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Fuzzy Adaptive PI Controller for DTC An electric vehicle With Two-Motor-Wheel Drive

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***Abstract*— this paper present the ordering of an electric vehicle EV at two driving wheels postpones by DTC and FDTC. This order is based on two estimators to control flux and the couple. The principal advantages of the FDTC are the speed of the dynamic response of couple and the weak dependence with respect to the parameters of the machine, as well as the simplicity of implementation in real time. This order is well adapted for the systems of electric traction.**

***Keywords*— PMSM; EV (Electric vehicle); DTC; FDTC (fuzzy direct torque control)**

I. INTRODUCTION

The vectorial order by orientation of rotor flow, presents the major disadvantage to be relatively sensitive to the variations of the parameters of the machine this is why one developed methods FDTC (fuzzy direct torque control) of permanent the magnet synchronous motor during the Eighties by Takahashi and Depenbrock, in these control methods stator flow and the electromagnetic couple are estimated starting from the only electric quantities accessible to the stator, and this without recourse to mechanical sensors.

In this work, a structure of vehicle was adapted allowing to obtain a vehicle with two independent wheel drives, Fig. 1.

This configuration with two traction wheels in the vehicle may present some advantages such as increasing the vehicle power with a better weight distribution and no power loss in the differential gear and will be possible to control the acceleration of each wheel individually for better stability in dangerous situations.

The traction system proposed consists of two permanent magnet synchronous machines (PMSM) that ensure the drive of the two back driving wheels. This system is called multi-machine multi-converter systems (MMS) [1].

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. The proposed control structure [2] called "independent machines" for speed control permits the achievement of an electronic differential based on direct torque fuzzy control (DTFC).

This paper proposes a novel fuzzy DTC system of PMSM for the purpose of minimizing the torque ripples. In this system, the errors of the stator flux linkage, torque, and flux angle of PMSM are all properly fuzzified into several fuzzy subsets to accurately select the voltage vector in order to smooth the torque ripples and accelerate the torque response. The stator flux angle was also mapped onto a reduced region to minimize the number of fuzzy rules, to shorten the computation time and to improve the response speed. In addition, the effects of zero voltage vectors in PMSM fuzzy DTC system are also analyzed. The proposed technique has been implemented in a practical industry drive system and verified by experiments.

II. PMSM MODEL AND DTC FUNDAMENTALS

For the design presented in this paper it is considered that the two rear wheels of the vehicle are driven permanent magnet synchronous motor.

A. *Machine equations*

The PMSM machine under the investigation can be model in the rotor reference frame as:

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

R_s : Stator resistance.

L_d, L_q : d, q axes inductances.

φ_f : Permanent magnet flux linkage.

i_d, i_q : Stator current .

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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:

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

Where E_α, E_β are phase BEMF and:

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

Where v_α , v_β are α axis and β axis voltage components, 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:

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

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

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

(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:

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

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

$$\varphi_s = \sqrt{\varphi_\alpha^2 + \varphi_\beta^2} \qquad (7)$$

The mechanical dynamic equation is given by

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

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

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

III. ELECTRIC TRACTION SYSTEM ELEMENTS MODELING

Fig. 1 represents general diagram of an electric traction system using an permanent magnet synchronous machines (PMSM) supplied by voltage inverter [3].

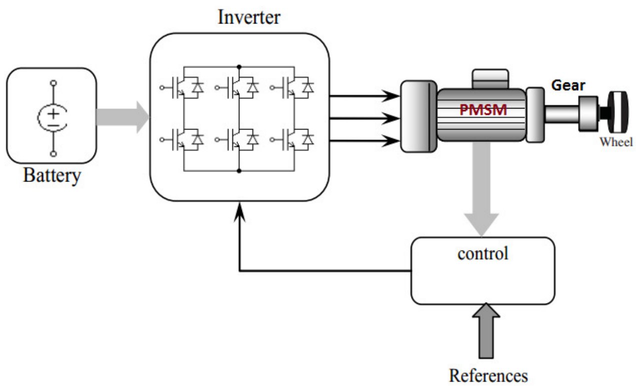

Fig. 1 Electrical traction chain.

A. *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 [3–4].

B. *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.

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

C. *Vehicle Dynamics Analysis*

Based on principles of vehicle dynamics and aerodynamics [5-6-7-8-14], the road load F_{res}

$$F_{res} = F_{roll} + F_{slope} + F_{aero} \quad (11)$$

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

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

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

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

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

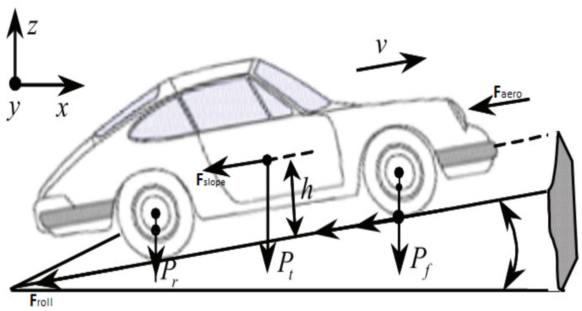

Fig. 2 Forces acting on vehicle

IV. THE ELECTRIC DIFFERENTIAL AND ITS IMPLEMENTATION

Fig.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.

