Electric Vehicle Stability with Rear Electronic Differential Traction

Yahia Miloud
Taher Moulay University of Saida

Abdallah Miloudi
Taher Moulay University of Saida

Electric Vehicle Stability with Rear Electronic Differential Traction

K. Hartani, Y. Miloud, A. Miloudi
Département d'Electrotechnique, Université de Saida
BP 138 En-Nasr, Saida 20000, ALGERIE
kada_hartani@yahoo.fr

Abstract* – In this paper, we model an electronic differential that will offer the best stability of vehicle in the curved road. The use of electronic differential constitutes a technological advance of vehicle design along the concept of more electric vehicles. Electronic differential have the advantages of replacing loosely, heavy and inefficient mechanical transmission and mechanical differential with a more efficient, light and small electric motors directly coupled to the wheels via a single gear or an in-wheel motor. To date, electronic differentials have been proposed for two and four wheeled vehicles. The proposed traction system consists of two permanent magnet synchronous (PMS) machines that ensure the drive of two back-driving wheels. The proposed control structure is based on the direct torque control for each wheel-motor. Different simulations have been carried out: vehicle driven on straight road, vehicle driven on straight road with slope, and vehicle driven over a road curved left and right. The simulation results show good vehicle stability on a curved road.

Keywords : *Eelectric vehicle, electronic differential, vehicle stability, direct torque control, multimachine drive.*

I. Introduction

Electric vehicle is a road vehicle, based on electric propulsion. The electric propulsion system is the heart of new generation of EV [1]. It consists of the motor drive, transmission device, and wheels. The motor drive consists of the electric motor, power converter, and electronic controller, which are the core of the EV propulsion system. Traditionally, DC motors have been prominent in electric propulsion because their torque-speed characteristic have suited to traction requirement well and their speed control is simple. Recently, technological developments have replaced commutatorless motors to a new era, leading with the advantages of high efficiency, high power density, low operating cost, enhanced reliability, and low maintenance over DC motors. Permanent magnet synchronous motors (PMSM) are a widely accepted commutatorless motor for EV propulsion because they are robust and highly reliable.

For improving the dynamic performance of PSM motor drives for electric vehicle propulsion, generally vector control technique is preferred. However vector control needs quite complicated coordinate transformations on line to decoupled the interaction between flux control and torque control to provide fast torque control of a permanent magnet synchronous motor. Hence the computation is time consuming and its implementation usually requires a high performance DSP chip. In recent years (DTC) an innovative control method called direct torque control has gained the attraction for electric propulsion system [2-4]; because it can also produce fast torque control of the induction motor and does not need heavy computation on-line, in contrast to vector control.

In order to characterise the electronic differential system for an electric vehicle driven by two permanent synchronous motors attached to the rear wheel using direct torque control (Fig. 1), different simulations have been carried out: simulating the vehicle driven vehicle on a straight road, a straight road with slope and driven over a road curved right and left.

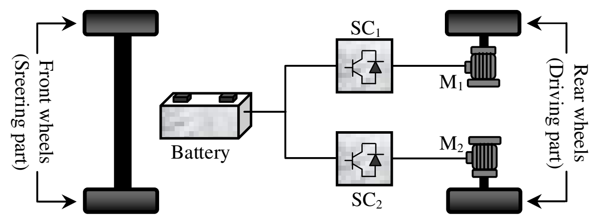


Fig. 1 : Vehicle structure with two independent rear wheels.

II. Traction Scheme

In traditional traction systems, the internal combustion engine transmits the propulsion force to the wheels through the mechanical differential. This mechanism consists of a set of gearings that basically applies the same torque on both traction wheels allowing different speed values. This traction system presents losses due to friction and cannot independently control torque in each wheel. An electronic differential, on the contrary, prevents such losses, while optimizing the device profitability. It also allows a stronger control of the vehicle traction. Fig. 2 shows the adopted scheme, which allows replacing the mechanical differential and satisfies the EV requirements. The traction motors, controlled by DTC[5]-[6] through two independent inverters, coupled to one of the rear wheels each, can be observer in this scheme. The motors used are three-phase PMS motors. The specific parameters of these motors are shown in Table A1.

Thus, the electronic differential must take account of the speed difference between the two wheels when cornering. The system uses the vehicle speed and steering angle as input parameters and calculates the required inner and outer wheel speeds where the two wheels are controlled independently by two PMS motors.

