International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 4, No. 4, December 2014, pp. 557~566
ISSN: 2088-8694

Fuzzy Adaptive Control for Direct Torque in Electric Vehicle

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Article Info

Article history:

Received Jun 6, 2013
Revised Oct 3, 2013
Accepted Oct 15, 2013

Keyword:

DTFC
Electric vehicle
Electronic differential
Fuzzy adaptive PI controller
MSAP

ABSTRACT

This paper presents a technique to control the electric vehicle (EV) speed and torque at any curve. Our propulsion model consists of two permanent magnet synchronous (PMSM) motors. The fuzzy adaptive PI controller is used to adjust the different static error constants, as per the speed error. The suggested based on the direct torque fuzzy control (DTFC). A Mamdani type fuzzy direct torque controller is first developed and then rules are modified using stator current membership functions. The computations are ensured by the electronic differential, this driving process permit to steer each driving wheels at any curve separately.Modeling and simulation are carried out using the Matlab/Simulink tool to investigate the performance of the proposed system.

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1. INTRODUCTION

Permanent magnet synchronous motors (PMSM) are widely used in high-performance drives such as industrial robots and machine tools thanks to their known advantages of: high power density, high-torque/inertia ratio, and free maintenance [1]. In recent years the DTC becomes widely used in term of control. However, there is another approach which has achieved a significant success and could be referred as the intelligent based DTC drives. In this case, one of the most successful types of PMSM DTC schemes are those based on fuzzy logic system. In fact, fuzzy logic based direct torque control (DTFC) has become a competitive control technique to traction motor in EV drive compared to vector control method.Where the classical schemes might fail to operate properly. Furthermore, with a well designed DTFC scheme, significant improvements in terms of flux, torque ripples could be attained. Also, it should be mentioned that for the DTFC schemes which are based on the classical DTC structure, the inherited advantages of such schemes (quick dynamic response) could be maintained.The main goal of using a DTFC algorithm for PMSM drives is to overcome some of the drawbacks of the original DTC. but, this reduces torque ripple greatly and the fast response and robustness merits of the classical DTC In order to present the electronic differential system for an electric vehicle driven by two permanent magnet synchronous motors attached to the rear wheel using fuzzy adaptive controller PI with direct torque fuzzy control, different tests have been carried out: driving vehicle on straight road, driving vehicle in curved road right and left [10].

The paper is organized as follows. In section II is presented, mathematical model of an PMSM, Electric Traction System Elements Modeling is outlined in section III and the electric differential system in the VI section. Finally the proposed fuzzy adaptive PI controller for DTFC and PMSM drive in electric vehicle is presented with simulation results.

2. PMSM MODEL AND DTC FUNDAMENTALS

For the design presented in this paper it is considered that the two rear wheels of the electric vehicle are driven PMSM.

2.1. Machine Equations

The mathematical model of the PMSM in the rotor reference frame (d–q) is given by [3- 4]:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_s + pL_d & -w_r * L_q \\ w_r * L_d & R_s + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ w_r * \varphi_f \end{bmatrix} \quad (1)$$

R_s : Stator resistance.

L_d, L_q : d, q axes inductances.

φ_f : Permanent magnet flux linkage.

i_d, i_q : Stator current .

v_d, v_q : Stator voltage.

w_r : Rotor angular velocity.

Transforming (1) from d-q to α-β coordinate, the following voltage equation (2) are given by:

$$\begin{cases} v_\alpha = R_s i_\alpha + L_d p i_\alpha + w_r (L_d - L_q) i_\beta + e_\alpha \\ v_\beta = R_s i_\beta + L_d p i_\beta - w_r (L_d - L_q) i_\alpha + e_\beta \end{cases} \quad (2)$$

Where e_α and e_β are phase BEMF and,

$$\begin{cases} e_\alpha = \{(L_d - L_q)(w_r p i_d - p i_q) + w_r \varphi_f\}(-\sin\theta_r) \\ e_\beta = \{(L_d - L_q)(w_r p i_d - p i_q) + w_r \varphi_f\}(\cos\theta_r) \end{cases} \quad (3)$$

Where v_α , v_β are α axis and β axis voltage components, i_α and i_α , i_β are α axis and β axis current components, θ_r is rotor angular, p is the differential operator(=d/dt).

