the MIMO-PID controller acts immediately to reduce the speed error by the constraints of the road slope and give increased efficiency to the electronic differential output references. We can say the slope sensitises the motorisation to develop efforts in order to satisfy the electric traction chain demand, as shown in Figs. 8 and 9. The error speed is reduced with MIMO-PID compared with PID, as shown in Figs. 6 and 7. The distance the vehicle travelled is improved with MIMO-PID compared with the classical PID (**Table 3**), travelling 460.2 m and 354.2 m, respectively, as shown in Figs. 14 and 15. The aerodynamic torque is also reduced with MIMO-PID in comparison with PID; it's maximum value is only 75.13 Nm (Fig. 17) compared to the maximum value of 93.2 Nm in PID (Fig. 16). This is by the means of the vehicle frontal area being reduced by 19 % in the case of MIMO-PID. Thus, the estimated used frontal area is only 2.8812 m^2. The rising time is improved for MIMO-PID, whereas the overshoot is equal to 9.33% for the case of PID. The global torque load is perfected in the MIMO-PID case (Fig. 19) compared with the PID controller in Fig. 18.

– Curved road at right side with speed of 60km/h at 2 and 4 s:

The vehicle is driving on a curved road on the right-hand side at a speed of 60 km/h. In this scenarion, 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 initially decreasing the speed of the driving wheel on the right-hand side, situated on the inside of the curve and by increasing the wheel motor speed on the external side of the curve, and then applying the inverse state at 5 s (left side). The MIMO-PID control ensures the vehicle's stability and safety through the curve by maintaining the motorisation error speed equal to zero, and by giveing better dynamical behaviour of the traction chain compared with that of PID one's (Figs. 12 and 13). We can summarise all the obtained results in the **Table 3**.

Table 3
PI *and* MIMO-PID *results.*

Controller	PID	MIMO-PID
travelled distance [m]	354.4	460.2
linear speed error [km/h]	0.13	0
rising time [s]	0.55	0.50
overshoot [%]	9.33	0
slope effect	yes	no effect
aerodynamic torque [Nm]	93.2	75.13
vehicle frontal area reduced rate [%]	0	19
estimated vehicle frontal area [m^2]	3.48m^2	2.8188

7 Conclusion

In this paper, a novel electronic differential control system for a two-independent-wheel drive electric vehicle was proposed based on a multi-variable PID controller. This maximum control structure method was employed to adjust the slip rate of each wheel. The results indicated that the electronic differential system operated satisfactorily and that a two-wheel-individual drive electric vehicle can operate smoothly on both a straight or curved path using a MIMO-PID controller. The electronic differential can realise all the functions of the mechanical differential while reducing the weight and potentially it has a future in commercial urban electric vehicles.

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