A Novel Electric Vehicle Drive Studies Based on Space Vector Modulation Technique and Direct Torque Control Strategy

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Abstract

Electric vehicles (EVs) speed and torque control undergo different road constraints is very difficult using classical control methods. To overcome this problem a comparative studies between two control methods is proposed, the first one is space vector modulation technique based direct torque control (DTC-SVM) and the second one is the direct torque control proposed. Acceleration, steering and speed reference computations are ensured by the electronic differential, this driving process permit to steer each driving wheels at any curve separately. The two proposed control methods constitute an efficient driving force estimations, the SVM-DTC is characterized with less torque ripple oscillations for this reason, the hysteresis controller is substituted by PI controller and switch table is replace with space vector modulation. Our double driven electric vehicle is simulated in Matlab SIMULINK environment. The electric vehicle was tested in different constraints road: straight, slope, inverse slope and curved roads, the present electric propulsion system results present satisfactory.

Keywords

electric vehicle, torque, electronic differential, SVM, DTC

1. INTRODUCTION

Actually, electric vehicles (EVs) including, full cell and hybrid vehicle have been developed very rapidly as a solution to energy and environmental problem. Vehicles are propelled by in-wheel or, simply, driven EVs are powered by electric motors through transmission and differential gears, while directly driven wheel motors [Yang et al., 2008]. The basic vehicle configurations of this research has two directly driven wheel motors installed and operated inside the driving wheels on pure EVs (Figure 5). These wheel motors can be controlled independently and have so quick and accurate response to the vehicle motion control [Nasri et al., 2010]. Like most research on the torque distribution control of wheel motor, wheel motors [Kang et al., 1999] proposed a dynamic optimal tractive force distribution control for an EV driven by four wheel motors, there by improving vehicle handling and stability [Chan et al., 2004]. The researchers assumed that wheel motors were all identical with the same torque constant neglecting motor dynamics the output torque was simply proportional to the input current with a prescribed torque constant. Direct torque control has become one of the most popular methods of control for induction motor drive systems [Zhu et al., 2007]. DTC can decouple the interaction between flux and torque control, based on both torque and flux instantaneous errors, and provide good torque response in steady state and transient operation conditions. The main advantages of DTC are: absence of coordinate transformation and current regulator, absence of separate voltage modulation block, the actual flux-linkage vector position does not have to be determined, but only the sector where the flux-linkage vector is located, etc. In addition, DTC minimizes the use of machine parameters, so it is very little sensible to the parameters variation [Itoh et al., 2005]. SVM method is an advanced, computation intensive PWM method and possibly the best among all the PWM techniques for variable speed drives application [Chen et al., 2003]. Because of its high performance characteristics, it has been finding a wide range electric vehicle drive application in recent years and this paper is one the most comparative DTC applications [Hartani, 2008]. The structure of the presented work is organized as follow: The principle components of the electric vehicle loads with their equations model is set in section 2. Section 3 shows the direct torque control of induction motor. Section 4 shows the development space vector modulation technique based DTC for electric vehicle motorization [Vasudevan et al., 2004]. The electronic differential speed references computations of the studied system is given in the section 5. The simulations results of the different studied cases are presented in section 6. Finally, the concluding remarks are given in section 7.

2. ELECTRIC VEHICLE MECHANICAL LOADS DESCRIPTION

According to Figure 1, the opposition forces acting to the vehicle motion are: the rolling resistance force $F_{t\text{-}ire}$, the aerodynamic drag force F_{aero}, and the climbing force F_{slope} that depends on the road slope [Yang et al., 2008].

