Improved Direct Torque Control of Permanent Magnet Synchronous Electrical Vehicle Motor with Proportional-Integral Resistance Estimator

Kada Hartani†, Yahia Miloud* and Abdellah Miloudi*

Abstract - Electric vehicles (EVs) require fast torque response and high drive efficiency. This paper describes a control scheme of fuzzy direct torque control of permanent magnet synchronous motor for EVs. This control strategy is extensively used in EV application. With direct torque control (DTC), the electromagnetic torque and stator flux can be estimated using the measured stator voltages and currents. The estimation depends on motor parameters, except for the stator resistance. The variation of stator resistance due to changes in temperature or frequency downgrades the performance of DTC, which is controlled by introducing errors in the estimated flux linkage vector and the electromagnetic torque. Thus, compensation for the effect of stator resistance variation becomes necessary. This work proposes the estimation of the stator resistance and its compensation using a proportional-integral estimation method. An electronic differential has been also used, which has the advantage of replacing loose, heavy, and inefficient mechanical transmission and mechanical differential with a more efficient, light, and small electric motors that are directly coupled to the wheels through a single gear or an in-wheel motor.

Keywords: Direct torque control, Electric vehicle, Fuzzy logic, Electronic differential

1. Introduction

An electric vehicle (EV) is a road vehicle, which runs on electric propulsion. The electric propulsion system is the heart of new generation EVs [1]. It consists of the motor drive, transmission device, and wheels. The motor drive consists of the electric motor, power converter, and electronic controller consisting of the core parts of the EV propulsion system. Traditionally, direct current (DC) motors have been prominent in electric propulsion because their torque-speed characteristics adequately address the traction requirement, and their speed control is simple. Recently, technological developments have brought commutatorless motors into a new era, with their advantages of high efficiency, high power density, low operating cost, enhanced reliability, and low maintenance over DC motors. Permanent magnet synchronous motors (PMSMs) are widely accepted commutatorless motors for EV propulsion because they are robust, highly reliable, and maintenance-free.

The vector control technique is generally preferred for improving the dynamic performance of PM synchronous motor drives for electric vehicle propulsion. However, vector control needs complicated online coordinate transformations to decouple the interaction between flux control and torque control in order to provide fast torque control in a PM synchronous motor. Hence, the computation usually requires a high performance digital signal processor (DSP) card. In recent years, an innovative control method called direct torque control for the electric propulsion system has gained interest [2]-[4]. It can also produce fast torque for the PM synchronous motor and does not need heavy online computation compared with vector control.

The design of full EVs needs the placement of the mechanical differential and mechanical transmission by an electronic differential (ED), where motors are directly coupled to the wheels. The electronic differential has the following features: i) there is no mechanical link between the drive wheels; ii) the traction power is applied to each wheel separately by the speed controller; iii) a turn of the speed controller will apply less power to the inner wheel; and iv) the electronic differential simulates a differential lock, while the front wheels are driving along a straight path. In this way, electronic differential operation supposes the solution of two technological problems: wheels synchronization and computation of relative wheel speed as a function of the steering angle.

The inner and outer wheel velocity relationship in a corner has been usually described through the Ackerman steering principle, which is used to compute the relative speed difference in the wheels by using the data of the steering angle.

The proposed traction system consists of two permanent magnet synchronous machines (PMSM) that ensure the drive of the two back driving wheels [5]-[6]. This system is called multi-machine multi-converter system (MMS) [7]. It is recognized through the existence of the coupling system type, either of an electric nature, a magnetic and/or a mechanical one used in several electric machines propulsing the vehicle. The proposed control structure for speed control [8], called “independent machines,” allows the achievement of an electronic differential based on fuzzy direct torque control (FDTC).
The fuzzy direct torque control uses the stator flux amplitude and the electromagnetic torque errors through two fuzzy logic controllers to generate a voltage space vector (reference voltage) by acting on both the amplitude and the angle of its components, which is used by a space vector modulation to provide the inverter switching states. The Mamdani and Sugeno methods are used for the fuzzy reasoning algorithms in the two fuzzy logic controllers.

The main goal of using an FDTC algorithm for PMSM drives is to overcome some of the drawbacks of the original DTC. However, this reduces torque ripple substantially, and the fast response and robustness merits of the classical DTC [9]-[13] are entirely preserved by eliminating the hysteresis regulators of flux and torque.

In this paper, the problems of stator resistance for the direct torque-controlled permanent magnet synchronous machine drive are examined. The relationship between the reference current vector and the reference flux and torque is determined and used for $R_s$ estimation. A PI compensation method of the $R_s$ variation based on stator current amplitude is also proposed and verified through modeling and simulation.