Based on (2), the mathematical models of PMSM under the stationary (α,β) reference frames are:

$$\begin{pmatrix} \frac{d i_\alpha}{dt} \\ \frac{d i_\beta}{dt} \end{pmatrix} = \begin{pmatrix} -\frac{R_s}{L_d} & -w_r\left(\frac{L_d - L_q}{L_d}\right) \\ w_r\left(\frac{L_d - L_q}{L_d}\right) & -\frac{R_s}{L_d} \end{pmatrix} \begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} + \begin{pmatrix} -\frac{1}{L_d} & 0 \\ 0 & -\frac{1}{L_d} \end{pmatrix} \begin{pmatrix} E_\alpha \\ E_\beta \end{pmatrix} + \frac{1}{L_d} \begin{pmatrix} v_\alpha \\ v_\beta \end{pmatrix} \quad (4)$$

The generated electromagnetic torque (T_e) of PMSM can be expressed in terms of stator flux linkage and current as:

$$T_e = \frac{3}{2} p \left(\varphi_\alpha i_\beta - \varphi_\beta i_\alpha \right) \quad (5)$$

For a uniform air gap surface-mounted PMSM motor, $L_d = L_q = L_s$, the state flux linkage in the α-β frame can also be given by:

$$\begin{cases} \frac{d\varphi_\alpha}{dt} = v_\alpha - R_s i_\alpha \\ \frac{d\varphi_\beta}{dt} = v_\beta - R_s i_\beta \end{cases} \quad (6)$$

The amplitude of the stator flux linkage (φ_α)is:

$$\varphi_s = \sqrt{\varphi_\alpha^2 + \varphi_\beta^2} \tag{7}$$

The mechanical dynamic equation is given by:

$$J \frac{dw_r}{dt} = p(T_e - T_L) - f\, w_r \tag{8}$$

Where T_e is electromagnetic torque, p is pole pairs ,J is the inertia of PMSM, f is friction factor and T_L is load torque.

Using (2)-(8), a dynamic model of the PM synchronous motors can be described as:

$$\begin{cases} \begin{pmatrix} \frac{d i_\alpha}{dt} \\ \frac{d i_\beta}{dt} \end{pmatrix} = \begin{pmatrix} -\frac{R_s}{L_d} & 0 \\ 0 & -\frac{R_s}{L_d} \end{pmatrix} \begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} + \begin{pmatrix} -\frac{1}{L_d} & 0 \\ 0 & -\frac{1}{L_d} \end{pmatrix} \begin{pmatrix} E_\alpha \\ E_\beta \end{pmatrix} + \frac{1}{L_d} \begin{pmatrix} v_\alpha \\ v_\beta \end{pmatrix} \\ T_e = \frac{3}{2} p \varphi_f (i_\beta \cos\theta_r - i_\alpha \sin\theta_r) \\ \frac{dw_r}{dt} = \frac{p}{J}(T_e - T_L) - \frac{f}{J} w_r \end{cases} \tag{9}$$

3. ELECTRIC TRACTION SYSTEM ELEMENTS MODELING

Figure 1 represents general diagram of an electric traction system using an permanent magnet synchronous machines (PMSM) supplied by voltage inverter [6].

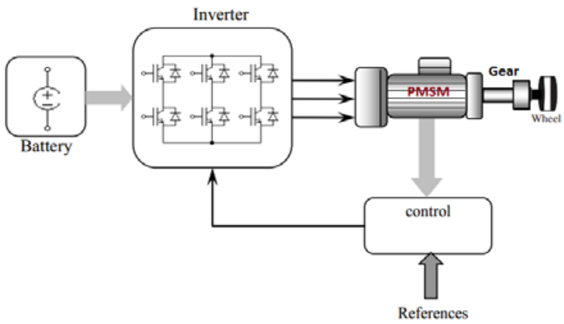

Figure 1. Electrical traction chain

3.1. Energy Source

The source of energy is generally a Lithium-Ion battery system. Lithium-Ion battery technology offers advantages of specific energy, specific power, and life over other types of rechargeable batteries [7-8].

