EXPERIMENTAL AND SIMULATION RESULTS OF AN ELECTRIC VEHICLE

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Abstract

The subject of this paper is presents the experimental and simulation results of an electric vehicle with two independent rear wheel drives and electric differential systems.
An electric differential was implemented assuring that, in straight right trajectory, the two wheel drives roll exactly at same velocity and, in curve, the difference between the two velocities assure a vehicle trajectory.
Analysis, simulation and experimental results of the proposed system are presented.

Keywords: Electric vehicle, electric differential, simulation and control.

I. INTRODUCTION

The importance of electric road vehicles are not limited to environmental impact benefits, but also, to its capability of control the generated torque with a better and precise dynamic performance. So, the major advantages of electric drives are the effective control traction force applied between the tire and the road surface.

From the easiness of control of the electric motors it is easy to implement an electric differential, using an electric motor associate to each wheel drive.

It will be, thus, presented a model of the vehicle, as well as, the relation of the speed difference between the wheel drives in a cornering path. A controller is considered to guarantee this speed difference in the wheel drives, by means of the reading of the speed of each wheel and the steering angle.

II. ELECTRIC VEHICLE STRUTURE WITH TWO INDEPENDENT REAR WHEEL DRIVES

The vehicle considered in the analysis and target for the implementation of the proposed control system is a kart (fig. 1). Starting from an usual vehicle structure, some adaptations are made with the objective of introducing two independent rear wheels propulsion system using electric drives.

Fig. 1 – Experimental electric vehicle with two independent wheel drives.

In figure 2 is showed the implemented system (electric and mechanical components) in the experimental vehicle, with a electrical differential of independent wheel drives.

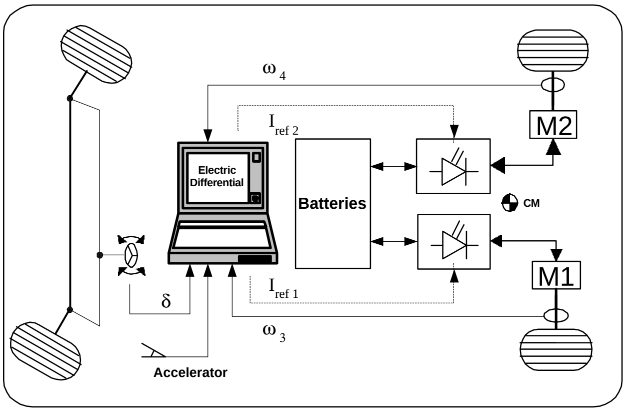
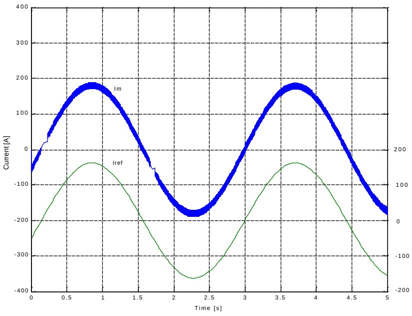


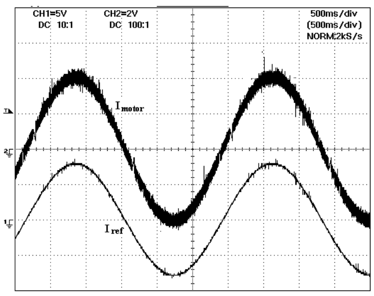
Fig. 2 – Propulsion and control system of the kart.

The electric differential controller was implemented in a microprocessor that receives the speed signal from the wheel drives and the steer angle calculating the speed difference in both the wheel drives, in function of the steer angle. As result, he places in the output the reference current for each electric motor, in order that the vehicle describes the desired path.