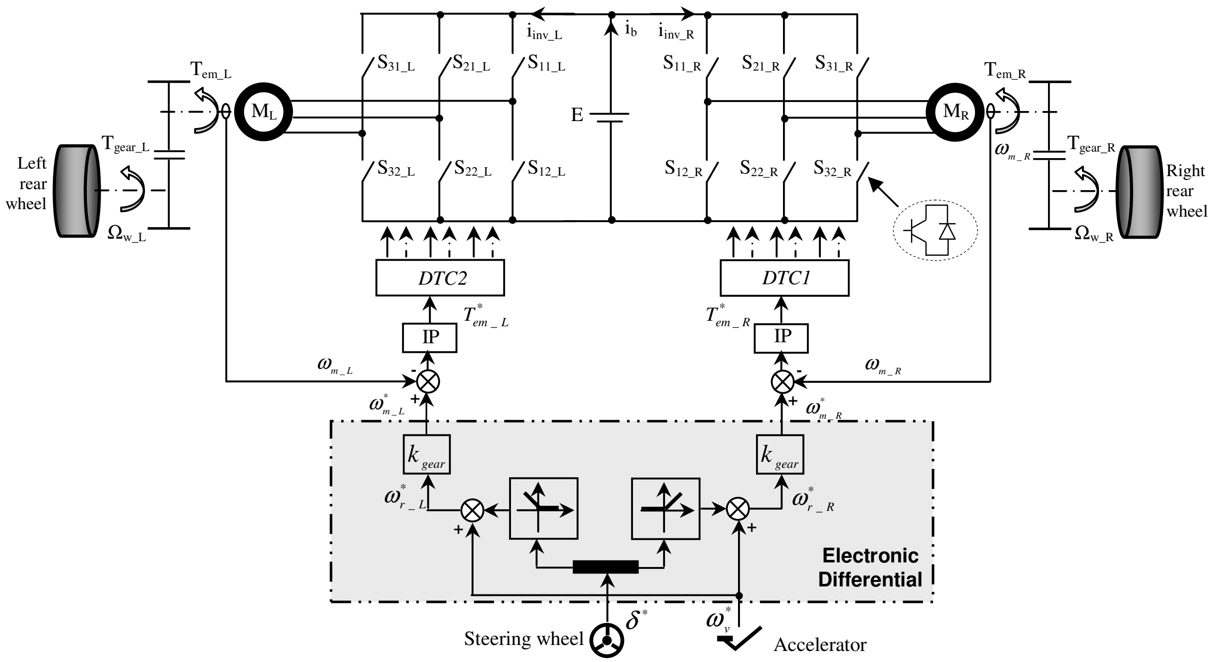


Fig. 2 : Components of the proposed control system.

A. Traction motor model

The PMSM model can be described in the stator reference frame as follows [7]:

$$\begin{cases} \frac{di_{s\alpha}}{dt} = -\frac{R_s}{L_s} i_{s\alpha} + \frac{\Phi_f}{L_s} \omega_m \sin\theta + \frac{1}{L_s} v_{s\alpha} \\ \frac{di_{s\beta}}{dt} = -\frac{R_s}{L_s} i_{s\beta} - \frac{\Phi_f}{L_s} \omega_m \cos\theta + \frac{1}{L_s} v_{s\beta} \\ \frac{d\omega_m}{dt} = -\frac{f}{J} \omega_m + \frac{p}{J}\left(T_{em} - T_r\right) \end{cases} \quad (1)$$

and the electromagnetic torque equation :

$$T_{em} = \frac{3}{2} p \Phi_f \left(-i_{s\alpha} \sin\theta + i_{s\beta} \cos\theta\right) \quad (2)$$

B. Inverter model

In this electric traction system, we use a voltage inverter to obtain three balanced phases of alternating current with variable frequency. The voltages generated by the inverter are given as follows:

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

C. Vehicle dynamic

The total resistive force is defined as [8]:

$$F_{res} = F_{roll} + F_{aero} + F_{slope} \quad (4)$$

and

$$F_{roll} = \mu M g \quad (5)$$

$$F_{aero} = \frac{1}{2} \rho C_x S V_h^2 \quad (6)$$

$$F_{slope} = Mg.\sin\alpha \quad (7)$$

Where F_{roll} is the rolling resistance, F_{aero} is the aerodynamic drag force and F_{slope} is the slope resistance.

