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States Feedback Control Applied to The Electric Vehicle

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Abstract

This paper presents the modelling and the control strategies based on the states feedback control of an Electrical Vehicle (EV). The Electromechanical behaviour of studied system is modelled by using the states representation deduced from the electrical and dynamical laws. Two kinds of methods are used to determine the values of control's parameters, first one is the states feedback regulator using pole placement, and the second one is the Linear Quadratic Regulator (LQR). The Pole-placement design allows determining the values of the controller's parameters by the displacement of the poles to specified locations according to the zeros of a desired polynomial, whereas the values of feedback vector gains are obtained by resolving the Ricatti equation in LQR method. Finally, the simulation of the proposed controller was carried out for the European, the American and the stander driving cycles as the EV speed references in order to validate its robustness and its dynamical performances.

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Keywords: Electric Vehicle, State Feedback, Modelling, Pole Placement, LQR, Ricatti equation;

1. Introduction

The orientation towards the use of Electric Vehicles (EVs) has received a thorough attention during the past few decades, because they meets the requirements doubling of the scarcity of fossil fuels and the air pollution caused by vehicles emissions [1]. Currently, Thanks to the development of the electric motors and the electrical sources e.g. batteries, Fuel Cell (FC), and SuperCapacitors (SCs), the performance of Electrical Vehicle (EV) is greatly improved in the past few years [2]. The most distinct advantage of an EV is the quick and precise torque response of the electric motors, and helps to protect the environment and the shortage of energy sources . The modelling and the control of EVs have received a thorough attention, because the EVs do not have issues with increasing oil prices or pollution problems. The EV modelling is very complex as it contains many different components, e.g. the transmission, electric machine, power electronics, and electric sources. In this paper, States space model has been developed by

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authors for modelling the Electromechanical behaviour of EV. This dynamic model should be useful for developing an effective control strategy based on states Feedback. The states feedback control has been used to control an EV speed, with two types of methods to determine the values of the controller parameters, the first one is Pole Placement and the second one is Linear Quadratic Regulator (LQR). The Pole placement design allows determining them by the displacement of the poles to specified locations according to the zeros of a desired polynomial, whereas the parameters of state feedback control are obtained by resolving the Ricatti equation in LQR method. The objective of the regulator problem is to bring back as quickly as possible the state in the vicinity of the origin, the solution sought here corresponding well with a compromise between the previous goal and the means implemented to reach that point. In addition, the last term of the the Ricatti equation translates the particular importance attached when the state is finally reached. The simulation of the proposed controller was carried out to the European, the American and the stander driving cycles which are imposed as EV speed references in order to validate the controller robustness and the its dynamical behaviour.The rest of the paper is organized as follows: Section 2 reviews the fundamentals of vehicle system modelling with the components modelling of a dc machine, a DC/DC boost power converter, and vehicle dynamics including wheels. Section 3 shows the developed state model of EV. The proposed State Feedback-Regulator using Pole Placement, and the LQR are deduced in section 4 and 5 successively. Section 6 presents the simulation results obtained with the proposed control strategies. Finally, some conclusions are given in Section 7.

2. Electromechanical modelling of studied vehicle

2.1. The studied architecture

The studied EV is driven by a 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 inspired from the L2EP researches work [3].

2.2. Modelling of EV components

2.2.1. Supplied electric source

Different electric sources and energy management methods are developed by authors for the EVs applications [4-7], but in this works a simple lithium battery has been used. The battery can be modelled as an equivalent circuit such as a voltage source in serial with an internal resistor.

2.2.2. Direct Current Machine

The DC machine is modelled with classical relationships, where the armature current I_{arm} is the state variable of armature windings and is obtained from the supply voltage 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} [8].

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

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.

2.2.3. Differential mechanical

The torque reduction is shared fairly on the left and the right wheels [9] 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.

2.2.4. The traction forces

The traction forces can be calculated from the torque of the differential [9].

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

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

2.2.5. 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 [3,9,10], 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 a block diagram as shown in Fig. 1. (b).