In order to characterize the electronic differential system for an electric vehicle driven by two permanent magnet synchronous motors attached to the rear wheel using fuzzy direct torque control, different simulations were carried out by driving the vehicle on a straight road and on a curved road in both directions (right and left).

2. Presentation of the Traction Control

In this paper, a structure was adapted, which allowed the vehicle to have two independent wheel drives. In the case of the rear-wheel drive, the electric vehicle motor drove the gearbox, which was mounted on the rear axle (Fig. 1). This configuration is for an EV using two propulsion motors. However, the use of two motors to drive two rear wheels simplifies the transmission and eliminates the mechanical differential. The electronic differential proposed in the traction system for an electric vehicle driven directly by a two-wheel motor was based on FDTC for each wheel-motor (Fig. 3). Thus, the electronic differential must take into account the speed difference between the two wheels when the vehicle traverses a corner. The system uses the vehicle speed and steering angle as input parameters and calculates the required inner and outer wheel speeds, where the two rear wheels are controlled independently by two PMS motors.

2.1 Vehicle Dynamic

Fig. 2 shows the forces acting on a vehicle moving up a grade. The tractive effort in the contact area between tires of the driven wheels and the road surface propels the vehicle forward. It is produced by the electric motor torque and is transferred through transmission and final drive to the drive wheels.

Below, (1) indicates the resistance force against the vehicle movement. The first term is the rolling resistance, the second term is the aerodynamic resistance, and finally, the last term is the slope resistance.

$$F_{res} = \mu Mg + \frac{1}{2} \rho C_s SV^2_h + Mg \sin \alpha$$  \hspace{1cm} (1)

By knowing the resistance force $F_{res}$, the effective wheel radius $r$, and the transmission ratio $\eta$, the load torque or the resistive torque at each speed can be calculated.

Fig. 2. Forces acting on a vehicle.

2.2 Modeling of Electronic Differential

The Ackerman Principle

A simplified, trigonometry-based Ackerman steering model was used in this paper. There are three main assumptions in this analysis: 1) the front wheels are considered passive wheels so that the velocity path defined by the rear wheels can be perfectly tracked by the front wheels; 2) since the rear wheels have no slip action, the velocity of the wheels are represented as a function of their radius; and 3) the vehicle rotation speed is half of the differential speed between the two traction rear wheels.

Fig. 4 shows the vehicle structure when taking a turn, where $L_{\alpha}$ represents the wheelbase, $\delta$ is the steering angle, $d_{\alpha}$ is the distance between the wheels of the same axle, and $\omega_R$ and $\omega_L$ are the angular speeds of the right and left wheel drives, respectively.

As shown in Fig. 3, the linear speed of each wheel drive is expressed as a function of the vehicle speed and the radius of the curve, which are derived through Eqs. (2) and (3) and given by:

$$v_L = \omega_L \left( R + \frac{d_{\alpha}}{2} \right)$$  \hspace{1cm} (2)
The radius of the curve depends on the wheelbase and steering angle expressed by:

\[ R = \frac{L_0}{\tan \delta} . \]  

Substituting (4) in (2) and (3), we obtain the angular speed in each wheel drive given by:

\[ v_r = \omega_L \left( R - \frac{d_{\omega}}{2} \right) . \]  

\[ \omega_{L} = \frac{L_0 + \frac{d_{\omega}}{2} \tan \delta}{L_0} \omega_v \]  

\[ \omega_{R} = \frac{L_0 - \frac{d_{\omega}}{2} \tan \delta}{L_0} \omega_v . \]  

The difference between the angular speeds of the wheel drives is expressed by (7). The signal of the steering angle indicates the curve direction and is derived using (8).

\[ \Delta \omega = \omega_L - \omega_R = \frac{d_\omega \tan \delta}{L_0} \omega_v \]  

\[ \begin{align*} 
\delta &< 0 \quad \Rightarrow \text{Turn right} \\
\delta &> 0 \quad \Rightarrow \text{Turn left} \\
\delta &= 0 \quad \Rightarrow \text{Straight ahead} 
\end{align*} \]  

When the vehicle arrives at the start 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 increasing the speed of the outer wheel. The driving wheel angular speeds are given by:

\[ \omega_{L}^* = \omega_v + \frac{\Delta \omega}{2} \]
Improved Direct Torque Control of Permanent Magnet Synchronous Electrical Vehicle Motor with Fuzzy Logic

\[ \omega_{r*} = \omega_r - \frac{1}{2} \Delta \omega . \]  

(10)

Meanwhile, the speed references of the two motors are given by:

\[ \omega_{m*} = k_{gear} \omega_{r*} \]  

(11)

and

\[ \omega_{m*} = k_{gear} \omega_{r*} \]  

(12)

where \( k_{gear} \) is the gearbox ratio.