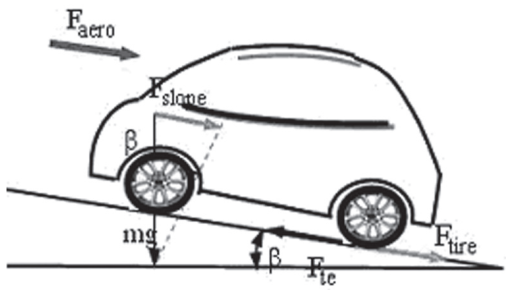

Fig. 1 The forces acting on a vehicle moving along a slope

The global resistive force is equal to F_r and is the sum of the resistance forces [Nasri et al., 2010], as in (1).

$$F_r = \underbrace{A_f C_d \frac{\rho_a v^2}{2}}_{\text{aerodynamic resistance}} + \underbrace{f_r M_v g \cos\beta}_{\text{rolling resistance}} + \underbrace{M_v g \sin\beta}_{\text{road slope}} \quad (1)$$

Where M_v is the vehicle masse, r is the tire radius, f_r is the rolling resistance force constant, g the gravity acceleration, ρ_{air} is Air density, C_d is the aerodynamic drag coefficient, A_f is the frontal surface area of the vehicle, v is the vehicle speed, β is the road slope angle. These coefficients values are shown in Table 1.

Table 1 Parameters of the electric vehicle model

r	0.32 m	A_f	2.60 m^2
M	1300 Kg	C_d	0.32
f_r	0.01	ρ_{air}	1.2 Kg/m^3

The vehicle simulated in this work consists of two-rear-driving wheels destined to urban transportation [Nasri et al., 2010], the two induction motors are coupled in each of the rear wheels. The energy source of the electric motors is assured by the Lithium-ion battery [Lam et al., 2006], controller by Buck boost DC-DC converter where the reference speeds of the two motors are computed by electronic differential which ensure these references speeds computations in straight and curved roads conditions [Nasri et al., 2008]. The propulsion system control schema of the EV is shown in Figure 5.

3. PRINCIPE OF SPACE VECTOR MODULATION SVM BASED DTC

This technique consist of two classical proportional integral (PI) controllers for the torque and the flux magnitude regulations instead of hysteresis band to generate the voltage command for inverter control as it shown in Figure 2. Due to the structure of the inverter, the DC bus voltage is fixed [Kang et al., 1999], therefore the speed of voltage space vectors isn't controlled, but we can adjust the speed by means of using the zero voltage vectors to control the electromagnetic torque generated by the induction motor [Chen et al., 2003]. The vectors selection isn't based on the flux linkage region, but on the error vector between the expected and the estimated Stator flux linkage ϕ_s given by:

$$\phi_s = \int_0^t (V_s - R_s i_s)dt \quad (2)$$

The electromagnetic torque can be calculated by:

$$T_{em} = \frac{3}{2} p\,(\phi_{s\alpha} i_{s\beta} - \phi_{s\beta} i_{s\alpha}) \quad (3)$$

The Block diagram of SVM based DTC induction motor drive is shown in Figure 2.

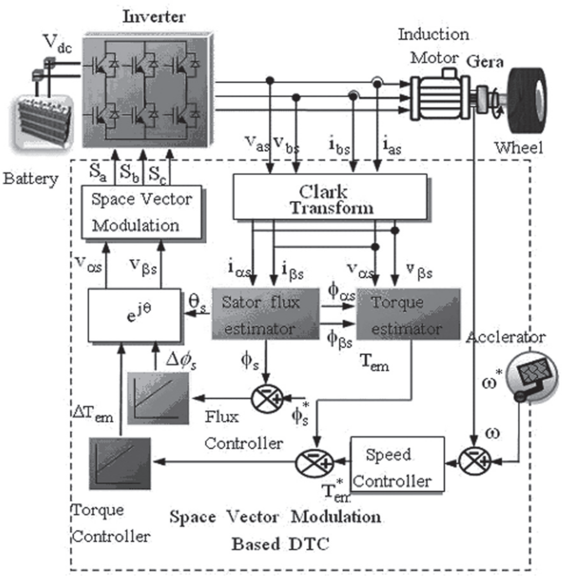

Fig. 2 Block diagram of SVM DTC induction motor drive

4. PRINCIPE OF DIRECT TORQUE CONTROL (DTC)

The basic DTC strategy is developed in 1986 by Takahashi. It's based on the determination of space vectors switching instances of each period by maintain desired flux and torque references corresponding. The block diagram of the original DTC strategy is shown in Fig-

