Sliding Mode Control for Speed's Tracking of an Electrical Vehicle

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***Abstract*—Advanced technics intended for systems control are introduced to overcome disadvantages of conventional technics, leading so to the improvement of systems' performances gathered to a gain in calculation time which makes easier their implementation on real-time control platforms. The present paper deals with a based sliding mode control of a leisure electrical vehicle enclosing a TORUS configuration of an axial flux permanent magnet synchronous motor. In order to evaluate the effectiveness of such controller, a comparative analysis with an adaptive PI controller has been performed, based on criterions that guaranty the improvement of the energetic and dynamic aspects of the electric vehicle.**

***Index Terms*--Electrical Vehicle, Sliding Mode Control, Adaptive PI control, Speed tracking.**

1. Nomenclature

r_m	: reduction ratio
L_d	: Direct induction
L_q	: In squaring inductance
R	: Statoric resistance
φ_a	: Permanent magnet flux
P	: Number of pole pairs
M_v	: Vehicle mass
R_{roue}	: Wheel radius
f_r	: Coefficient to bearing pneumatic
S_f	: Frontal surface
C_x	: Drag coefficient
M_{va}	: Density of the magnets
I_d	: Direct component of the current
I_q	: In squaring components of the current
u_d	: Direct component of the voltage
u_q	: In squaring components of the voltage
Ω	: Angular motor's speed
C_{em}	: Electromagnetic torque of the motor
C_r	: Load torque
C_{rb}	: Resistant torque corresponding to the friction at bearings
C_{aero}	: Resistant torque corresponding to aerodynamic effect
C_g	: Resistant torque corresponding to the gravity effect.
U_{eq}	: Equivalent component of the control law,
U_s	: Discontinuous component
V	: Instantaneous EV speed
V_{ref}	: Speed reference
$(V_{ref}-V)=e$	: Pursuit error
ts	: Startup time

2. Introduction

Numerous countries and global organizations, since several years, are trying to promote the use of electrical vehicles (EV) in order to overcome the environmental pollution and to decrease the demand of the transport sector on the petroleum and fuel energy. However, due to the autonomy and cost of the batteries, the EV represented just 0.02 % of the worldwide vehicles by the end of 2012 [1,2]. To remedy such a problem, the improvement of the energetic aspect of the batteries by ameliorating the dynamic aspect of the vehicle could be a good solution. Indeed, these aspects are strongly related to the control law insuring the mechanical and electrical magnitudes of the traction chain.

The control of the EV passes chronologically through different technics. For instance, in [3], authors discussed a nonlinear robust and optimal model-based controller for an EV enclosing a brushed DC motor, where the robustness is principally considered. Besides and in order to ameliorate the speed tracking of an EV incorporating the same category of motor as used in [3], the researchers had realized an internal current regulation using a classical PI regulator and the external speed regulation loop was realized via another PI controller [4]. In addition, in [5], a multi-machine multi-converter system (MMS) was considered and controlled through an electronic differential based on direct torque fuzzy control. In this work, it has been considered that a PI regulator was not able to provide respectable performance especially for the transient regime and an adaptive PI controller was designed to govern separately the two rear wheels and give a kind of robustness especially when the EV across a straight or a curved road. In [6,7], the authors aimed a better performance and a good quality of speed tracking by developing two neuro-PID controllers to control the speed and the torque of 4-in-wheel motors integrated in two EVs.

On another hand, the variable structure control system (VSS), which is also called sliding mode control, is a specific control for a huge range of systems, presented as a solid and effective solution in the industry [8]. Nasri and al. treated the case of an EV with two asynchronous motors controlled separately using the sliding mode in [9]. Furthermore, they presented in [10] the same control strategy applied on a 4 wheels' vehicle.

The present work concerns the study of a mono-motor structure of leisure EV enclosing a traction chain powered by an axial-flux permanent magnets synchronous motor

(AFPMSM). It is aimed to establish a satisfying control of the vehicle speed tracking, based on the sliding mode. To do so, the traction chain is firstly described and modelled. Then, the second part is devoted to the design of the sliding mode controller. Finally, established model is implemented on Simulink-Matlab platform and simulation results are discussed.

3. Traction chain

The considered traction chain adopted in this paper is illustrated in Fig. 1.