2.3 PMS Motor Model

The PMSM model can be described in the stator reference frame as \([14]\):

\[
\begin{align*}
\frac{d i_{sa}}{dt} &= \frac{R_s}{L_s} i_{sa} + \frac{\Phi_f}{L_s} \omega_m \sin \theta + \frac{1}{L_s} v_{sa} \\
\frac{d i_{sb}}{dt} &= \frac{R_s}{L_s} i_{sb} \frac{\Phi_f}{L_s} \omega_m \cos \theta + \frac{1}{L_s} v_{sb} \\
\frac{d \omega_m}{dt} &= -\frac{f}{J} \omega_m + \frac{P}{J} (T_{em} - T_f)
\end{align*}
\]

(13)

and the electromagnetic torque equation is represented by:

\[ T_{em} = \frac{3}{2} p \Phi_f \left( -i_{sa} \sin \theta + i_{sb} \cos \theta \right). \]  

(14)

2.4 Inverter Model

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

\[
\begin{bmatrix}
    v_a \\
v_b \\
v_c
\end{bmatrix} = \frac{E}{3} \begin{bmatrix}
    2 & -1 & -1 \\
    -1 & 2 & -1 \\
    -1 & -1 & 2
\end{bmatrix} \begin{bmatrix}
    S_a \\
    S_b \\
    S_c
\end{bmatrix} .
\]

(15)

2.5 Energy Source

The source of energy is generally a lithium-ion accumulator battery. Lithium-ion battery technology offers advantages in terms of specific energy, specific power, and life over other types of rechargeable batteries \([15]\)-[19].

3. Fuzzy Direct Torque Control

A fuzzy logic method was used in this paper to improve the steady-state performance of a conventional DTC system. Fig. 5 depicts schematically a direct torque fuzzy control, in which the fuzzy controllers replace the flux linkage and torque hysteresis controllers and the switching table normally used in conventional DTC system \([20]\)-[21].

The proposed fuzzy DTC scheme uses the stator flux amplitude and the electromagnetic torque errors through

\[
\text{Fig. 5. Fuzzy direct torque control scheme.}
\]
two fuzzy logic controllers (i.e., FLC1 and FLC2) to generate a voltage space vector $V_*$ (reference voltage); it does so by acting on both the amplitude and the angle of its components, which uses a space vector modulation to generate the inverter switching states. The errors of the stator flux amplitude and the torque were selected as the inputs, the reference voltage amplitude as the output of the fuzzy logic controller (FLC1), and the increment angle as the output of the fuzzy logic controller (FLC2) that were added to the angle of the stator flux vector. The results were delivered to the space vector modulation, which calculated the switching states $S_a$, $S_b$, and $S_c$.

The Mamdani and Sugeno methods were used for the fuzzy reasoning algorithms in the FLC1 and FLC2, respectively. Figs. 6 and 7 show the membership functions for the fuzzy logic controllers FLC1 and FLC2, respectively. Fig. 8 shows the fuzzy logic controller structure.

![Fig. 6. Membership functions for the FLC1.](image)

![Fig. 7. Membership functions for the FLC2.](image)

![Fig. 8. Fuzzy logic controller structure.](image)

<table>
<thead>
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<th>Table 1. FLC1 rules</th>
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<tr>
<td>$\tilde{e}_F$</td>
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<tr>
<td>$\tilde{e}_\Phi$</td>
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<tr>
<td>$\tilde{e}_T$</td>
</tr>
<tr>
<td>$\tilde{e}_s$</td>
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<td>$\tilde{e}_s$</td>
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<th>Table 2. Reference voltage increment angle</th>
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<tr>
<td>$\delta$</td>
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<td>$\delta$</td>
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3.1 Effect of Stator Resistance Variation

It has been clarified in a previous study [22] that variation in stator resistance causes a change in stator current that, in turn, causes the variation in flux linkage and torque. The process is shown in Fig. 9.

The steady state performances of PMSM fuzzy DTC drive system with and without stator resistance variations are compared. When an error in stator resistance occurred, the torque and flux control deteriorated (Fig. 10). In this case, the compensation of the effect of resistance variation is necessary. Thus, a PI estimator was used in this paper.
4. PI Resistance Estimator for PMSM-Fuzzy DTC Drive

The system diagram can be shown in Fig. 11. It is seen that the input to the PI resistance estimator is torque and flux reference, together with the stator current. Rotor position is not needed for the PI estimator.