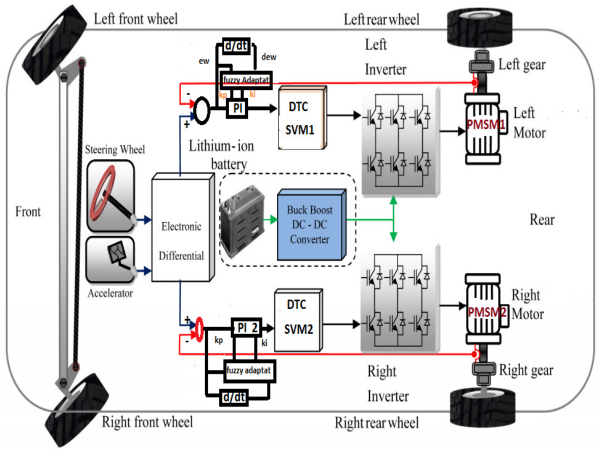

Fig. 3 EV propulsion and control systems schematic diagram

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).

This condition however can be easily met if a position encoder is used to sense the angular position of the steering wheel. The common 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 common 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 w heel speed remains equal to the common reference speed Wref. If the vehicle is turning le ft the right wheel speed is increased and the left wheel speed remains equal to the common reference speed Wref[9-10].

Modern cars do not 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 Fig. 4.

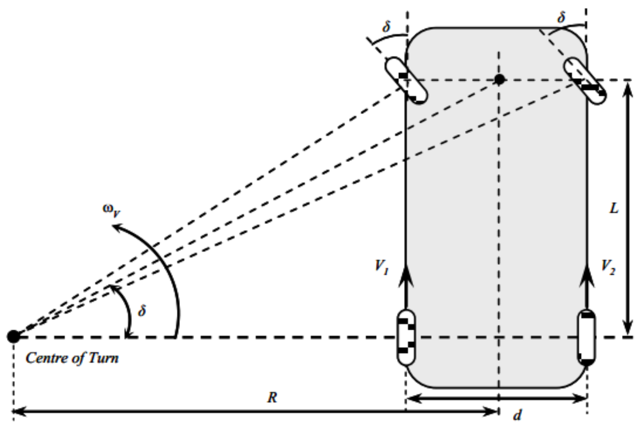

Fig. 4 Driving trajectory model

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

$$\Delta w = w_{mes\,1} - w_{mes\,2} = -\frac{d_w \tan \delta}{L_w} w_v \qquad (15)$$

and the steering angle indicates the trajectory direction

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

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

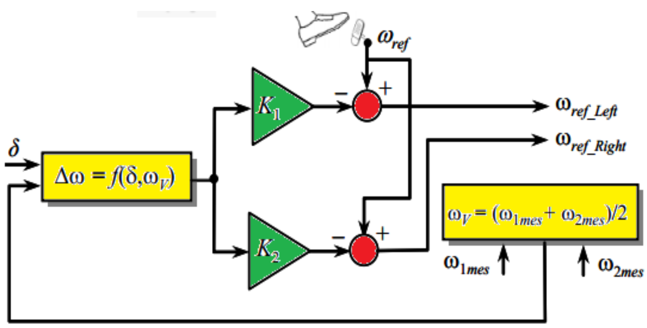

Fig.5 Block diagram show use of the electronic differential.

V. FUZZY DIRECT TORQUE CONTROL

The PI-speed controller does not have a satisfying performance in the transient state especially when a load is applied. Therefore, a fuzzy controller is presented to replace the PI block in order to improve the transient speed response [12,13]. Fuzzy controller has got two inputs: speed error (e) and its differential (de). Membership functions for inputs and the output are the same and illustrated in Figure 6. Subsequently, the fuzzy rule base is like Table I.

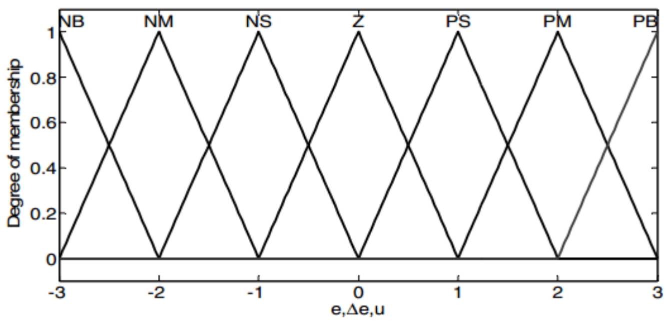

Fig. 6 Membership functions.