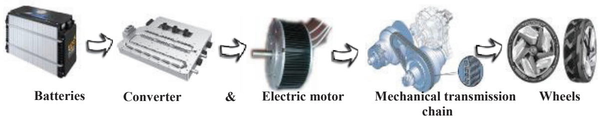


Fig. 1: Mono-motor traction chain of the studied EV

We consider in this work a leisure electrical vehicle highly solicited in tourism activities, especially in Tunisia. The traction chain modeling as well as choices justification were presented in [2]. Studied motor is a TORUS AFPMSM. Its layout and characteristics are also detailed in [2], whereas the dimensioning aspect and the analytical model were developed in [11,12]

The bloc diagram of the whole powertrain is shown in Fig.2. Each bloc represents an element of the traction chain and it is described through mathematical equations. However, the EV model can be simply derived from electric and dynamic equations, as illustrated below:

- Electric equations [11]:

In the dq frame, the voltages are defined as in (1) and the electromagnetic torque is given by (2).

$$\begin{cases} u_d = Ri_d + L_d \frac{di_d}{dt} - p\Omega L_q i_q \\ u_q = Ri_q + L_q \frac{di_q}{dt} + p\Omega (L_d i_d + \varphi_a) \end{cases} \quad (1)$$

$$C_{em} = \frac{3p}{2} \varphi_a i_q \quad (2)$$

- Dynamic equations:

The transmission of the electromagnetic torque C_{em} to the EV wheels is realized through the reduction ratio r_m [12]:

$$C_w = r_m C_{em} \quad (3)$$

The fundamental law of dynamics applied to the EV [2,10] leads to equation (4), where the elementary components are given by equations (5) to (8). Referring to (4), the EV must develop a useful torque C_w on wheels that can overcome the resistant torque and create motion.

$$C_w = C_{rb} + C_{aero} + C_g = C_a + C_r \quad (4)$$

$$C_{rb} = R_{roue} f_r M_v g \quad (5)$$

$$C_{aéro} = R_{roue} V^2 \frac{M_{va} C_x S_f}{2} \quad (6)$$

$$C_g = R_{roue} M_v g \sin(\lambda) \quad (7)$$

$$C_a = \sigma M_v R_{roue}^2 \frac{dV}{dt} \quad (8)$$

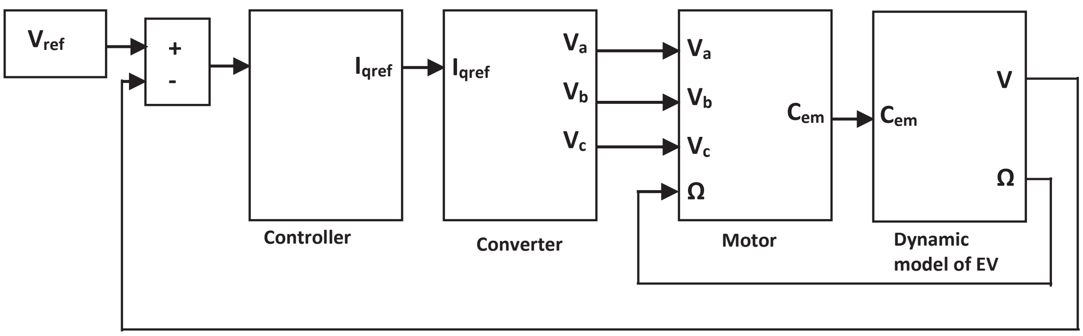


Fig.2: Block diagram of the powertrain implemented on MATLAB/SIMULINK

4. Sliding Mode Control (SMC) for EV's speed tracking

A. Principle

As said previously, the dynamic aspect of the electric vehicle can be seriously affected by the internal and external constraints. So, the studied system can be counted as a variable structure system. As a result, the speed's control law must be at the same register.

The sliding mode control represents a particular class of the variable structure control law for both linear and nonlinear systems. Such a technique consists on establishing a switching surface depending on existence and convergence laws, and then compels the dynamic behavior of the system to bring back toward this surface and slides around it till attaining the equilibrium state. This action is realized using a control law U as defined by (9) [13,14].

The idea to guarantee the convergence point through an additive component to the control strategy leading to the switching phase. Generally, beginning from 'any point', the trajectory-state converges toward the sliding surface S=0 in a finite time. Such a phase is so called the 'convergence mode'. When the manifold S=0 is reached and the regulated variable attempts to reach the equilibrium point, we said that we are in the 'sliding mode'. The system tries to cross this phase to attain its equilibrium. When done, we are in the 'equilibrium point' [15].

