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Energy Procedia 50 (2014) 178 – 185
Energy Procedia

The International Conference on Technologies and Materials for Renewable Energy, Environment and Sustainability, TMREES14

Fuzzy Logic Maximum Structure and State Feedback Control Strategies of The Electrical Car

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Abstract

This paper treats the design and control of different models and control strategies for an Electric Vehicle (EV). An hybrid controller is designed using a fuzzy logic integrated in Maximum Control Structure (FL-MCS) , the FL nonlinear controller involves online estimation of the total reference force which corresponds to a torque reference to be applied to MCS. The second proposed regulator is a states feedback controller using the Linear Quadratic Regulation (LQR) to optimise and to determine the feedback control parameters. The LQR allows reducing the consumption of the energy according to the desired EV's dynamic performances , these lasts can be changed depending on the choice of Q and R matrices. In this work, we apply and validate the proposed control strategies by a comparison between our simulation results and the results of the classical MCS, which has been developed by L2EP (Lille, France) to control the EV speed under Matlab/Simulink,

Selection and peer-review under responsibility of the Euro-Mediterranean Institute for Sustainable Development (EUMISD)
Keywords: Electrical Car, Maximum Control Structure, Fuzzy Logic, State Feedback, LQR;

1. Introduction

In the race to cut carbon emissions, global demand for the clean, green technology and more sustainable modes of a transport is rising, the renewable energy has gained in popularity, since their efficiency is continuously improved and their cost is continuously reduced. Indeed, the renewable energy systems produce electric power without polluting the environment, transforming free inexhaustible energy resources, like the solar radiation, full cell or wind, into electricity. The world's demand for electrical energy has been continuously increasing and is expected to continue growing, while the majority of the electrical energy in most countries is generated by conventional energy sources. The ongoing global climate change, the diminution of fossil fuel resources and the collective fear of energy supply shortage

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Selection and peer-review under responsibility of the Euro-Mediterranean Institute for Sustainable Development (EUMISD)
doi:10.1016/j.egypro.2014.06.022

have made the global energy trends more complex [1]. The orientation towards the use of Electric Vehicles (EVs) has received a thorough attention during the past few decades, because the EVs do not have issues with the increasing oil prices or the pollution problems (at least around the vehicle) and for this increases the EVs industrial and academic searches especially their modelling and control strategies. A nonlinear Hybrid controller is designed, using the Fuzzy Logic integrated in MCS (FL-SMC) technique, to achieve two objectives: (i) facilitate the inversion of accumulation element by FL; (ii) improve the robustness of MCS. Accordingly, the controller involves online estimation of the total reference force which corresponds to a torque reference to be applied to the MCS. It is formally shown, using the theoretical analysis and simulations, that the developed controllers actually meets its control objectives. However, there are still some points about the control methods to be studied, particularly in the area of robustness, stability and efficiency. State-Feedback is the most important aspect of modern control system. Using an appropriate state-feedback, unstable systems can be stabilized or damping oscillatory can be improved. The state-feedback and linear quadratic regulator are given a robust command, increase the stability and reduce the energy consumption of EV.

2. Modelling of the electric vehicle

2.1. The studied architecture

The studied EV is driven by a Direct Current (DC) machine with a differential mechanical device. It is supplied by a battery through a DC/DC converter. The Fig. 1. (a) illustrates the EV structure which couples the dynamics of vehicle to the electrical motorization. The modelling step is widely inspire from the L2EP researches work [2].

2.1.1. Direct Current Machine

The DC machine is modelled with the classical relationships. The armature current I_{arm} is the state variable of armature windings and it is obtained from the supply voltage U_{chop} and the electromotive force e_{em}.

$$L_{arm}\frac{dI_{arm}}{dt} = U_{chop} - e_{em} - R_{arm}I_{arm} \tag{1}$$

Where R_{arm} and L_{arm} are the resistance and inductance of the armature windings. An electromechanical conversion link current to the produced motor torque (T_{mot}). As shown in (2) the e_{em} is also deduced from the nominal motor rotation Ω_{nom} [3].