Each wheel drive is coupled to a 10kW permanent magnet DC machine. A compact power electronics converter with two independent 4Q choppers, handling each one with 48V, 200A and a maximum switching frequency of 33 kHz, was developed in the team (for 36V, the motor nominal power output is only 7,2 kW).
Figure 3 show some simulation and experimental results of the proposed methodology, where a current control was assumed.



a)

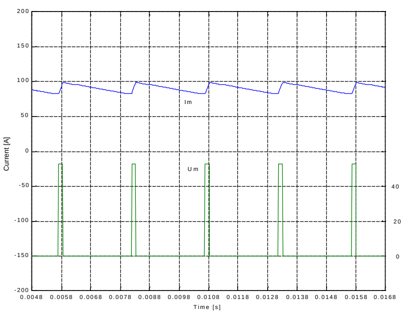


Im (20 A/div)
Iref (20 A/div)

b)

Fig. 3 – Histeretic current control of 3 level chopper results for sinusoidal reference. a) Simulations, b) Experimental.

In order to reduce the power switching frequency a 4Q chopper with 3 level output voltage was developed. The figure 4 show the voltage and current output of 3 level chopper results.



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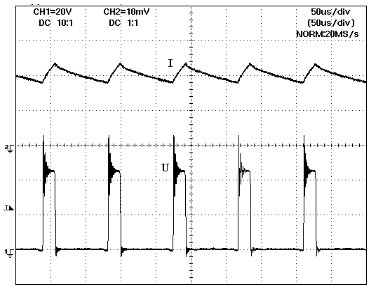


U (20 V/div)
I (50 A/div)

b)

Fig. 4 – Voltage and current output of 3 level chopper results. a) Simulations, b) Experimental

III. ELECTRIC DIFFERENTIAL

A. Speed difference of the wheel drives

Figure 5 presents the vehicle structure describing a curve, where *L* represents the wheelbase, *d* the steering angle, *d* the distance between the wheels of the same axle and w_3 and w_4 the angular speeds of the wheel drives, respectively.

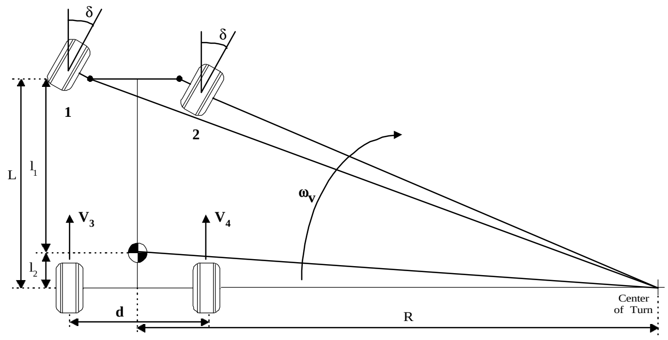


Fig. 5 – Vehicle struture in curve.

In accordance with figure 5, the linear speed of each wheel drive is express as a function of the vehicle speed and the radius of turn, by equations (1) and (2).

$$V_3 = w_V\left(R + d/2\right) \quad (1)$$
$$V_4 = w_V\left(R - d/2\right) \quad (2)$$

The radius of curve depends on the wheelbase and steering angle (equation (3)):

$$R = \frac{L}{\tan d} \quad (3)$$

Substituting (3) in equations (1) and (2), we obtain the angular speed in each wheel drive (equations (4) and (5)):

$$w_3 = \frac{L + d/2\tan d}{L} w_V \quad (4)$$

$$w_4 = \frac{L - d/2\tan d}{L} w_V \quad (5)$$

The difference between the angular speeds of the wheel drives is express by equation (6). The signal of the steering angle indicates the curve direction (7).

$$\Delta w = w_3 - w_4 = \frac{d \tan d}{L} w_V \tag{6}$$

$$\begin{cases} d > 0 & \Rightarrow \textit{Turn right} \\ d = 0 & \Rightarrow \textit{Straight ahed} \\ d < 0 & \Rightarrow \textit{Turn left} \end{cases} \tag{7}$$

The simulation results of the described system were obtained from the block diagram represented in figure 6.

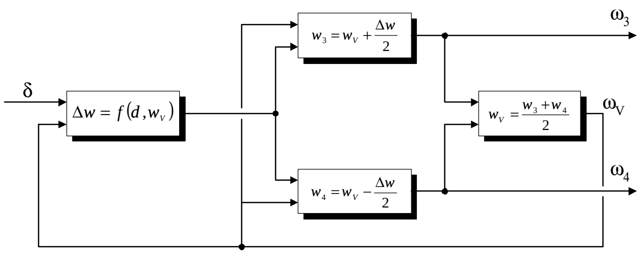


Fig. 6 – Block diagram of the electric differential system.