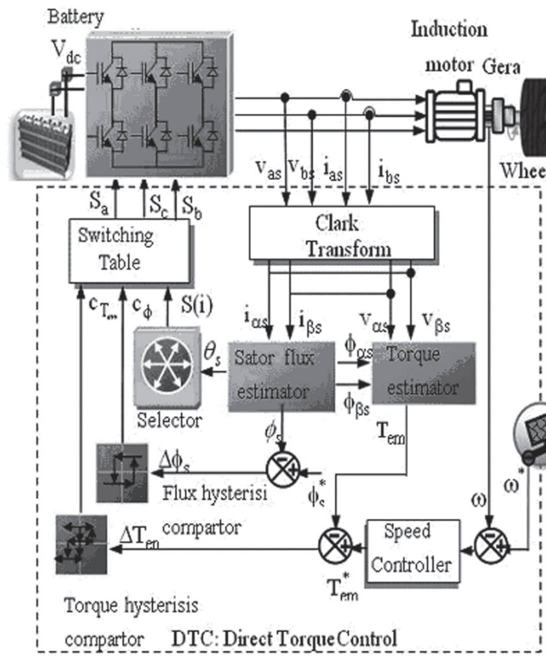

Fig. 3 Bloc diagram of DTC for an EV induction motor

ure 3. The reference speed is compared to the measured one. The obtained error is developed by the PI speed regulator, the output reference torque provided. The estimated stator flux and torque are compared to the corresponding references [Vas, 1998]. The stator flux and torque hysteresis errors are controlled by two PI regulators. The outputs of the stator flux, the torque regulators and the stator flux phase θ_s are the space vector selection table block inputs which generates the corresponding (ON or OFF) combinations states for the inverter power switch control [Chen et al., 2003].
Figure 3 shows the Bloc voltage space vectors for a two-level inverter [Kang et al., 1999]. There are eight switching combinations, two of which correspond to zero voltage space vectors which are (000) and (111) [Schell et al., 2005]. The estimation value of flux and its phase angle is calculated in expression:

$$\phi_{s\alpha} = \sqrt{\phi_{s\alpha}^2 + \phi_{s\beta}^2} \tag{4}$$

$$\theta_s = artg\left(\frac{\phi_{s\beta}}{\phi_{s\alpha}}\right) \tag{5}$$

And the electromagnetique torque controlled by three-level Hysteresis bands, its estimated value is given by expression (6).

$$T_{em} = \frac{3}{2} p(\phi_{s\alpha} i_{s\beta} - \phi_{s\beta} i_{s\alpha}) \tag{6}$$

5. ELECTRIC DIFFERENTIALS SPEED REFERENCES COMPUTATIONS

The main purpose of the electronic differential is to substitute the mechanical differential in multi-drive systems providing the required torque for each driving wheel. Each wheel drive linear speed is given by [Nasri et al., 2010]:

$$V_1 = w_v\left(R - d/2\right) \tag{7}$$

$$V_2 = w_v\left(R + d/2\right) \tag{8}$$

Where $R = L/tan\delta$ and δ is the steering angle [Nasri et al., 2008], d is the width of the car, where this angle are zero we're in straight road [Hartani, 2009]. The angular speeds in curved roads are:

$$w_1 = \frac{L - (d/2)\tan\delta}{L} w_v \tag{9}$$

$$w_2 = \frac{L + (d/2)\tan\delta}{L} w_v \tag{10}$$

Where L is the length of the car w_v is the centre of turn angular speed's expressed by:

$$w_V = \frac{w_1 + w_2}{2} \tag{11}$$

When w_{1ref} and w_{2ref} are the output of electronic differential speed references submitted for wheels

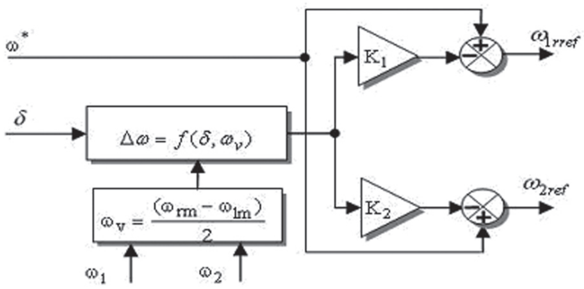

Fig. 4 Bloc diagram of the differential system

6. SIMULATION RESULTS

Electric vehicle simulations were carried on the following trajectories as it show in Figure 6.