3.2. Inverter Model

In this electric traction system, we use an inverter to obtain three balanced phases of alternating current with variable frequency from the current battery [5].

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \frac{U_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \tag{10}$$

3.3. Vehicle Dynamics Analysis

Based on principles of vehicle mechanics and aerodynamics [2], the road load F_{res} can be described with accuracy via (1).

The power P_v, required to drive a vehicle at a v speed has to compensate the roed load Fw.

$$P_v = v\,F_{res} = v\left(F_{roll} + F_{slope} + F_{aero}\right) \quad (11)$$

F_{roll} :is the rolling resistance.
F_{slope} :is the slope resistance.
F_{aero} :is the aerodynamic drag.

$$F_{roll} = \mu M g \quad (12)$$

$$F_{slope} = Mg\ \sin(\alpha) \quad (13)$$

$$F_{aero} = \frac{1}{2}\rho\, C_x A_f \left(v - v_0\right)^2 \quad (14)$$

The forces acting on the vehicle are shown in Figure 2.

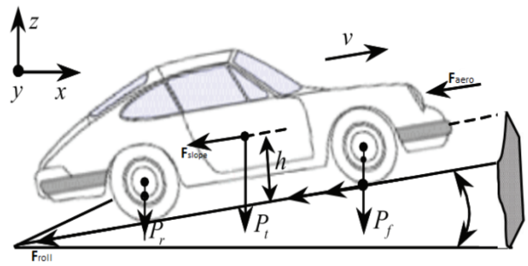

Figure 2. Forces acting on vehicle

4. THE ELECTRIC DIFFERENTIAL AND ITS IMPLEMENTATION

Figure 3 illustrates the implemented system (electric and mechanical components) in the Matlab Simulink environment.The proposed control system principle could be summarized as follows: (2) A current loop, based on fuzzy mode control, is used to control each motor torque, The speed of each rear wheel is controlled using speeds difference feedback.

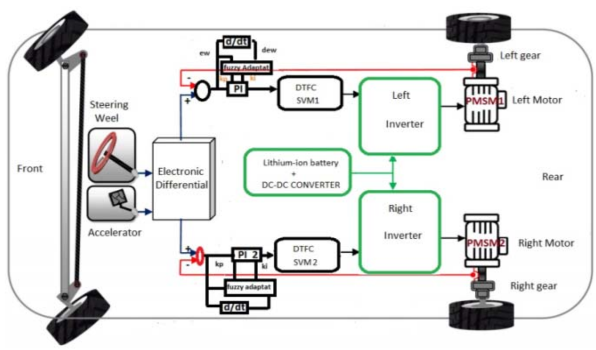

Figure 3. EV propulsion and control systems schematic diagram

Since the two rear wheels are directly driven by two separate motors, the speed of the outer wheel will require being higher than the speed of the inner wheel during steering maneuvers (and vice-versa) [14].

In this case however can be easily met if a position encoder is used to sense the angular position of the steering wheel. The reference speed Wref is then set by the accelerator pedal command. The actual reference speed for the left drive Wref – left and the right drive Wref – right are then obtained by adjusting the reference speed Wref using the output signal from the position encoder. If the vehicle is turning right, the left wheel speed is increased and the right wheel speed remains equal to the reference speed Wref.

If the vehicle is turning left the right wheel speed is increased and the left wheel speed remains equal to the reference speed Wref [9-10].

Modern cars can't use pure Ackermann-Jeantaud steering, partly because it ignores important dynamic and compliant effects, but the principle is sound for low speed maneuvers [11]. It is illustrated in Figure 4.