B. Global model of the electric differential

Figure 7 presents the functional principle of the proposed system control for the electric differential. A current loop is used to control each motor torque. The speed of each rear wheels is controlled using a feedback of the relative speed difference of the two wheels drives (w_3 and w_4).

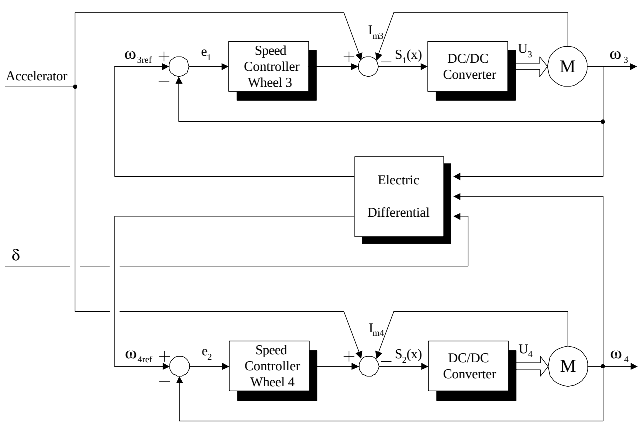


Fig. 7 – System control struture.

From the electric and mechanical equations of a DC permanent magnets motor we obtain the state model: $\dot{x} = Ax + Bu$

$$\begin{bmatrix} \frac{di}{dt} \\ \frac{dw}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & -\frac{K_f f}{L} \\ \frac{K_f f}{J} & 0 \end{bmatrix} \cdot \begin{bmatrix} i \\ w \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & -\frac{1}{J} \end{bmatrix} \cdot \begin{bmatrix} u \\ T_R \end{bmatrix} \tag{8}$$

where u and i are the motor armature voltage and current values and w is the motor angular speed. The magnetic flux f is imposed by the permanent magnets and T_R is the load torque. Parameters R, L and J are, respectively, armature resistance, inductance and global inertia moment.

The speed control includes a solution in cascade with an internal current control in the electric motor. The speed controller is a *PI* controller; this act in the current motor in order to assure the desired trajectory. The *PI* controller is implemented by software, in the microprocessor; the inputs are the speeds in each wheel drive and the steering angle.

The current control is a sliding mode control, where the function S(X) is the switching function that returns the logic value of command f(t) for the DC/DC converter, and is expressed by: $S(X) = i_{ref} - i$.

The current reference is obtain by the following equations:

$$i_{ref} = \left(K_P + \frac{K_I}{s}\right) \cdot \left(w_{ref} - w\right) + i_{acc} \tag{9}$$

By substitution the equations (9) in *S(X)*, result a switching function *S(X)*, equation (10) and their derivate (11):

$$S(X) = \left(K_P + \frac{K_I}{s}\right) \cdot \left(w_{ref} - w\right) - i \tag{10}$$

$$\dot{S}(X) = K_P \dot{w}_{ref} - K_P \dot{w} + K_I w_{ref} - K_I w - \frac{di}{dt} \tag{11}$$

Equally the switching function derivate to $\dot{S} = 0$, and substituting in the motor model (8) the result is a global state model, equation (12):

$$\begin{bmatrix} \frac{di}{dt} \\ \frac{dw}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{K_P K_f f}{J} & -K_I \\ \frac{K_f f}{J} & 0 \end{bmatrix} \cdot \begin{bmatrix} i \\ w \end{bmatrix} + \begin{bmatrix} K_P & K_I & \frac{K_P}{J} \\ 0 & 0 & -\frac{1}{J} \end{bmatrix} \cdot \begin{bmatrix} \frac{dw_{ref}}{dt} \\ w_{ref} \\ T_R \end{bmatrix} \tag{12}$$