6.1 Space Vector Modulation based Direct Torque Control (DTC-SVM)

In order to characterize the driving wheel system behavior, simulations were carried using the model of Figure 5. In the first case we use DTC-SVM controller. EV have tested under several speed and roads topologies conditions during the various driving periods.
At t = 0 sec, the vehicle speed go from zeros to 70 km/h. as it shown in Figure 7, the developed attractive

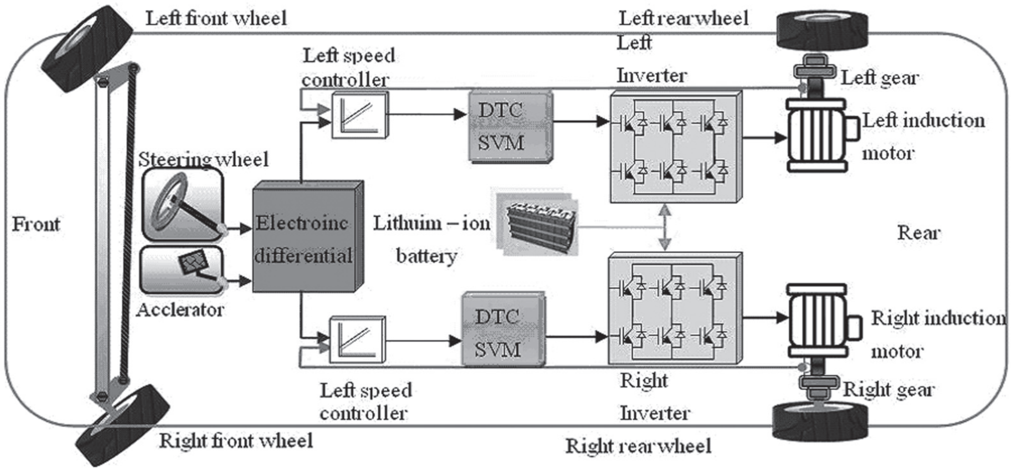

Fig. 5 The driving wheels control system

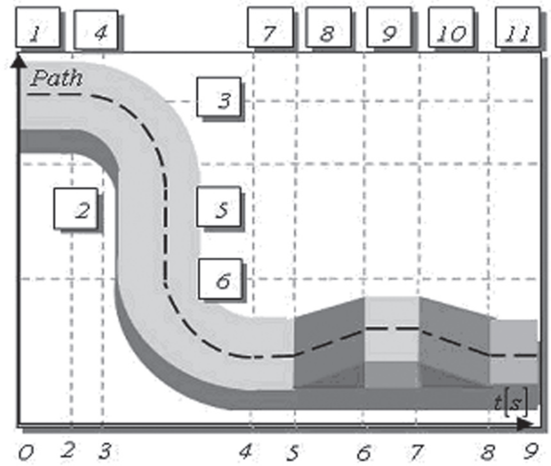

Fig. 6 Different road test topologies for electric vehicle driving cycles

Table 2 Different time periods events for electric vehicle during the driving

N° [Paths]	Time (sec)	Road topology nature
1	$0< t <0.67$	Drive beginning
2	$0.67 < t < 2$	Straight road
3	$t = 2$	Acceleration
4	$t = 3$	Curved at right side
5	$3 < t < 4$	Straight road
6	$t = 4$	Curved at left side
7	$4 < t < 5$	Straight road
8	$5 < t < 6$	Inverse slope of 10 %
9	$6 < t < 7$	Straight road
10	$7 < t < 8$	Slope 10 %
11	$8 < t < 9$	Straight road

forces corresponding to an effort of (346.70 Nm) and current demand of 132.30 A. each motor is sensitized by the electronic diferantial to obtain the reference speed imposed by the driver.