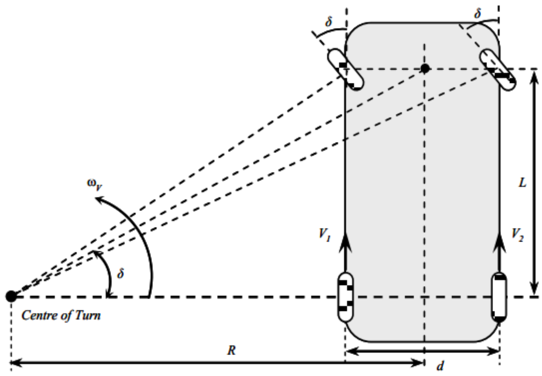

Figure 4. Driving trajectory model

The difference between the angular speeds of the wheel drives is expressed by the relation:

$$\Delta w = w_{mes\ 1} - w_{mes\ 2} = -\frac{d_w \tan\ \delta}{L_w} w_v \tag{15}$$

And the steering angle indicates the trajectory direction.

$$\begin{cases} \delta \rangle 0 \rightarrow turn\ ...left \\ \delta \langle 0 \rightarrow turn\ ...right \\ \delta = 0\, straight\ \ ...ahead \end{cases} \tag{16}$$

In accordance with the above described equation, Figure 5 show the electric differential system block diagram as used for simulations.

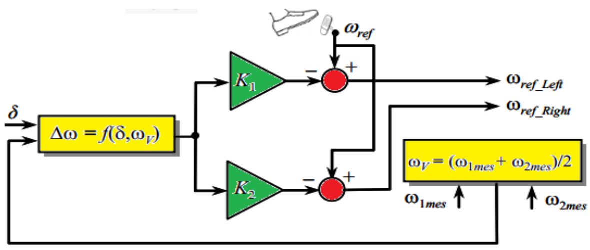

Figure 5. Block diagram show use of the electronic differential.

5. FUZZY ADAPTIVE PI CONTROL ALGORITHM

The fuzzy adaptive PI controllers have been widely applied to industrial process. The application of this technique in the speed control of EV is shown in Figure 3. The application contains two steps the first is a simple PI controller and the second is fuzzy logic controller. the fuzzy adaptive control system select the parameter of the PI control by the mamdani rules. This will be produce automatic control strategies for our system.The fuzzy adaptive PI controller is illustrated in Figure 6(a).

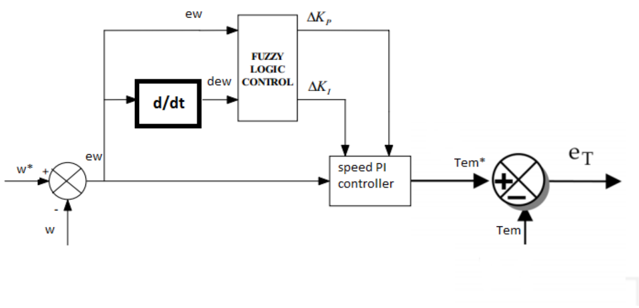

Figure 6(a). Structure of fuzzy adaptive PI controller

The expression of the PI is given in the Equation (17).

$$x(t) = \Delta K_p * e(t) + \Delta K_i * \int_0^t e(t)dt \tag{17}$$

The membership function used by fuzzy controller are defines as Negative large (NL), Negative Small (NS), negative medium (NM), Zero (Z), Positive Small (PS), and Positive Big (PB).

The control rules are framed to achieve the best performance of the fuzzy controller. These rules are given in the Table 1 and 2.

Table 1. Kp Fuzzy control rule

de(w) \ e(w)	NL	NM	NS	Z	PS	PM	PB
N	L	M	S	M	S	M	L
Z	L	M	L	Z	L	M	L
P	L	M	L	Z	L	M	L

Table 2. Ki Fuzzy control rule

de(w) \ e(w)	NL	NM	NS	Z	PS	PM	PB
N	Z	S	M	L	M	S	Z
Z	Z	S	M	L	M	S	Z
P	Z	M	L	L	L	M	Z

the surface view of Kp, Ki are shown in Figure 6(b), and 6(c), respectively.