When the stator resistance changes, the compensation process will be applied. Therefore, the change of stator resistance will change the amplitude of the current vector. So, the error between the amplitude of current vector and that of the reference current vector will be used to compensate the change in stator resistance until the error becomes zero.

Fig. 9. Effect of stator resistance variation on a fuzzy DTC drive system.

![Fig. 9](image.png)

Fig. 10. Effects of stator resistance variations on a FDTC-PMSM drive system.

![Fig. 10](image.png)
Based on the relationship between change of resistance and change of current, a PI resistance estimator can be constructed by Eq. (16), as shown in Fig. 12. Here, $i_s^*$ is the current vector corresponding to the flux and torque, and $i_s$ is the measured stator current vector.

$$\Delta R_s = \left(k_p + \frac{k_i}{s}\right) \Delta i_s$$  \hspace{1cm} (16)

The stator current amplitude is obtained using the relation given by:

$$|i_s^*| = \sqrt{i_d^2 + i_q^2} \hspace{1cm} (21)$$

A Matlab/Simulink model was built in order to verify the performance of the PI resistance estimator. The system performances with and without the resistance estimator were then compared. Fig. 13 shows the result of flux, torque, and amplitude of current of the system with PI stator resistance estimator.

4.1 Amplitude of Stator Reference Current

The PMS machine’s torque and flux vector are given by (17) and (18) in the vector reference frame. The amplitude of flux vector can be calculated using (19).

$$T_{em} = \frac{3}{2} p \left[\Phi_f i_q - (L_q - L_d) i_d i_q \right]$$  \hspace{1cm} (17)

$$\begin{align*}
\Phi_d &= L_d i_d + \Phi_f \\
\Phi_q &= L_q i_q \\
|\Phi_s| &= \sqrt{\Phi_d^2 + \Phi_q^2}
\end{align*} \hspace{1cm} (18)$$

The reference torque and flux are given, respectively, by:

$$\begin{align*}
T_{em}^* &= \frac{3}{2} p \left[\Phi_f i_q^* - (L_q - L_d) i_d^* i_q \right] \\
|\Phi_s^*| &= \sqrt{(L_d i_d^* + \Phi_f)^2 + (L_q i_q^*)^2}
\end{align*} \hspace{1cm} (20)$$

5. Simulation Results

In order to characterize the electronic differential system for an electric vehicle driven by two permanent magnet synchronous motors attached to the rear wheel using fuzzy direct torque control with PI resistance estimator, three different cases of simulations were carried out using the model in Fig. 3, which shows the motor current, electromagnetic torque, and the speed variations of each motor.

5.1 Straight Road

An 80 km/h speed step is applied to the system. A good tracking of the speed step can be observed in Fig. 14 (a), which shows that the vehicle speed can reach the step speed of \(\sim 5.33\)s. The delay of this tracking speed is due to
the mechanical time constant, which is related to vehicle mass. In Figs. 14 (g) and (h), the variation of phase currents for each motor is represented. Two intervals of dynamics exist for the vehicle. First, it is present at the start, during which 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 $5.33$ s, during which each motor tries to develop an electromagnetic torque (Fig. 14 (e)) in order to compensate for the total resistive torque (Fig. 14(i)).

Fig. 14. Simulation results for Case 1.

5.2 Curved Road at the Right Side

In this case, the system attains a permanent state, which is $80$ km/h, wherein the vehicle is involved in a right turn at $t = 8s$. This curved road is traversed at a constant speed; however, the driver makes a steering angle, which is a steering angle of the front wheels. When the speed of the right wheel is decreasing according to its new reference (5), 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 a battery energy recuperation tool. Once the speed of the right wheel is stabilized, the torque returns to its initial value (Fig. 15(c)). Outside the curved road at $t = 18s$, the driver makes an inverse steering angle of the front wheels, and the electronic differential acts in the same manner to arrive at the difference speed of zero (Fig. 15(d)). The variation of phase currents are shown in Figs. 15 (g), (h), (i), and (j).

Fig. 15. Simulation results for Case 2.
5.3 Curved Road at Left Side

In this case, the vehicle is moving on a curved road on the left side at a speed of 80 km/h. Here, although the driving wheels follow different paths, they move toward the same direction at different speed levels. The left driving rear wheel runs at less speed than the right one. The behavior of these speed levels is given by Figs. 16 (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 rate of the speed. This change leads to a positive peak, which corresponds to the speed of the right wheel. Once this speed stabilizes itself, the torque returns to its initial value, which corresponds to the total resistive torque applied on the motor wheels (Fig. 16(e)).