So, to tuning a sliding mode controller, requires to:

- Choose the sliding surface S=0,
- Determine the existence and convergence conditions,
- Establish the appropriate control law which can be able to oblige the trajectory to match the manifold S=0 and keep it switching around this surface.

$$U = U_{eq} + U_s \tag{9}$$

To find the sliding mode, JJ Slotine proposed, as given by (10), a general form that can be adopted [16]:

$$S(V) = \left(\frac{d}{dt} + \lambda\right)^{h-1} \left(V_{ref} - V\right) \tag{10}$$

Where $\lambda \in \mathbb{R}_+^*$ and h is the relative degree of derivation number to be applied to the output signal V to generate explicitly the control component.

Such a choice of S is justified by the fact that the characteristic polynomial of S must contain real, multiple and negative poles to insure the system stability. In fact:

If S➔0 then e and its derivatives are also tending to 0.

Concerning the convergence condition, it is recommended to define a scalar function which makes the surface S=0 attractive and invariant. To do we can choose the Lyapunov function υ defined as (11) [17]:

$$\mathcal{V}(V) = \frac{1}{2} S^2(V) \tag{11}$$

To insure the attractive phenomenon of the regulated variable toward the desired trajectory (reference), this function must realize:

$$\begin{cases} \mathcal{V}(X) > 0 \\ \dot{\mathcal{V}}(X) < 0 \end{cases}$$

B. Application of SMC on speed tracking of the EV

To elaborate a SMC able to govern the electric speed behavior, we must realize the three steps defined in the last section.

To regulate vehicle's speed V, we must act on the in-square component I_q of the motor current. So, the control component will be presented as shown in (12):

$$I_{qref} = I_{q\,eq} + I_{q\,c} \tag{12}$$

Before developing the control law, we must mention that the equivalent term represents a low frequencies term while $(I_q)_c$ is a high frequencies component. Otherwise, the continuous term $(I_q)_{eq}$ regroups the desired performance to be reached in the steady state, whereas the discontinuous term $(I_q)_c$ will solicit the system to attain this stage. So, we can choose $(I_q)_c$ as represented in (13):

$$(I_q)_c = -K\, Sign\big(S(X)\big);\ K \in \mathbb{R}_+^* \tag{13}$$

Referring to (4), we can write $\dot{V}$ as:

$$\dot{V}(s) = \frac{3.6}{M_v R_{wheel}} (r_m C_{em} - C_r) \tag{14}$$

$$\text{So } \dot{V}(s) = \frac{3.6}{M_v R_{wheel}} \left(\frac{3}{2} r_m p \varphi_f I_q - C_r\right) \tag{15}$$

Therefore, h=1.

Consequently, and referring to (10) we can write:

$$\dot{S}(V) = \dot{V}_{ref} - \begin{bmatrix} \frac{3}{2}\frac{3.6}{M_v R_{wheel}} r_m p \varphi_f (I_q)_{eq} \\ + \frac{3}{2}\frac{3.6}{M_v R_{wheel}} r_m p \varphi_f (I_q)_c \\ - \frac{3.6}{M_v R_{wheel}} C_r \end{bmatrix} \tag{16}$$

When the steady state is attained, we have:

$$\begin{cases} S(V) = 0 \\ \dot{S}(V) = 0 \\ (I_q)_c = 0 \end{cases}$$

Whence,

$$(I_q)_{eq} = \frac{2}{3} \frac{M_v R_{wheel}}{3.6\, r_m p \varphi_f} \left[\dot{V}_{ref} + \frac{3.6}{M_v R_{wheel}} C_r\right] \tag{17}$$

By substituting (17) in (16), we have:

$$\dot{S}(V) = -\frac{3}{2}\frac{3.6}{M_v R_{wheel}} r_m p \varphi_f (I_q)_c \tag{18}$$

During the sliding mode, we must verify the convergence condition so called direct switching relation (19), [18].

$$\dot{S}(V) S(V) < 0 \tag{19}$$

Such a condition is verified by choosing $(I_q)_c$ as represented in (20):

$$I_{q\,c} = I_{0c} \frac{S(V)}{|S(V)| + \mu}; \quad I_{0c} > 0 \tag{20}$$

$(I_q)_c$ is called continuous term with integral component.

The choice of the integral function instead of the sign one is justified by the fact that this latter introduces, as shown in Fig.3, the chattering phenomenon [19]. Such a phenomenon generates oscillations and high frequencies dynamics around the sliding surface, provoke a mechanical stress for the traction chain and produce vibrations. This latter induces high energy consumption which demeans the energetic aspect of the batteries and bothers the comfort of the conductor. This noxious effect represents the major problem of the designed sliding mode controller via the function sign.