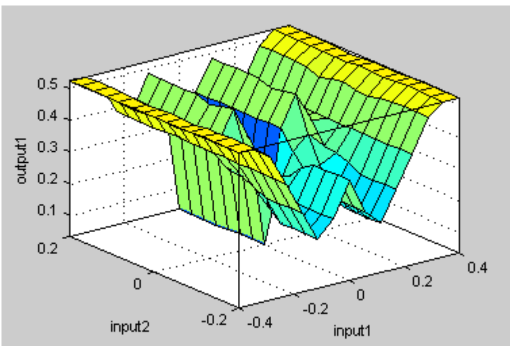

Figure 6(b). Surface view of Kp

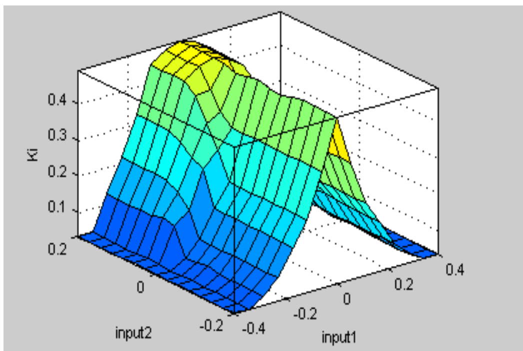

Figure 6(c). Surface view of Ki

6. FUZZY DIRECT TORQUE CONTROL

In this present paper, We present DTFC of PMSM drive controlled by fuzzy Adaptive PI is the letter is generally based on classical DTC scheme.

A block diagram of the proposed drive scheme is illustrated in Figure 3. It could be seen that it has structure similar to the classical DTC schemes, while the hysteresis controllers are replaced by a single fuzzy controller. The fuzzy controller is a Mamdani type with two inputs and one output.

It receives two inputs of torque error (e_T)flux error (e_φ) and fuzzity them with adequate number of fuzzy subsets. Then, based on the provided fuzzy reasoning rules, for each state of flux and torque error values the most appropriate control signal is chosen, used along with stator flux position section to index grid of optimum voltage vectors. A fuzzy logic controller is appled to the direct torque controls [11]-[12] so as to minimizethe torque ripple and to maximize the drive efficiency. The major problem with switching table based DTC drive is high torque and current ripples. To increase precision of traditional DTC of induction motor control and decrease large torque ripple, a fuzzy DTC control system along with a fuzzy adaptive PI controller is proposed. Figure 3 shows the control scheme with the fuzzy logic controller which modifies the DTC by incorporating fuzzy logic into it. A Fuzzy logic method is used in this study to improve the steady state performance of a conventional DTC system.Fig 6.d schematically shows a direct torque fuzzy control in which the fuzzy controllers replace the flux linkage and torque hysteresis controllers.

The switching table is the sume as the one used in a conventional DTC system [13]. Basically, a Fuzzy controller is composed of a fuzzification part, a fuzzy inference part and a defuzzification part. The input membership functions for this fuzzy controller are shown in Figure 4. It could be clearly seen that torque error is fuzzified into five fuzzy subsets of EZ (zero), SP (small positive), SN (small negative), LP (large positive), LN (large negative), MP (mean positive), MN (mean negative), in order to provide a proper torque control by using zero voltage vectors. Additionally, this methode enables more appropriate control actions to be taken for the small and large torque error values. In terms of flux error, three membership functions of EZ (zero), SP (small positive), SN (small negative), LP (large positive), LN (large negative), MP (mean positive), MN (mean negative), are employed. Actually, the further subsets for flux error input would be excessive and would add to the system complexity.