$$\begin{cases} T_{mot} = k\phi I_{arm} \\ e_{em} = k\phi\Omega_{nom} \\ k\phi = \dfrac{U_{arm}^{nominal} - R_{arm}I_{arm}^{nominal}}{\Omega_{nom}^{nominal}} \end{cases} \tag{2}$$

Where k is the machine constant parameter related to the torque and to the e.m.f. ϕ is the magnetic flux. The following equation allows finding the numerical value for the mechanical conversion (shaft + gearbox).

$$\begin{cases} T_{gear} = k_{gear}T_{mot} \\ \Omega_{mot} = k_{gear}\Omega_{gear} \end{cases} \tag{3}$$

Where T_{gear} is the torque after reduction, k_{gear} is the gearbox reduction coefficient.

2.1.2. Differential mechanical

The torque reduction is shared fairly on the left and the right wheels [2] as shown in (4).

$$\begin{cases} T_{diff_{left}} = \frac{1}{2}T_{gear} \\ T_{diff_{right}} = \frac{1}{2}T_{gear} \\ T_{diff_{Tot}} = T_{diff_{right}} + T_{diff_{left}} \end{cases} \tag{4}$$

Where $T_{diff_{left}}$, $T_{diff_{right}}$ and $T_{diff_{Tot}}$ are the left, right and total torques after differential, respectively.

2.1.3. The traction forces

The traction forces can be calculated from the torque of the differential [2].

$$\begin{cases} F_{left} = \frac{1}{R_{wheel}} T_{diff_{left}} \\ F_{right} = \frac{1}{R_{wheel}} T_{diff_{right}} \\ F_{Tot} = F_{left} + F_{right} \end{cases} \tag{5}$$

Where R_{wheel} is the wheel radius, F_{left} and F_{right} are the forces for the left and right wheels, respectively.

2.1.4. Vehicle as load

In order to test the robustness of controller, the vehicle velocity V_{veh} is obtained with a different dynamic relationships contrary to the model given in [4,5], where It yields a resistive force F_{res} as variable perturbation and measured disturbance from the vehicle velocity, as is shown in (6).

$$M\frac{dv_{veh}}{dt} = F_{tot} - F_{res} - f.v_{veh} \tag{6}$$

Where M is the vehicle mass. The EV model can be developed with the following block diagram as shown in Fig. 1. (b). The transfer function of the EV is obtained from the block diagram, and can be written by the following expression:

$$\frac{V_{veh}(s)}{U(s)} = \frac{G}{s^2 + a.s + b} \tag{7}$$

Where

$$G = \frac{k_{ind}.k.\phi.k_{gear}.k_{chass}\frac{2}{R_{wheel}}}{\tau_{ind}.\tau_{chass}}$$

$$a = \frac{\tau_{ind} + \tau_{chass}}{\tau_{ind}.\tau_{chass}}$$

$$b = 1 + k_{ind}.k_{chass}(k.\phi.K_{gear}.\frac{1}{R_{wheel}})^2\tau_{ind}.\tau_{chass}$$

2.2. EMR of the electric vehicle

The EMR is based on the action-reaction principle to organize the interconnection of sub-systems according to the physical causality (i.e. integral relation) [1,4]. This description highlights energetic properties of the system (energy accumulation, conversion and distribution). Moreover, an inversion-based control can be systematically deduced from EMR using specific inversion rules. The EV-EMR simulator is based on the one given by the L2EP lectures [2]

2.3. The state-space model of the electric vehicle

From the Bloc diagram of the EV (Fig. 1. (b)), the e_{em} and F_{Tot} are written by the following expressions:

$$\begin{cases} F_{tot} = \frac{2k\phi k_{gear}}{R_{wheel}}.I_{arm} \\ e_{em} = \frac{k_{gear}.k\phi}{2R_{wheel}}.V_{veh} \end{cases} \tag{8}$$

Then V_{veh} and I_{arem} can be written as:

$$\begin{cases} V_{veh} = \frac{2k\phi k_{gear}}{M.R_{weel}}.I_{arm} - \frac{f}{M}.V_{veh} \\ I_{arm} = \frac{-R_{arm}}{L_{arm}}.I_{arm} - \frac{k_{gear}.k\phi}{2L_{arm}R_{weel}}.V_{veh} + \frac{1}{L_{arm}U} \end{cases} \tag{9}$$