At $0 < t < 0.67$ sec, in this step the vehicle is moving in straight road topology, as it shown in Table 2, we observe that the vehicle linear speed stay at reference value of 70 km/h given by the electronic differential according to the driver references.

At $t = 2$ s, the EV situated in acceleration and the speed phases, the linear sped pass from 70 km/h to 80 km/h as it shown in Figure 7. The electromagnetic torque and current developed the necessary effort to satisfy the propulsion system demands, when the electronic differential present an virtual driver which combine between the real driver decision and road topologies.

At $t = 3$ s, the vehicle is situated in right side curved roads where the electronic differential gives the references speeds of each wheels and ensure the vehicle stability inside and outside the curve.

At $3 < t < 4$ s, the EV are driving in straight road with fixed of 80 km/h, A good speed step tracking can be observed in Figure 7.

At $t = 4$, the vehicle is driving on a curved road on the left side with 80 km/h speed. The assumption is that the two motors are not disturbed. In this case 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 decreasing the speed of the driving wheel on the right side situated inside the curve, and on the other hand by increasing the wheel motor speed in the external side of the curve. The behavior of the developed efforts of each motors and driving forces are show in Figures 10 and 11 respectively.

At 4 s < t < 5 s, the EV are driving in straight road, current demand decreases and the EV torque jumps down to 127.73 Nm.

At 5 s < t < 6 s, this test clarify the inverse slope effect on the electric vehicle propulsion systems e moving on straight road, this situation causes a great phase current decrease of each motor, as it shown in Figures 8 and 9 by means that the battery charge his empty cells and all resistive torques became motor torques as it shown in Figure 12, the right and left motor develop only 86.99 Nm of their attractive energy.

At 7 s < t < 8 s in this test the vehicle is moved in slope road again, both of the two motor develops the necessary efforts to pass this slope's, the current increase speedily and still to its, maximal value, and the speed is maintaining to 80 km/h. The variation of driving force, are illustrate in Figure 11.The motor absorbed more energy, the EV torque go to 169 Nm.

At 8 s < t < 9 s, the EV are driving in straight road, and the reference linear speed stay at 80 km/h and the EV torque decrease to 127.73 Nm.