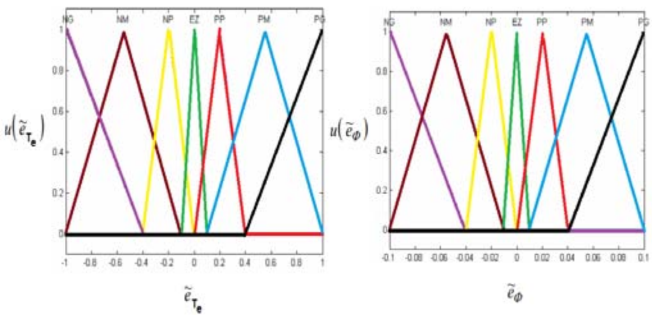

Figure 6(d). Input membership functions for (a) Torque error, (b) Flux error

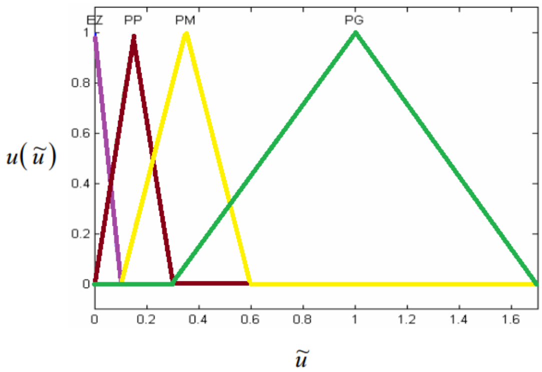

Figure 6(e). Output membership functions for reference voltage

As mentioned earlier, for a complete fuzzy control scheme besides fuzzy inputs and outputs, a list of fuzzy rules is also required which basically relates each set of possible inputs state to the proper output. In this control scheme, a fuzzy inference system with forty-nine fuzzy rules is employed. In fact, the number of required fuzzy rules could be easily calculated from the presented fuzzy subsets for each one of the inputs. A desirable fuzzy control would be seized just with the convergence of all possible input states. The list of provided fuzzy rules is shown in Table 3.

Table 3. Shows the table proposed for the selection of the angle δ

ε_{φ}	P			Z			N		
ε_{T}	P	Z	N	P	Z	N	P	Z	N
δ	$+\frac{\pi}{3}$	0	$-\frac{\pi}{3}$	$+\frac{\pi}{2}$	$+\frac{\pi}{2}$	$-\frac{\pi}{2}$	$+\frac{2\pi}{3}$	$+\pi$	$-\frac{2\pi}{3}$

Table 4. List of fuzzy in reference rules

$e_{\varphi}e_{T}$	NG	NM	NP	EZ	PP	PM	PG
NG	PG	PM	PS	PS	PS	PM	PG
NM	PG	PM	PS	PS	PS	PM	PG
NP	PG	PM	PS	EZ	PS	PM	PG
EZ	PG	PM	PS	EZ	PS	PM	PG
PP	PG	PM	PS	EZ	PS	PM	PG
PM	PG	PM	PS	PS	PS	PM	PG
PG	PG	PM	PS	PS	PS	PM	PG

7. SIMULATION RESULTS

In order to characterize the driving wheel system behavior, simulations were carried using the model of Figure 3. They show motor current and the variation of speed for each motor. The following results was simulated in MATLAB

7.1. Straight Road

In this step the speed of the EV is equal 60Km/h. The Figure 5 shows that the speed of EV has two phases the first is between [0 4]s the second is between [4 5]s with speed equal 80 Km/h.

As we remark the speed of the tow back wheels are equal this improve that the electronic differential doesn't work in this case.When we apply resistive torques at 3s the figure shows that the only changed is in the direct torques, the developed motor torque is noticed. The slope effect results in high improvement in the electromagnetic motor torque, both on the left and the right of each motor. The system behavior is illustrated by Figure 7(a), 7(b), 7(d), and 7(e). Resistive torques are shown in Figure 7(f) .