Transfer functions:

$$\begin{cases} i = \dfrac{s^2 \cdot K_P + s \cdot K_I}{s^2 + s \cdot \dfrac{K_P \cdot K_f \cdot f}{J} + \dfrac{K_I \cdot K_f \cdot f}{J}} \cdot w_{ref} + \\ \quad + \dfrac{\dfrac{s \cdot K_P}{J} + \dfrac{K_I}{J}}{s^2 + s \cdot \dfrac{K_P \cdot K_f \cdot f}{J} + \dfrac{K_I \cdot K_f \cdot f}{J}} \cdot T_R \\ w = \dfrac{s \cdot \dfrac{K_P \cdot K_f \cdot f}{J} + \dfrac{K_I \cdot K_f f}{J}}{s^2 + s \cdot \dfrac{K_P \cdot K_f \cdot f}{J} + \dfrac{K_I \cdot K_f \cdot f}{J}} \cdot w_{ref} + \\ \quad + \dfrac{s}{s^2 + s \cdot \dfrac{K_P \cdot K_f \cdot f}{J} + \dfrac{K_I \cdot K_f \cdot f}{J}} \cdot T_R \end{cases} \tag{13}$$

In order to obtain a good response in terms of *w*, the parameters of the *PI* controller, K_I and K_P, must be correctly selected. As, for a second order system, the solution of the characteristics equation is $s_{1,2} = -xw_n \pm jw_n$. To achieve an optimum performance, the PI controller parameters are chosen as $x = 0{,}707$, $T_s = 0{,}5\ s$ and $w_n = 10{,}5\ rad/s$, to obtain the values $K_P = 183$ and $K_I = 1370$.

The figure 8 shows a block diagram of speed controller.

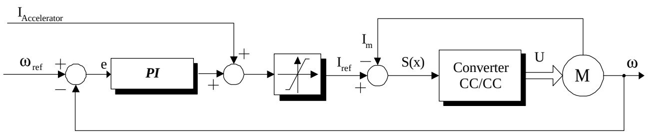
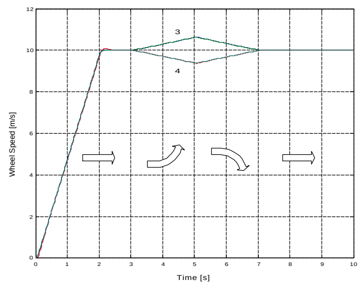


Fig. 8 – Speed Controller.

IV. SIMULATION RESULTS

Figure 9 shows the simulation results of the performance of the electric differential. The figure 9 a) presents the evolution of the speed of each wheel drives for the steering angle variation during $3 < t < 7\,s$. The figure 9 b) shows an electrical current evolution in each electric motors of form to guarantee the speeds of the figure a) and figure 9 c) shows de vehicle trajectory.



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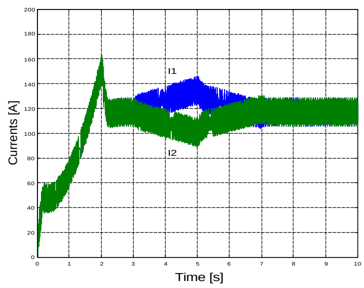

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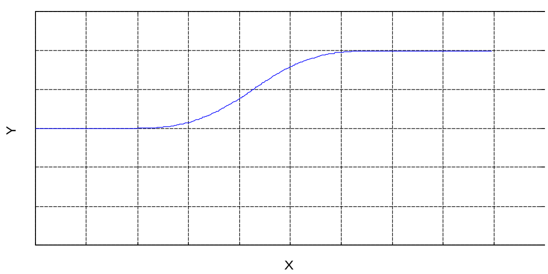


c)

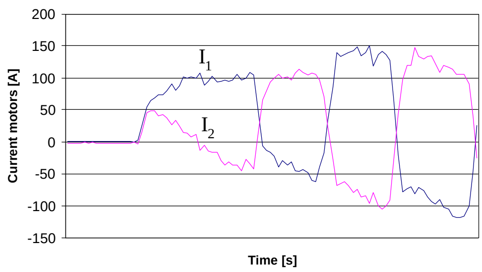
Fig. 9 – Simulations results: a) Wheels speed, b) Current motors, c) Trajectory.