The global states space representation is presented by (10).

$$\begin{cases} \dot{X} = A.x + B.u \\ Y = C.x \end{cases} \tag{10}$$

Where $x = \begin{bmatrix} V_{veh} \\ I_{arm} \end{bmatrix}$ and $Y = V_{veh}$ with

$$A=\begin{bmatrix} \frac{-f}{M} & \frac{2k\phi k_{gear}}{M.R_{wheel}} \\ \frac{-k_{gear}.k\phi}{2L_{arm}R_{wheel}} & \frac{-R_{arm}}{L_{arm}} \end{bmatrix}, B=\begin{bmatrix} 0 \\ \frac{1}{L_{arm}} \end{bmatrix} and C=\begin{bmatrix} 1 & 0 \end{bmatrix}$$

3. Maximum control structure of the studied vehicle

The MCS is composed of several inversion blocks and different EMR parts. Then the EMR blocks are inverted regardless of practical issues: the conversion blocks are directly inverted and the accumulation blocks are inverted using the controllers in order to respect physical causality as is shown in (11) [5].

$$F_{ref} = Con\left(V_{veh_{ref}} - V_{veh_{mes}}\right) \tag{11}$$

Where $Con\left(x_{ref} - x_{mes}\right)$ is the controller of the variable x toward its reference, the classical inversion of the accumulation bloc using the PID or IP controller needs the calculation of the controller parameters (integral and proportional gains). In this paper, an Fuzzy Logic Controller (FLC) is proposed and developed by authors to invert the accumulation element contrary to the controllers which are proposed by [2,5,6], where the IP and PID controllers are used.

3.1. Development of the fuzzy logic control

Recently, a lot of researches intend to apply intelligent control theory to the control strategy of EV such as the fuzzy control [7], the neural network and the adaptive control. Since the fuzzy control is simple, easy to realize, no need for modelling and has strong robustness, it is suitable for nonlinear control where parameters and/or model are unknown or variable [8]. Hence, it is very suitable for EV control. The FL is developped to invert the accumulation element associated with the chassis to estimate the total force reference $F_{tot_{ref}}$. The FLC input parameters are the error (ξ) and the change of error $\left(\frac{d\xi}{dt}\right)$ between $v_{veh_{ref}}$ and $v_{veh_{mes}}$, the output is the total reference force which corresponds to a torque reference to be applied to the motor.

3.1.1. Fuzzification Interface

It will transform the error (ξ) and the change of error $\left(\frac{d\xi}{dt}\right)$ between $v_{veh_{ref}}$ and $v_{veh_{mes}}$, of the fuzzy logic controller from distinct quantity to fuzzy quantity. A nine-term sets are negative big (NB), negative average (NA),negative small (NS), zero negative (ZEN), zero (ZE), zero positive (ZEP), positive small (PS) , positive average (PA) and positive big (PB) are used to define FLC output and inputs linguistic variables.

3.1.2. Rule Base System

The fuzzy rule base is a set of linguistic rules defined with IF-THEN conditions. All rules base system of FLC memberships function are shown in Table. 1 and Fig. 2. (b).

Table 1. The rule base system of FLC.

...... $\frac{d\xi}{dt}$ ξ	NB	NA	NS	ZE	PS	PA	PB
B	NB	NB	NB	NA	NS	P	PB
NA	NB	NB	NA	NS	NS	ZEN	PS
NS	NA	NA	NS	NS	ZEN	PS	PS
ZE	NS	ZEN	ZEN	ZE	ZE	ZEP	PS
PS	NS	NS	ZE	PS	PS	PA	PB
PA	NS	ZE	PS	PS	PA	PB	PB
PB	PB	PS	PS	PA	PB	PB	PB