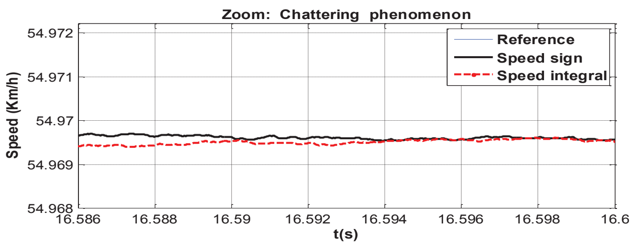


Fig.3: Chattering phenomenon attenuation

It's to point out that the positive constant I_{0c} must verify the inequality (21):

$$I_{0c} > |C_r|_{\max} \qquad (21)$$

This choice will perfectly insure:

- The condition $\dot{S}(V)S(V) < 0$ will be always verified which makes the manifold S=0 invariant and attractive under the disturbance torque effect.
- The stability margin.
  - The control law robustness against disturbances, especially when we remembered that the EV can encounter a convulsive load torque due to the functional environment.

To test the SMC contribution in speed tracking, the scheme of Fig.4 is implemented under Simulink-Matlab platform.

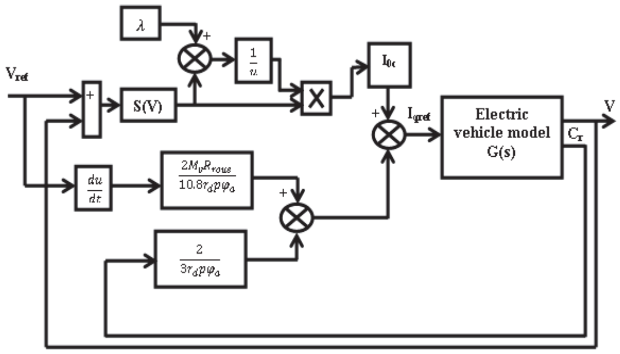


Fig.4: Scheme of the SMC setting the vehicle's speed

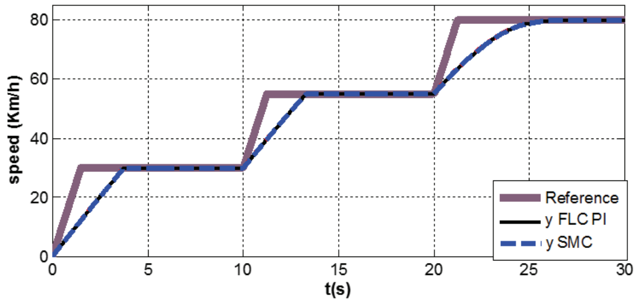
5. Results & Comparison

To evaluate the contribution of the designed SM controller, the vehicle's speed is carried out using established model then compared to an adaptive PI controller synthesized in [2] for same traction chain and considering a speed tracking problem. Comparison criterions concern essentially the performance, the robustness and the calculation time.

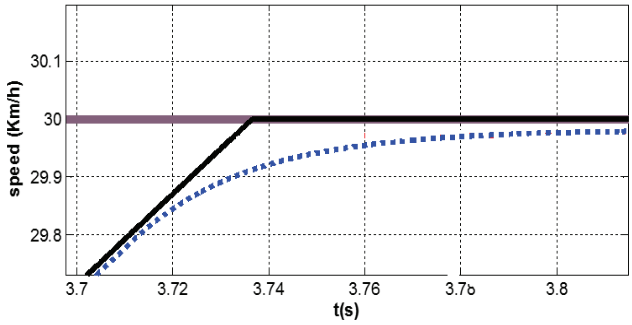
A. Performance Test

To criticize the effectiveness of each controller in terms of performance, a scaled speed reference is applied, and obtained results using each controller are represented in Fig.5. Referring to this latter, we can notice that:

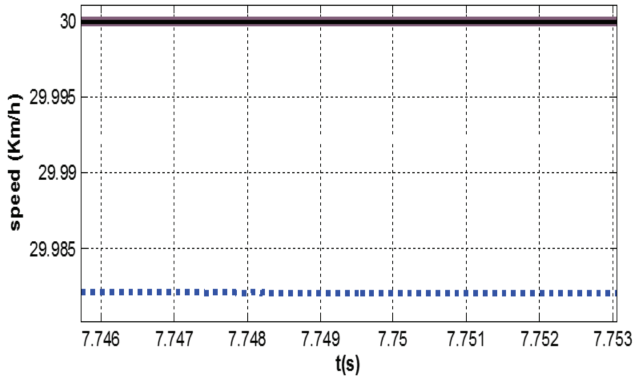
- Both controllers lead the system to stability,
- Any overshoot is marked, which represents an important asset compared to the Fuzzy Logic Controller.
- To reach 30 km/h, the vehicle with the SMC needs 3.77 s which satisfying according to required specifications (4 s). Consequently, we can notice the significant contribution of the SMC approach, as the FLC-PI one, to the improvement of the control of EVs.
- The compromise Rapidity/Precision provides a little advantage to the adaptive FLC-PI controller. Indeed, the settling time and the steady state error of the system are summarized in Table.1, for both control technics.



a. Speed tracking with FLC_PI, SMC & FSMC



b. Rapidity test



c. Precision test

Fig.5: Vehicle response under a scaled speed sequence.

TABLE I

Comparison from the performance point of view

Criterion / Technique	Setting time	Steady state error
SMC	3,7761	1,75x10-2
Adaptive PI	3,7364	≈ 0

B. Robustness Test

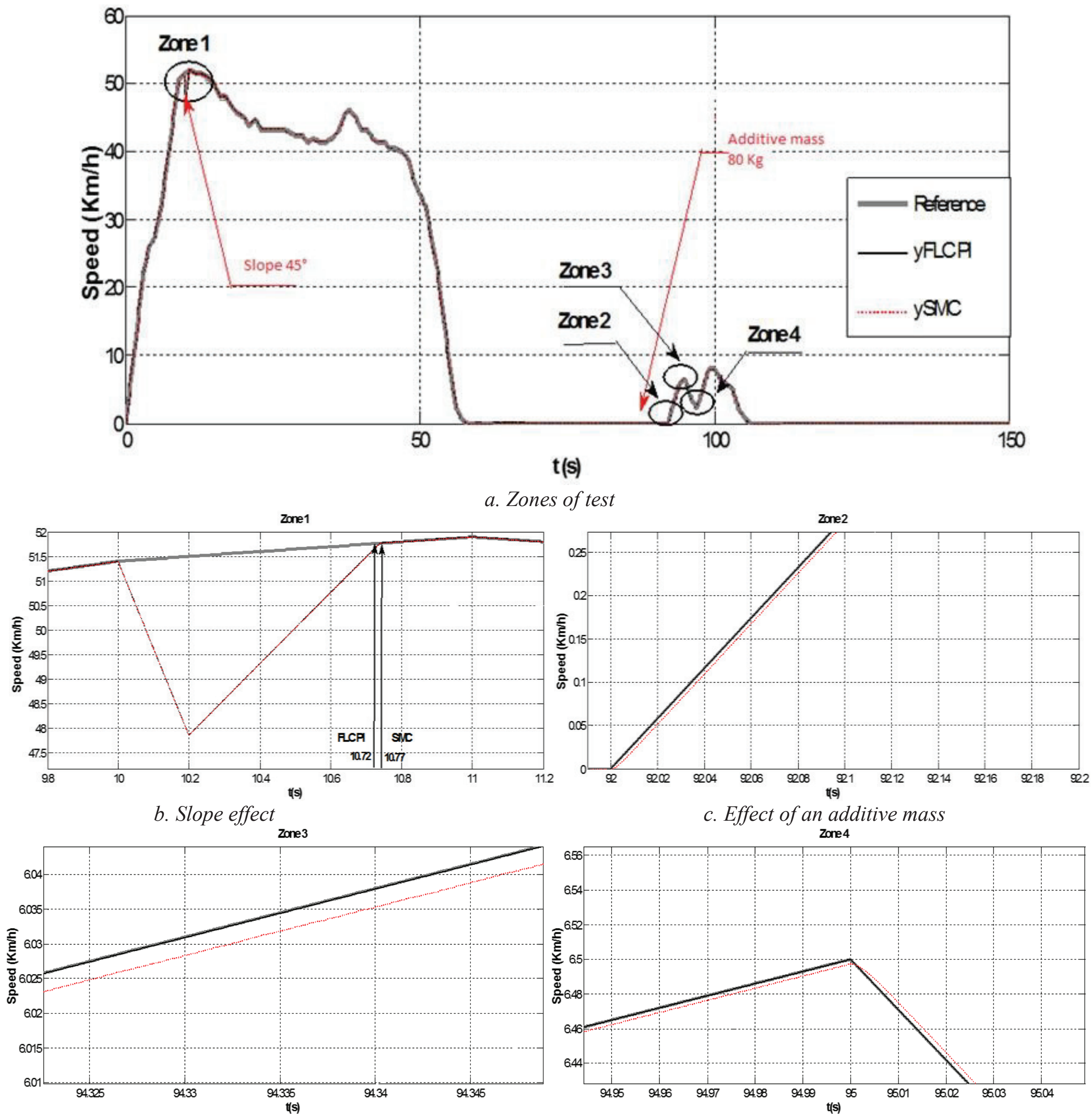
The electrical vehicle parameters can undergo some variations. Hence, the robustness of the control law must be mightily considered. Thus, the choice of the tests to be performed must be typical according to the considered application. In what follows, the robustness degrees of each technic (SM and FLC-PI) are tested is tested considering the following conditions:

- A variation of + 50% of the stator resistance and a decrease of -25% of its inductance
- A wet ground leading to the variation of the friction factor by +50% (low-speed area),

- A vehicle inclination of 45 ° at t = 10s,
- At t=80s, the vehicle is stopped then restarted considering a supplement weight of 80 kg.

To be systematic, the speed reference is a portion of a driving cycle used by the IFSTTAR for the test of leisure electrical vehicles [19]. The Considered zone of test and corresponding obtained performances are illustrated in Fig.6. It is noteworthy that, from the point of view of robustness, the SM controller is very convinced as the FLC-PI. In fact, both controllers were able to neutralize the slope effect successively after 1.77 and 1.72 s, Fig.6b. Such a test lets us conclude about the effectiveness of the designed controller, especially when the EV undergoes a sudden change in a hill climbing angle. On the other hand, the behavior of the EV is not affected due to the bad quality of the sol, Fig.8.a, as the quality of the speed tracking still intact throughout the zone of test despite the application of this test from the beginning of the test cycle. Such a test can confirm that the SM controller insures the security measures of the conductor, the pedestrian as well as the prohibition of the EV skid.

Besides, the second test focuses the effect of a sudden change of the set-point (when the vehicle crosses a slippery road). As shown in the Fig.6.e, the regulated speed via the SMC wasn't widely affected as well as the FLC-PI one, which proves the immunity of the designed controller versus these disturbances. Moreover, both controllers permit to overcome disturbances caused by additive mass or a sudden change of the set-point as shown in Fig.6c and Fig.6e.



a. Zones of test

b. Slope effect

c. Effect of an additive mass

d. Steady state behavior

e. Effect of a sudden set-point change

Fig.6: Robustness test under a portion of the driving cycle

C. Calculation time

This criterion is adopted because it reflects the aptitude of the designed controller to solicit the calculator. In fact, if a conceived control law introduces a high calculation time, it will provoke an early aging of the calculator and a high-energy consumption.

It is remarkable that the SM control needs less calculation time then the FLC-PI one as shown in Table II. This result shows that the adoption the SM controller instead of the FLC-PI one leads to longer autonomy of the EV.

TABLE II

THE TIME NEEDED BY EACH CONTROLLER TO ACHIEVE SIMULATION.

Technic / Pursuit Nature / Calculation time	Stairs	Driving cycle
SMC	22 min	16h 15min
Adaptive PI	30 min	17h 10min

7. Conclusion

The present work was aimed to the synthesis of a sliding mode controller for speed tracking considering as application a leisure electrical vehicle enclosing a TORUS configuration of an axial flux permanent magnet synchronous motor. In order to evaluate the effectiveness of such controller, a comparative analysis with an adaptive PI controller has been performed. Adopted criterions are performance, robustness and calculation time.

From the performance point of view, it has been noticed that both controllers lead the system to stability, any overshoot was marked, and the compromise Rapidity/Precision provides a little advantage to the adaptive FLC-PI controller. Moreover, from the robustness point of view, the SM controller nears the FLC-PI one when a slop disturbance is considered. Besides, both controllers permit to overcome disturbances caused by additive mass or a sudden change of the set-point. Furthermore, from calculation rapidity point of view, the SM controller needs less calculation then the FLC-PI one.

Finally, authors are convicted that the actual control based on sliding mode could be improved through the controller hybridization. Indeed, we are actually working on the integration of an adaptive Fuzzy tuner to be associated with the SM controller, leading so to an FLC-SM controller.

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