III. Electronic Differential

The differential system allows the traction wheels to spins at different speeds. This condition is necessary when the vehicle follows a curve so that the external traction wheel moves describing a circumference whose radius is larger than that of the external traction wheel moves describing a circumference whose radius is larger than that of the internal traction wheel and therefore its speed must be higher [8]. The principle that explains a mechanical differential mechanism lies on applying the same torque on both traction wheels allowing the speed at each wheel to adopt the necessary value to balance the opposite torque [9]. This task is easily achievable through a torque control of the PMSMs. However, each wheel maximum speeds must be also controlled to prevent rotation speed from reaching dangerous speed values for the vehicle mechanical system if either slipping or off-the ground situation of one of the wheel occur. Considering that a vehicle performs a curve manoeuver at low speed, neglecting in consequence lateral forces and slipping over the traction wheels, the geometric model proposed by Ackerman and Jeantad [8] shown Fig. 3 can be used. Such model allows determining the rotation radius (R) from steering angle (δ) and in turn the angular speed values that each traction wheel must adopt ($\omega_{r\_R}, \omega_{r\_L}$).

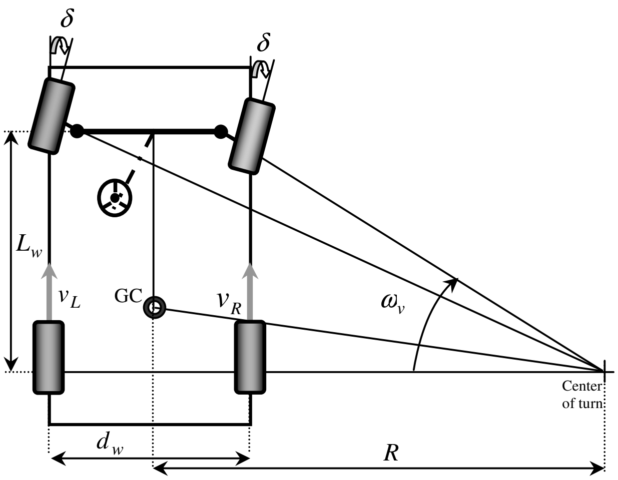


Fig. 3 : Ackerman geometry model.

The linear speed of each wheel drive is expressed as a function of the vehicle speed and the radius of curve, equations (8) and (9)

$$v_L = \omega_v\left(R + \frac{d_w}{2}\right) \tag{8}$$

$$v_R = \omega_v\left(R - \frac{d_w}{2}\right) \tag{9}$$

The radius of curve depends on the wheelbase and steering angle (equation (10)):

$$R = \frac{L_w}{\tan\delta} \tag{10}$$

Substituting (10) in equations (8) and (9), we obtain the angular speed in each wheel drive (equation (11) and (12)):

$$\omega_{r\_L} = \frac{L_w + d_w/2.\tan\delta}{L_w}\omega_v \tag{11}$$

$$\omega_{r\_R} = \frac{L_w - d_w/2.\tan\delta}{L_w}\omega_v \tag{12}$$

The difference between the angular speeds of the wheel drives is express by equation (13). The signal of the steering angle indicates the curve direction (14).

$$\Delta\omega = \omega_{r\_L} - \omega_{r\_R} = \frac{d_w.\tan\delta}{L_w}\omega_v \tag{13}$$

$$\begin{cases} \delta\rangle 0 & \Rightarrow \quad Turn \;\; right \\ \delta = 0 & \Rightarrow \quad Straight \;\; ahead \\ \delta\langle 0 & \Rightarrow \quad Turn \;\; left \end{cases} \tag{14}$$

When the vehicle arrives at the beginning of a curve, the driver applies a steering angle on the wheels. The electronic differential however acts immediately on the two motors reducing the speed of the inner wheel, and increases the speed of the outer wheel, Figure 4. The driving wheel angular speeds are:

$$\omega^*_{r\_L} = \omega_v + \frac{\Delta\omega}{2} \tag{15}$$

$$\omega^*_{r\_R} = \omega_v - \frac{\Delta\omega}{2} \tag{16}$$

The speed references of the two motors are:

$$\omega^*_{m\_L} = k_{gear}\omega^*_{r\_L} \tag{17}$$

$$\omega^*_{m\_R} = k_{gear}\omega^*_{r\_R} \tag{18}$$

where k_{gear} is the gearbox ratio.