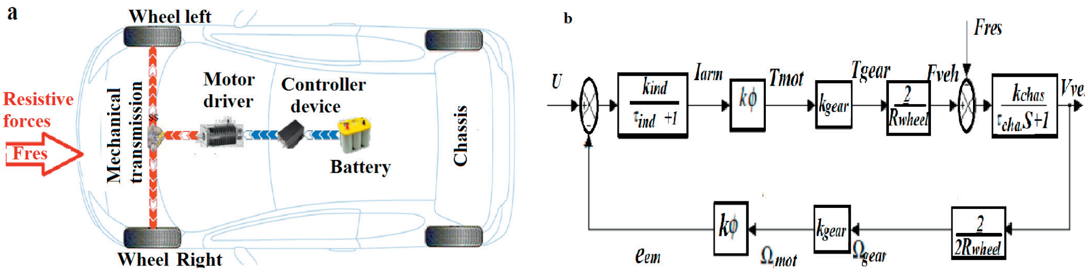

Fig. 1. (a) The studied architecture (b) The Bloc diagram of the EV

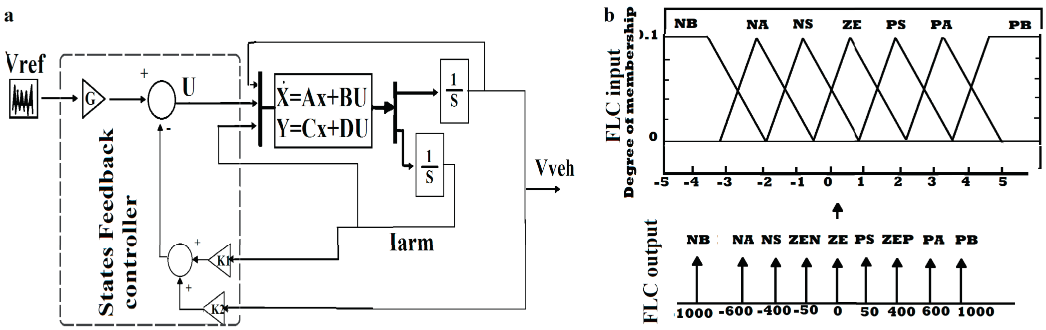

Fig. 2. (a) States feedback control of EV under Matlab/simulink (b) FLC inputs and output MF

4. State Feedback Controller

4.1. State Feedback Controller using LQR

The control is achieved by feeding back the state variables through a regulator with a constant vector control gains K and G. The controllability of the system is conserved after integrating this regulator. To achieve the preceding goal, the control law is written by (12)[9-11].

$$U(t) = -Kx(t) + GY_{ref}(t) \tag{12}$$

4.2. Reconstruction of the state

For the practical implementation problem of a state feedback control law. Its solution consists of building a system, whose inputs are u and Y and whose exit is a vector $\tilde{x}$, estimated from the state vector x [9] of the EV process. After some simple calculations, the equilibrium states can be expressed as:

$$\bar{x} = \begin{bmatrix} V_{ref} \\ \dfrac{\frac{f}{M}}{\frac{2k\phi k_{gear}}{M.R_{wheel}}} V_{ref} \end{bmatrix} \quad (13)$$

And

$$\bar{u} = G.V_{veh} \quad (14)$$

Where V_{ref} is the reference vehicle velocities, and G is a parameter of the control law given in (12), it is written by:

$$G = \frac{1}{L_{arm}^2}\left(\frac{RarmfRwheel}{2k\phi k_{gear}} + \frac{k\phi k_{gear}}{2R_{wheel}}\right) \quad (15)$$

After dynamic's error by replacing $\tilde{x} = x - \bar{x}$, the new state-space model is:

$$\begin{cases} \dot{\tilde{X}} = A.\tilde{x} + B.\tilde{u} \\ Y = C.\tilde{x} \end{cases} \quad (16)$$

Where the new control low $\tilde{u} = -K\tilde{x}$ and K is the same constant gain vector of regulators presented in (12). The state-feedback regulator is then applied to the estimated states. The new states matrix of closed loop system becomes[9]:

$$\overline{A} = A - BK \quad (17)$$

4.3. Linear quadratic regulator

In this study, The problem of the optimal regulator at the finished horizon consists of determining the control parameters of u_{opt}, which optimizes the criterion:[10]

$$J = \frac{1}{2}\int_{t_0}^{t_1} [x(t)Q(t)x(t)^T + u(t)R(t)u(t)]dt \quad (18)$$

Where $Q(t)$ and $R(t)$ are a symmetric positive semi-definite and a symmetric positive definite matrices, respectively. The optimal control of the problem formulated above is given by [9]:

$$u_{opt} = -R^{-1}B^T Px \quad (19)$$

Then, the expression of the optimal solution is a linear control in closed loop, given by:

$$u_{opt} = -R^{-1}B^T Px = -Kx \quad (20)$$

5. Results and discussion

In the following simulations, the battery, the chopper and the gears are considered ideals and without losses. The parameters of the DCM, the main geometrical data and inertial properties of the vehicle and wheels are shown in [5]. By using the LQR algorithm in the Matlab Tool and integrating the feedback control, the obtained numerical system characteristics are:

- The eigenvalues of the original system equal: $[-53.4953 \;\; -0.6842]^T$

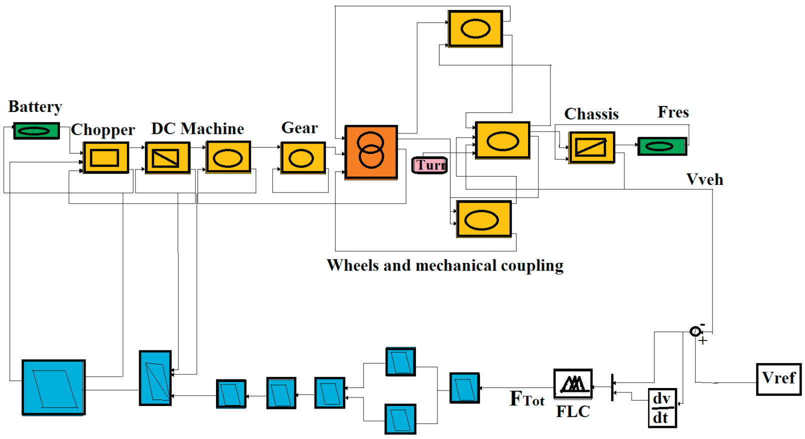

Fig. 3. FL-SMC and EMR simulator for the studied EV under Matlab/simulink

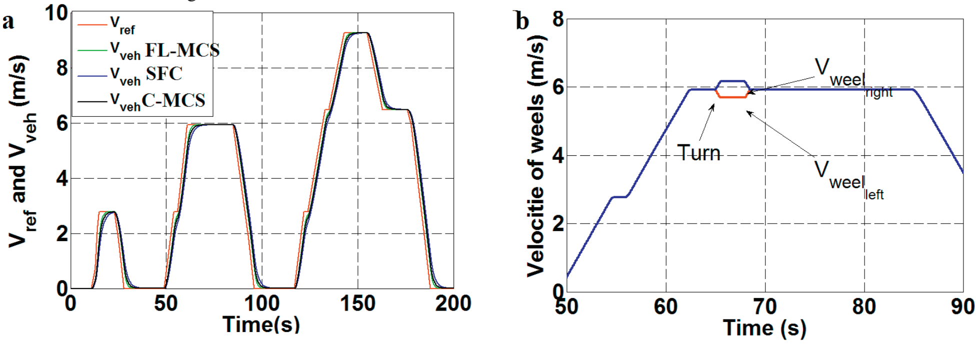

Fig. 4. (a) Reference and EV velocities using proposed controllers (b) Left and right wheels velocities

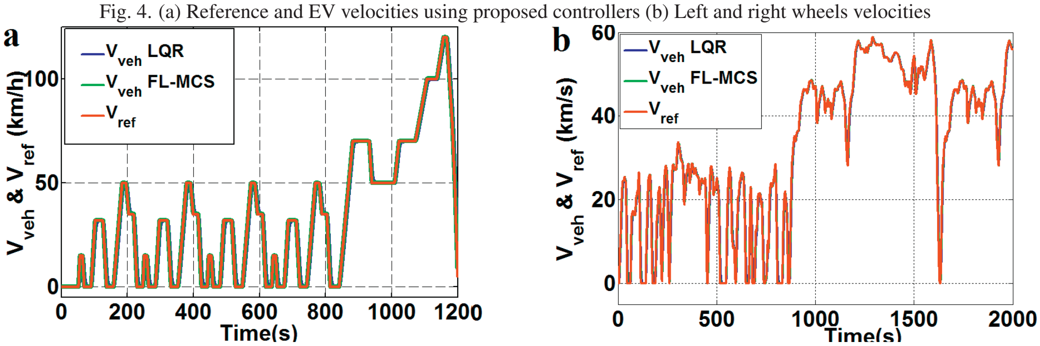

Fig. 5. (a) Reference and vehicle velocities with NEDC (b) Reference and vehicle velocities with FTP-75