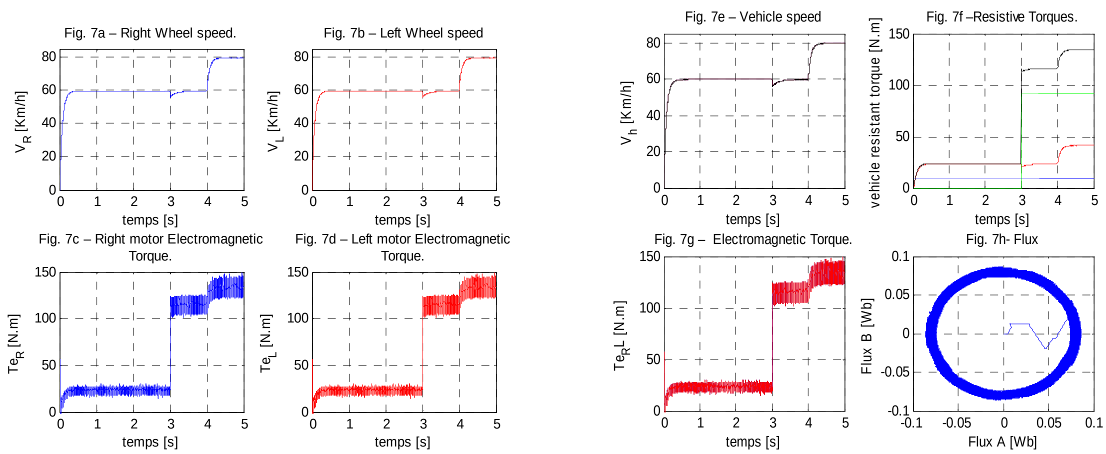

Figure 7. Straight road

7.2. Curved Road on the Right at Speed of 60km/h

The vehicle is driving on a curved road on the right side with 60km/h. In this case the driving wheels follow different paths, and they turn in the same direction but with different speeds.

At time equal 4s (straight road) we change the speed to 80Km/h. In this step the electronic differential change the speed of the two motor by decreasing the speed of the driving wheel on the right side, and increase the speed of the left wheel. The behavior of these speeds is given by Figure 8(a), 8(b) and 8(c).

Once this speed stabilizes, the torque returns to its initial value which corresponds to the total resistive torque applied on the motor wheels; the behavior is shown in Figure 8(f).

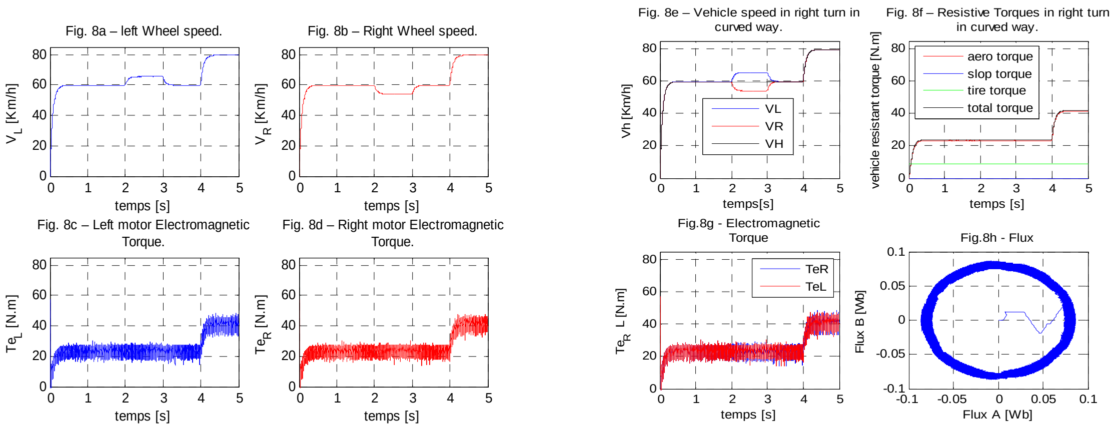

Figure 8. Curved road on the right

8. CONCLUSION

Our study is depend on the speed control of the EV through left or right road. This paper proposed a Adaptive Fuzzy Logic based Speed Control Of PMSM. The proposed control method considers the disturbance inputs representing the system nonlinearity or the unmodelled uncertainty to guarantee the robustness under motor parameter and load torque variations. Simulation and experimental results clearly demonstrated that the proposed control system can not only attenuate the chattering to the extent of other control methods (e.g., PI control, fuzzy control, etc.) but can also give a better transient performance.

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