TABLE I

FUZZY RULE BASE

e \ de	PB	PM	PS	Z	NS	NM	NB
PB	Z	Z	Z	PB	PM	Z	Z
PM	Z	Z	Z	PM	Z	Z	Z
PS	Z	Z	Z	PS	Z	Z	NM
Z	PB	PM	PS	Z	NS	NM	NB
NS	PM	Z	Z	NS	Z	Z	Z
NM	Z	Z	Z	NM	Z	Z	Z
NB	Z	Z	NM	NB	Z	Z	Z

VI. SIMULATION RESULTS

In order to characterize the driving wheel system behavior, simulations were carried using the model of fig 3. They show motor current and the variation of speed for each motor.

A. 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 behaviour is illustrated by Figs. 7a, 7b, 7d, and 7e. Resistive torques is shown in Fig. 7f.

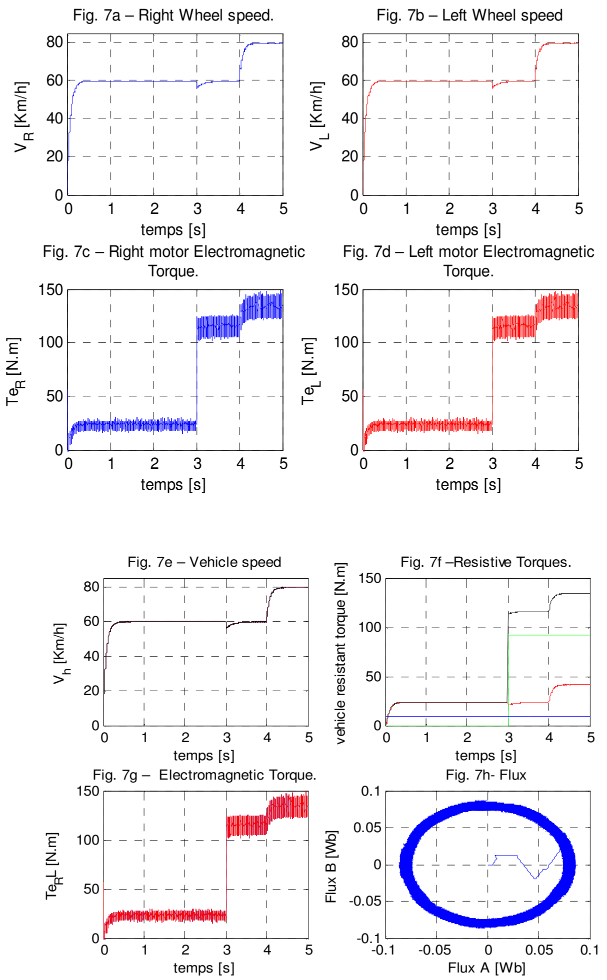

Fig. 7 Straight road.

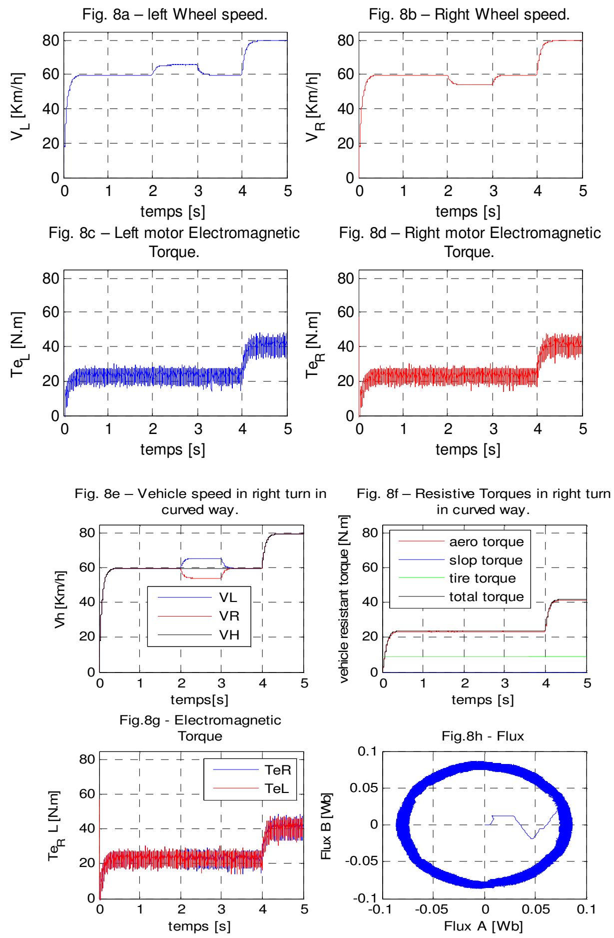

Fig. 8 Curved road on the right

B. 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 behaviour of these speeds is given by Fig. 8a, 8b and 8c.Once this speed stabilizes, the torque returns to its initial value which corresponds to the total resistive torque applied on the motor wheels; the behaviour is shown in Fig 8(f).

VII. CONCLUSIONS

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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