V. EXPERIMENTAL RESULTS

During the experimental tests performance of the electric differential, it was applied free wheels in the front of the vehicle, to guarantee that the steering wheel don't contact the road, as it shows in figure 10.

Fig. 10 – Experimental electric vehicle with free wheels.

Figure 11 shows the experimental results of the performance of the electric differential in the slalom trajectory. The figure 11 a) shows an electrical current evolution in each electric motors of form to guarantee the speeds of the figure b). The figure 11 b) presents the evolution of the speed of each wheel drives for the steering angle variation shows in the figure 11 c).



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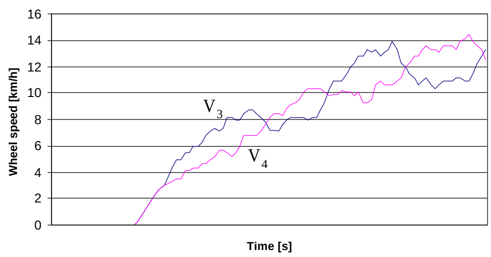

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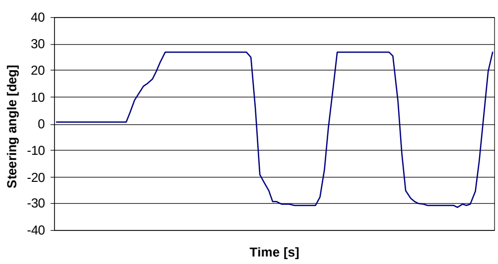

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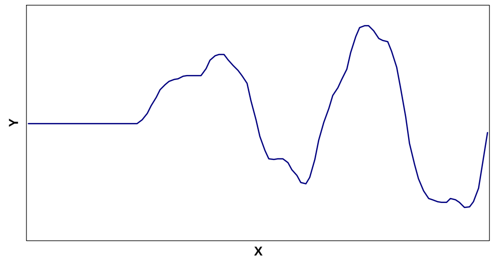
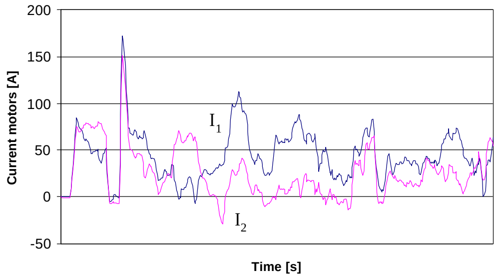


d)

Fig. 11 – Experimental results: a) Current motors, b) Wheels speed, c) Steering angle, d) Trajectory.

The figure 12 shows the experimental results of the performance of the electric differential in another type of trajectory. The figure 12 a) shows an electrical current evolution in each electric motors of form to guarantee the speeds of the figure b). The figure 12 b) presents the evolution of the speed of each wheel drives for the steering angle variation shows in the figure 12 c).



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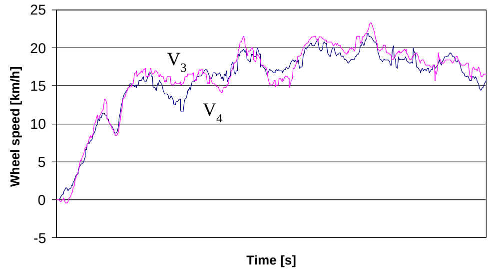

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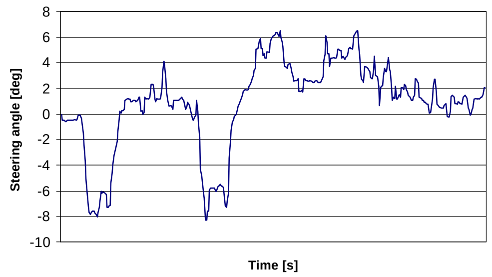

c)

Fig. 12 – Experimental results: a) Current motors, b) Wheels speed, c) Steering angle.

VI. CONCLUSIONS

In this paper analysed the simulation and experimental results of an electric vehicle with two independent rear wheel drives and electric differential.

In vehicles the electric traction, the electrical differential assuring in this way the difference wheel drives speed during a curve. It was showed in the experimental results the performance the electric differential with front free wheels vehicle that describe a trajectory in accordance with the steering angle.

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