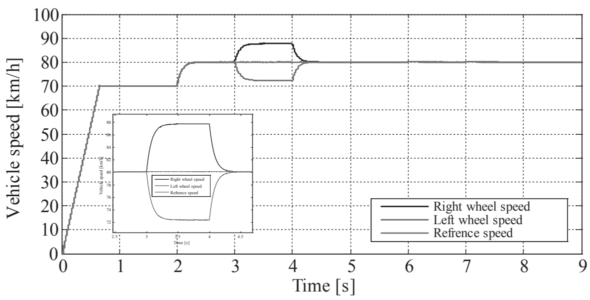

Fig. 7 Vehicle wheel speed

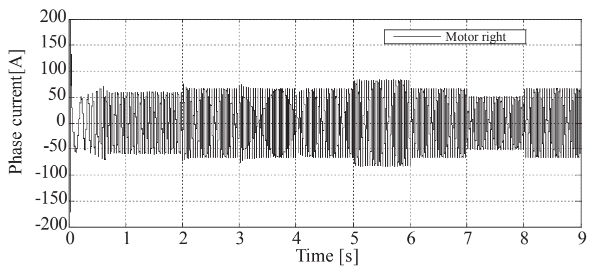

Fig. 8 Phase current motor right

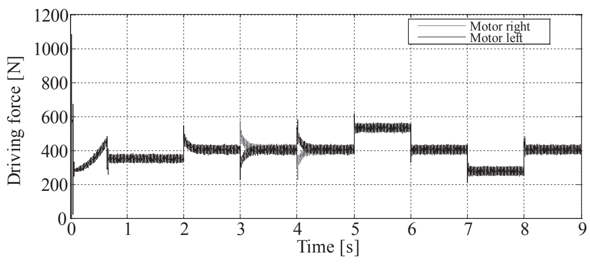

Fig. 9 Phase current motor left

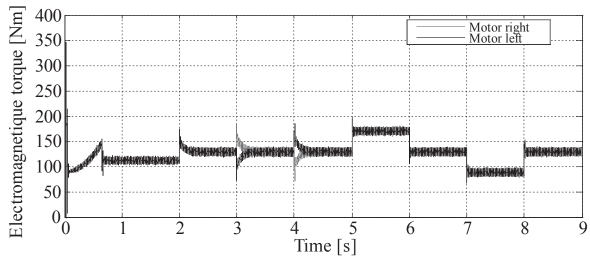

Fig. 10 Electromagnetic torque

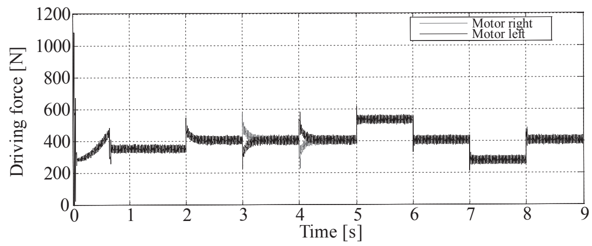

Fig. 11 Motor driving forces

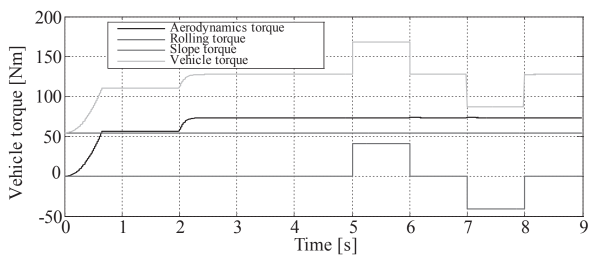

Fig. 12 Vehicle resistive torques

Table 3 Variation of vehicle torque in different paths

t [s]	T_{aero} [N]	T_{tire} [N]	T_{slope} [N]	T_v [N]
0.678 < t < 2	71.97	54.28	0.00	120.00
2 < t < 5	73.45	54.28	0.00	127.73
5 < t < 6	73.45	54.28	-40.80	169.00
6 < t < 7	73.45	54.28	0.00	127.73
7 < t < 8	73.45	54.28	40.80	87.00
8 < t < 9	73.45	54.28	0.00	127.73

Referring to Figure 12, we observe that the EV torques present 22 % in the slope road when the tow induction motors develops an electromagnetic torque of 170.50 Nm. The Figure 10 shown below illustrates the vehicle torque behavior in different road constraint.

6.2 Direct torque control

We apply the DTC controller in the second case. The electric vehicles are submitted in the same road trajectories, the different results are shows below:

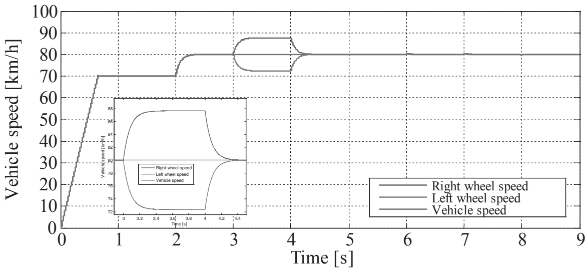

Fig. 13 Vehicle wheel speed

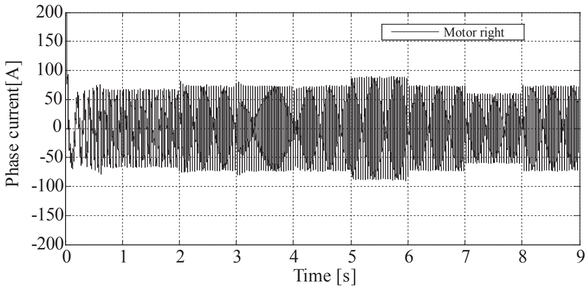

Fig. 14 Right motor phase current

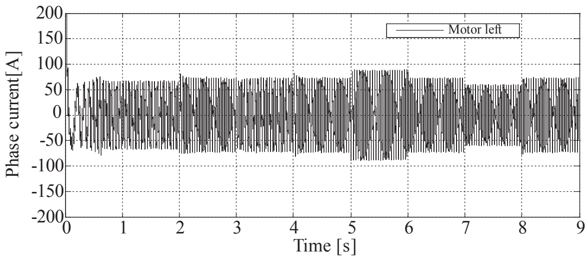

Fig. 15 Left motor phase current

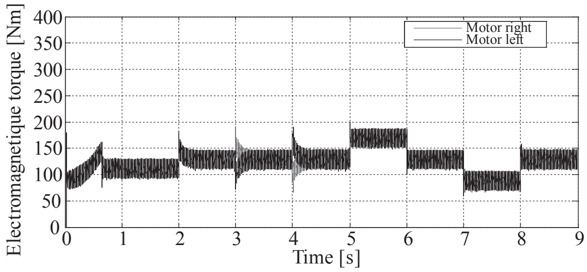

Fig. 16 Electromagnetic torque

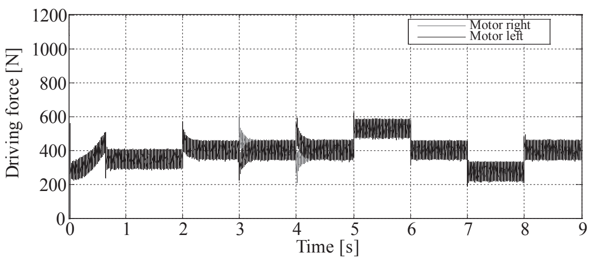

Fig. 17 Electromagnetic torque

6.3 Comparative studies of the controllers

In simulations the two different methods to control the EV were used. The SVM-DTC and DTC controllers was proved in efficiency of EV stability dynamical behavior in different road constraints. For clarify and observe the effect of disturbances on the vehicle speed in the cases of two types of control. Electric vehicle are submitted a constant speed 80 km/h during all simulation. Figures 18 and 19, shows the system response in two cases DTC, and SVM based DTC controllers. We can summaries the vehicle speed results in the following table:

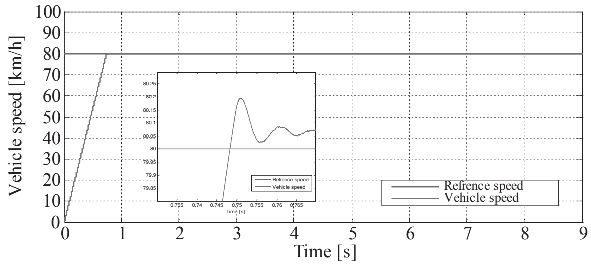

Fig. 18 Vehicle wheel speed control using SVM-DTC

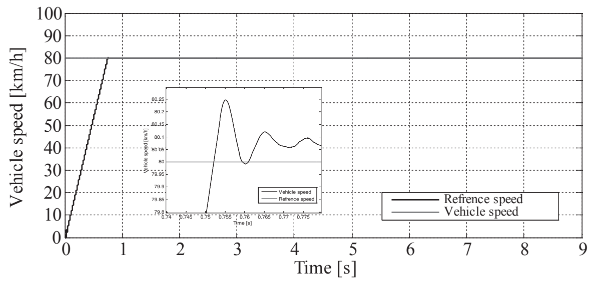

Fig. 19 Vehicle wheel speed using DTC controller

Table 4 Performance of the DTC and SVM-DTC speed responses

Results	Rising time [Sec]	Overshoot [%]	Steady state error [%]
SVM_DTC	0.752	0.310	0.080
DTC	0.784	0.250	0.040

SVM presents a 4.08 % the rising time reduction compared to DTC controller, where the DTC gives large ripple oscillations of 19.35 % difference compared to SVM-DTC moreover SVM-DTC controller present better performances more than DTC controller on the speed control efficiency. Both of two the controllers permits the realization of an modern control, with good dynamic performances. The advantage of tow controller are there robustness, there capacity to maintain ideal trajectories for two driving wheels controlled independently and ensure good disturbances

Table 4 SVM-DTC and DTC comparatives studies

Controller	SVM-DTC	DTC
Systems of electric propulsion	More adaptive	More adaptive
Vehicle wheel speed	less adaptive	More adaptive
Oscillation in torque and deriving force	Less oscillation	More oscillation
Comportment of EV in different road	Stability and robustness	Stability and robustness

rejections in slope and inverse slope state and the vehicle stability during the curved road driving. These characteristics yielded robust electric traction chain in recent electric vehicle propulsion systems key point and offer a good advantages for industrial control using and implementations.