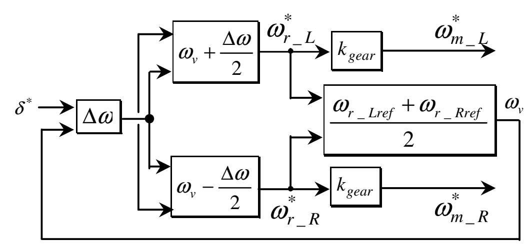


Fig. 4 : Block diagram of the electronic differential

IV. Simulation Results

In this section, the proposed technique is analyzed and evaluated in a two motor system during the transient and steady state via Matlab/Simulink. IP compensators are used in all the controllers, which was improved with anti-windup device in order to remove the characteristic PI transient overshoot. Different simulations have been carried out : simulating the vehicle driven vehicle on a straight road, a straight road with slope, and driven over a road curved right.

A. Straight road with zero slope

In this test, a 80km/h speed step is applied to our system. A good tracking of the speed step can be observed (Figure 5(a)). The vehicle speed reaches the step speed around 5,33s . The delay of this tracking speed is due to mechanical time constant which is related to the vehicle mass. In figures 5(g) and (h), the variation of phase currents for each motor is represented. We notice that it exists two intervals of dynamics of our vehicle. First, during the starting where each motor solicits a high current to attain the reference speed imposed by the driver. This current is due to the starting torque caused by the inertia of the vehicle. The second interval starts after $5{,}33s$ where each motor tries to develop an electromagnetic torque, Figure 5(e) to compensate the total resistive torque, Figure 5(i).

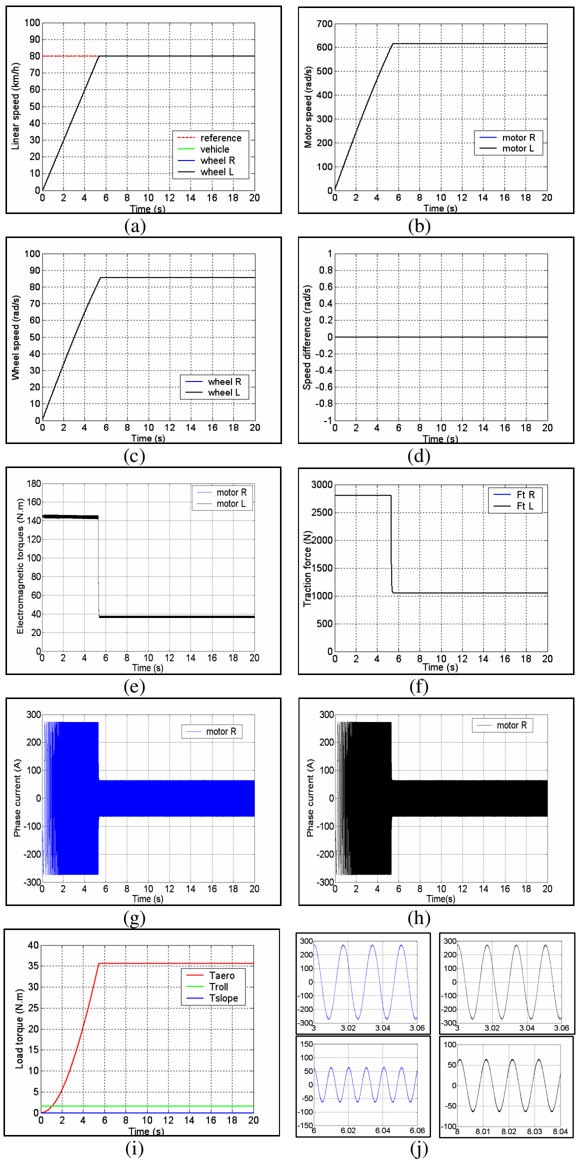


Fig. 5. Simulation results for case A.

B. *Clockwise-cureved road*

In this case, one the system attains the permanent state which is $80km/hr$, the vehicle is involved in a right turn at $t = 8s$. We consider that this curved road is carried out with a constant speed, however the driver makes a steering angle which will be a steering angle of the front wheels. When the speed of the right wheel is decreasing according to its new reference the torque tries to change sign due to the sudden change of speed step. Hence, the motor works in a braking mode by developing a negative torque. This working phase can be exploited as an energy recuperation towards the battery. Once the speed of the right wheel is stabilised, the torque returns to its initial value as it is shown in Figure 6(c). outside the curved road at $t = 18s$, this time the driver makes an inverse steering angle of the front wheels and the electronic differential will act at the same manner to make the difference speed zero, Figure 6(d). The variation of phase currents are shown in Figure 6(g), (h), (i), and (j).