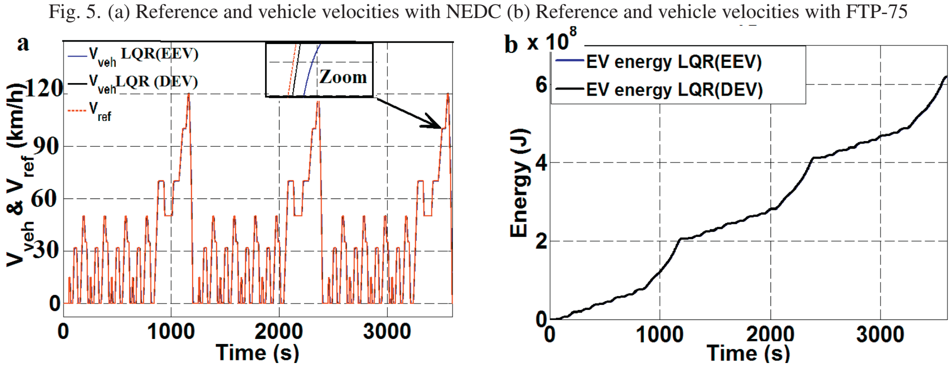

Fig. 6. Energy consumption of a EEV and DEV.

- The desired closed-loop eigenvalues after control system equal: $[-0.3868\ \ -162.8825]^T$
- The calculated constant gains of controller K using LQR equal: $[-5.0915\ \ 0.7091]^T$

In order to validate the proposed controllers, the simulation results of the proposed controllers are compared with the simulation results obtained by the Classical MCS (CMCS), which has been developed by L2EP (Lille, France) are illustrated in Fig. 4. It is clearly seen that the response of the system tracks its reference without steady error or overshoot, so the proposed controllers have the same behaviour like the CMCS. In order to test the control robustness, at 65s the vehicle makes a turn during 3.46 s as a disturbance on the road. Indeed, when the vehicle makes a turn, the wheels left and right are not running with the same speed as presented in Fig. 4. (b), but that does not effect on the vehicle speed as illustrated in the Fig. 4. (a). The results in Fig. 5 show the reference and vehicle velocities of EV obtained by using the FL-MCS and the State Feedback Controller (SFC) separately, where simulations were carried out to standard European (NEDC)and USA (FET-75) driving cycles. these lasts are used as an imposed reference velocities for the vehicle, it is clear that the controllers work well and acts on the EV dynamic performance to track its reference. These simulation results demonstrate the robustness and the dynamic performance of the proposed state feedback and FL-MSC controllers, Under the same driving cycles and simulation conditions, Fig. 6. (a) presents a comparison between the EV velocities response with the same SFC, but the Q and R matrices of LQR have been adjusted off-line to make the EV works as a Dynamic EV (DEV fast response) then as an Economic EV (EEV) less dynamic is imposed in order to safe energy consumption. The energy consumption of the EV using LQR for EEV is less than the energy consumption of the DEV (Fig. 6. (b)) and the average difference between them equals $1457.5kJ$.

6. Conclusions

This paper shows the modelling and control strategies for an electric vehicle using an EMR and state space for the EV modelling , and a new hybrid FL-MCS and state feedback controller for the traction drive System. This study shows a good agreement between the MCS and fuzzy logic which offers a robust and a realizable controller acting as a PID. Whereas the states feedback controller based on Linear Quadratic Regulator allows reducing the energy consumption of the EV and improving the process performances and stability according to the choice of Q and R matrices. The simulation results demonstrate the robustness and the dynamic performance of the proposed controllers applied to the traction drive for Electric Vehicles.

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