6. Conclusion

This paper presented the application of an EV controlled by an electronic differential with two permanent magnet in-wheel synchronous motor drives. The application of fuzzy direct torque control in permanent magnet synchronous motor drive was proposed in this paper in order to achieve a good steady state and a dynamic performance. A PI stator resistance estimator compensate was designed and applied to eliminate the effect of stator resistance variation in FDTC-controlled PMSM motor drives. The simulation results also verified the analysis and the proposed control. The compensator shows promising performance for the stator compensation. The electronic differential controls the driving wheel speeds with high accuracy, whether in straight roads or curved ones.

Nomenclature

\( L_d, L_q \): \( d \) and \( q \) axis inductance

\( i_{\alpha d}, i_{\beta q} \): \( \alpha \) and \( \beta \) axis stator currents

\( v_{\alpha d}, v_{\beta q} \): \( \alpha \) and \( \beta \) axis stator voltage

\( i_d, i_q \): \( d \) and \( q \) axis currents

\( v_d, v_q \): \( d \) and \( q \) axis voltage

\( R_s \): Resistance

\( L_s \): Inductance

\( p \): Pole pairs

\( \theta \): Electric position

\( \Phi \): Permanent magnet flux

\( T_{em} \): Electromagnetic torque

\( T_L \): Load torque

\( l_w \): Distance between two wheels and axes

\( d_w \): Distance between the back and the front wheel

\( \rho \): Air density

\( S \): Front area of vehicle

\( C_s \): Aerodynamic coefficient

\( g \): Acceleration of gravity

\( \mu \): Friction coefficient

\( \alpha \): Angle of the slope

\( v_s \): Linear speed of vehicle

\( E \): Battery voltage

\( M \): Vehicle mass

\( r \): Wheel radius
Appendix

Table A.1. Vehicle specifications used in the simulation

<table>
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<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Vehicle total mass</td>
<td>1, 200 kg</td>
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<tr>
<td>Distance between two wheels and axes</td>
<td>2.5 m</td>
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<tr>
<td>Distance between the back and the front wheel</td>
<td>1.5 m</td>
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<tr>
<td>Wheel radius</td>
<td>0.26 m</td>
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<tr>
<td>Vehicle frontal area</td>
<td>1.9 m²</td>
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<tr>
<td>Aerodynamic drag coefficient</td>
<td>0.25 N/(ms)²</td>
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<tr>
<td>Gearbox ratio</td>
<td>7:2</td>
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<td>Efficiency of the gearbox</td>
<td>98%</td>
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Table A.2. Motor specifications

<table>
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<tr>
<td>Resistance</td>
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<td>d-axis inductance</td>
<td>0.2 mH</td>
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<tr>
<td>q-axis inductance</td>
<td>0.2 mH</td>
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<tr>
<td>Permanent magnet flux</td>
<td>0.08 Wb</td>
</tr>
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<td>Pole pairs</td>
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</table>

References


Hartani Kada was born in Saida (Algeria) in 1976. He obtained his B.S. degree in Electrotechnical Engineering in 1997. He studied for his Master’s degree at the University of Sciences and Technology of Oran (Algeria) from 2001 to 2003. He received the degree of “Doctorat Es-Science” in Electrical Control from the same institution in 2007. He is currently an Associate Professor at the University Center of Saida. His fields of interest include multimachine multiconverter systems, antilock brake systems, traction control systems, and anti-skid control for electric vehicles.

Miloud Yahia was born in June 1955. He received his BEng degree from Bradford University, UK (1980), an MSc degree from Aston University in Birmingham, UK (1981), and a Ph.D degree from the Electrical Machines Department of the Electrical and Electronics Engineering, University of Oran (U.S.T.O), Algeria in 2006. From 1982 to 1988, he was a Senior Engineer for the Sonatrach LNG1 Plant, Arzew ALGERIA, for which he was in charge of the methods section of the maintenance department and was responsible for the operation of all UPS of the plant. In 1988, he joined the Department of Electrotechnics at the University Center of Saida, Algeria, where he still works as a lecturer. His main areas of research include power electronics, multilevel inverters, and intelligent control of AC drives. His current activities include works on direct torque control, fuzzy control of AC drives, and electrical vehicles.

Miloudi Abdallah was born in Saida, Algeria in October 1958. He received a BSc degree in Mechanical Engineering and his MSc degree in Control Engineering from Bradford University, England, in 1981 and 1983, respectively. He received his PhD in Electrical Engineering in 2006 from USTO in Algeria. His main research interests are in the field of analysis and intelligent control of electrical drives and DSP programming. He is now a senior lecturer at the Department of Electrical Engineering at the University of Saida, Algeria.