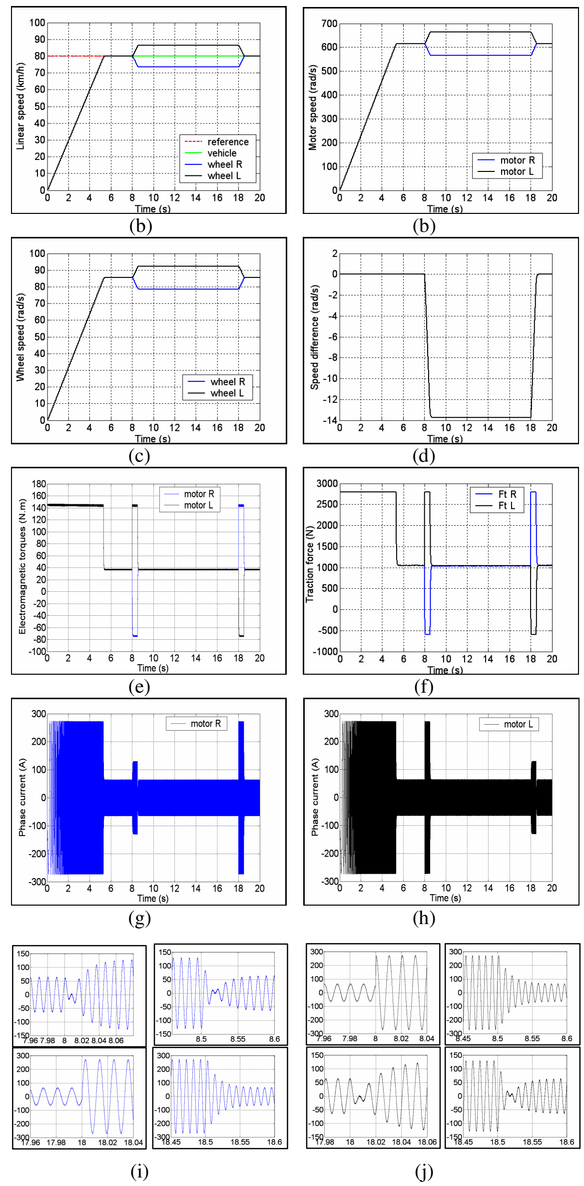
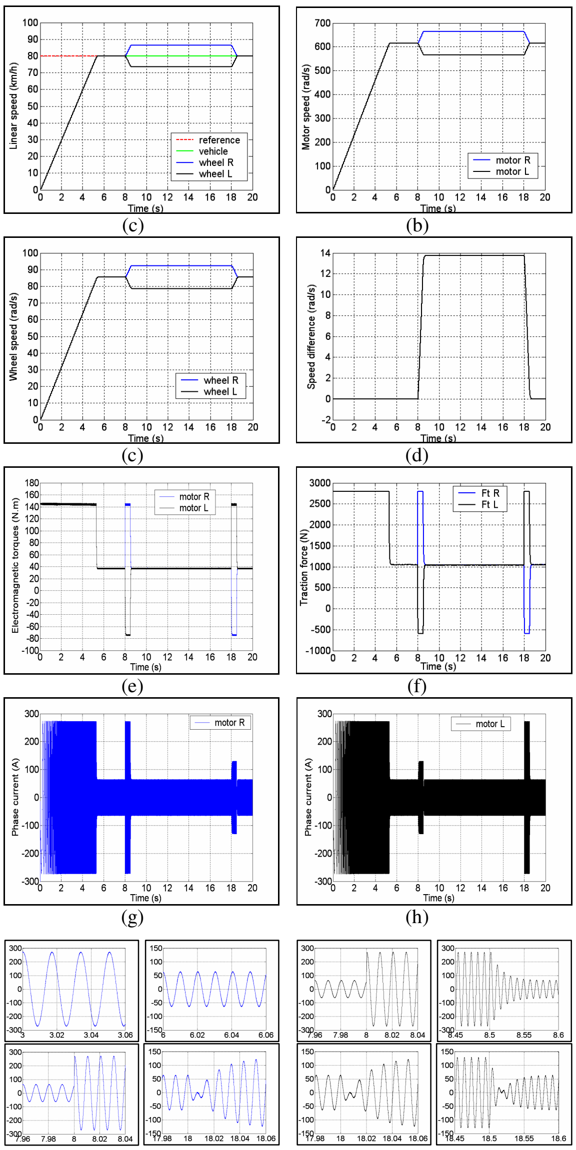


Fig. 6. Simulation results for case B.