7. CONCLUSION

The twin proposed control methods was Improved EV steering and stability during different road trajectories. The advantage of DTC and DTC-SVM controls are there robustness, there capacity to maintain ideal trajectory for two wheels controlled independently and ensure good disturbances rejections during driving. The SVM-DTC is more adaptive for electric propulsion system, gives less oscillation amplitude for torque and driving force. The DTC controller weakened the battery which cause heating around the battery cells and the engine wires which decreases the motors life's cycles and the battery too, furthermore SVM-DTC and DTC controllers improve the driving wheels speeds control with high accuracy either in flat roads or curved ones. The major advantages of a vehicle using independent wheel control are the ability to traverse steep slopes, and the ability to have larger wheels and improved load carrying and distributions, compared to conventional vehicles of the type. The electric vehicle was proved best performances and stability during different road Paths by maintaining the motorization error speed equal zeros and gives a good driving forces distribution. Finally the simulation results show clearly the performance of tow controllers. The electric vehicle was proved it's control efficiency in the different road constraints.

References

Chan, C. C., and Y. S. Wong, Electric vehicles charge forward, IEEE Power and Energy Magazine, Vol. 2, No. 6, 24-33, 2004.

Chen, L., and K. L. Fang, A novel direct torque control for dual-three-phase induction motor, *Machine Learning and Cybernetics, 2003 International Conference on*, 876-88, 2003.

Hartani, K., Electronic differential with direct torque fuzzy control for vehicle propulsion system, *Turkish Journal of Electrical Engineering & Computer Sciences*, Vol. 17, No. 1, 123-129, 2009.

Itoh, K., and H. Kubota, Thrust ripple reduction of linear induction motor with direct torque control, P*roceedings of the Eighth International Conference on Electrical Machines and Systems*, Vol. 1, 655-658, 2005.

Kang, J. K., and S. K. Sul, New direct torque control of induction motor for minimum torque ripple and constant switching frequency, IEEE Transaction Industrial Applications, Vol. 35, No. 5, 1076-1082, 1999.

Lam, L. T., and R. Lovey, Developpement of ultra-battery for hybrid-electric vehicle applications, *Power Sources*, Vol. 158, 1140-1148, 2006.

Nasri, A., A. Hazzab, I. K. Bousserhane, S. Hadjeri, and P. Sicard, Fuzzy logic speed control stability improvement of lightweight electric vehicle drive, *Korean Journal of Electrical Engineering & Technology*, Vol. 5, No. 1, 123-134, 2010.

Nasri, A., A. Hazzab, I. K. Bousserhane, S. Hadjeri, and P. Sicard, Two wheel speed robust sliding mode control for electric vehicle drive, *Serbian Journal of Electrical Engineering*, Vol. 5, No. 2, 199-216, 2008.

Schell, A., H. Peng, D. Tran, and E. Stamos, Modeling and control strategy development for fuel cell electric vehicle, *Annual Review in Control Elseiver*, Vol. 29, 159-168, 2005.

Vas, P., *Sensorless Vector and Direct Torque Control*, Oxford University Press, 1998.

Vasudevan, M., and R. Arumugam, New direct torque control scheme of induction motor for electric vehicles, *Proceedings of 5th Asian Control Conference*, Vol. 2, 1377-1383, 2004.

Yang, Y. P., and C. P. Lo., Current distribution control of dual directly driven wheel motors for electric vehicles, *Control Engineering Practice*, Vol. 16, No. 11, 1285-1292, 2008.

Zhu, Q. Z., and D. Howe, Electrical machines and drives for electric, hybrid, and fuel cell vehicles, Proceedings of IEEE, Vol. 95, No. 4, 764-765, 2007.

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