C. *Counter-Clockwise-cureved road*

In this case, The vehicle is moving on a curved road on the left side at a speed of $80 km/hr$. Despite the driving wheels follow different paths but they turn in the same direction with different speeds. The left driving rear wheel turn with less speed than the right one. The behaviour of these speeds is given by figures 7(a), (b), (c), and (d). When the speed of the right wheel increases, the torque motor associated with this wheel, increases and tries to reach the growth of the speed. This change leads to a positive peak that corresponds to the speed of the right wheel. Once this speed stabilises itself, the torque returns to its initial value which corresponds to the total torque resistive applied on the motor wheels as it is shown in Figure 7(e).



(c) (b) (c) (d) (e) (f) (g) (h) (i) (j)

Fig. 7. Simulation results for case C

V. Conclusion

This work has presented the application of an electric vehicle controlled by an electronic differential with two permanent magnet in-wheel synchronous motor drives. The results obtained by simulation show that this structure permits the realisation of an electronic differential and ensure good dynamic and static performances. The electronic differential controls the driving wheels speeds with high accuracy either in flat roads or curved ones.

Appendix

Table A.1.
The specifications of motors

Resistance	0,03 Ω
d -axis inductance	0,2 mH
q -axis inductance	0,2 mH
Permanent magnet flux	0,08 Wb
Pole pairs	4

Table A.2
The specifications of the vehicle used in simulation

Vehicle total mass	1200 kg
Distance between two wheels and axes	2,5 m
Distance between the back and the front wheel	1,5 m
Wheel radius	0,26 m
Vehicle frontal area	1,9 m²
Aerodynamic drag coefficient	0,25 N/(ms)²
Gearbox ratio	7,2
Efficiency of the gearbox	98 %

References

[1] C. Chan, , "The state of the art of electric and hybrid vehicles," *Proc. Of the IEEE,* vol. 90, no. 2, pp. 247-275, Feb. 2002.
[2] J. Faiz, M. B. B. Sharifian, A. Keyhani, A. B. Proca, , "Sensorless direct torque control of induction motors used in electric vehicle," *IEEE Trans. Energy Conversion*, vol. 18, no. 1, Mars. 2003.
[3] J. Faiz, S.H. Hossieni, M. Ghaneei, A. Keyhani, A. B. Proca, "Direct torque control of induction motor for electric propulsion system," *Electric Power System Research,* vol. 51, pp. 95-101, Aug. 1999.
[4] K. Jezemik, "Speed sensorless torque control of induction motor for EVs," *Proc. IEE Intl. Workshop on Advanced Motion Control,* 2002, pp. 236-241.
[5] Cao, Xianqing, Zang, Chunhua, Fan, Liping, "*Direct Torque Controlled Drive for Permanent Magnet Synchronous Motor Based on Neural Networks and Multi Fuzzy Controllers,* " *IEEE International Conference on* Robotics and Biomimetics, 2006. ROBIO '06. pp. 197 – 201, 2006.
[6] I. Takahachi and T. Noguchi, "A new quick-response and high-efficiency control strategy of an induction motor," *IEEE Trans. Ind. Applicat.,* vol. 22, no. 5, pp. 820-827, 1986.
[7] P. Pragasen, R. Krishnan. "Modeling, Simulation, and Analysis of Permanent Magnets Motor Drives, Part I: The Permanent Magnets Synchronous Motor Drive," *IEEE Transactions on Industry Applications*. Vol.25, no.2, 265-273, 1989.
[8] T. Gillespice. "Fundamentals of vehicle dynamics," *Society of Automotive Engineers*, ISBN 1-56091-199-9.
[9] F. Willian, Millioken and L. Douglas Milliken, "Race car vehicle dynamics," *Society of Automotive Engineers*, SAE, 1995.