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:

$$\begin{cases} F_{tot} = \frac{2k\phi k_{gear}}{R_{wheel}}.I_{arm} \\ e_{em} = \frac{k_{gear}.k\phi}{2R_{wheel}}.V_{veh} \end{cases} \tag{7}$$

So V_{veh} and I_{arem} can be written by (8).

$$\begin{cases} V_{veh} = \dfrac{2k\phi k_{gear}}{M.R_{weel}}.I_{arm} - \dfrac{f}{M}.V_{veh} \\ I_{arem} = \dfrac{-R_{arm}}{L_{arm}}.I_{arm} - \dfrac{k_{gear}.k\phi}{2L_{arm}R_{weel}}.V_{veh} + \dfrac{1}{L_{arm}U} \end{cases} \tag{8}$$

The general system equation can be written as:

$$\begin{cases} \dot{X} = A.x + B.u \\ Y = C.x \end{cases} \tag{9}$$

Where $x \in R^2$ is the state vector, $u(t)$ the command vector and Y the output vector. A, B, C and D are matrices with appropriate dimensions. without loss of generality information and D equals zero. $x = \begin{bmatrix} \mathrm{V}_{veh} \\ \mathrm{I}_{arm} \end{bmatrix}$ and $Y = V_{veh}$

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

4. Formulation of the control problem

The desired objective is to synthesize a linear control law, such that the poles of the controlled system coincide exactly with the zeros of a polynomial:

$$P(s) = s + a_{n-1}s^{n-1} + a_{n-2}s^{n-2} ... + a_1 s^1 + a_0 \tag{10}$$

The law of control, which satisfies the preceding objective, is called: state feedback.

4.1. State Feedback Controller using poles placement

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 [11]. Pole-placement design allows the displacement of the poles to specified locations, provided the system is controllable. The control is achieved by feeding back the state variables through a regulator with a constant vector control gains K and G as it is shown in the following control law [12].

$$u(t) = -Kx(t) + GY_{ref}(t) \tag{11}$$

4.2. Reconstruction of the state model

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 of the EV process. After some simple calculation, the equilibrium states are expressed by:

$$\bar{x} = \begin{bmatrix} V_{ref} \\ \frac{\frac{f}{M}}{\frac{2k\phi k_{gear}}{M.R_{wheel}}} V_{ref} \end{bmatrix} \tag{12}$$

and

$$\bar{u} = \frac{V_{ref}}{L_{arm}^2} \left(\frac{R_{arm} f R_{wheel}}{2k\phi k_{gear}} + \frac{k\phi k_{gear}}{2R_{wheel}} \right) \tag{13}$$

Where V_{ref} is the reference vehicle velocities. So the parameter G of the control law (11) is written by;

$$G = \frac{1}{L_{arm}^2} \left(\frac{Rarm f Rwheel}{2k\phi k_{gear}} + \frac{k\phi k_{gear}}{2R_{wheel}} \right) \tag{14}$$

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

$$\begin{cases} \dot{\tilde{X}} = A.\tilde{x} + B.\tilde{u} \\ Y = C.\tilde{x} \end{cases} \tag{15}$$

Where the new control low $\tilde{u} = -K\tilde{x}$ and K is the same constant gain vector of regulators presented in (11).

The state-feedback regulator is then applied to the estimated states. The new state matrix of closed-loop system takes the following form [13]:

$$\overline{A} = A - BK \quad (16)$$

In order to place the poles of the system, it needs to calculate the difference between the desired eigenvalues and those of the state matrix A. The desired closed-loop performances are presented by the following characteristics:

- The desired system Eigenvalues are $[-3; -1]$ (given by $\det(A - BK) = 0$)
- EV speed response time $tr = 1,8s$
- EV speed response is without overshoot ($D\% = 0\%$) and steady error equals ,zero

5. Linear quadratic regulator

In this study, The problem of the optimal regulator at the finished horizon consists of determining the control u_{opt} of system (15), which optimizes the criterion:[14]

$$J = \frac{1}{2}\int_{t_0}^{t_1} [x(t)^T Q(t)x(t) + u(t)R(t)u(t)]dt \quad (17)$$

Where $Q(t)$ and $R(t)$ are a symmetric positive semi-definite and a symmetric positive definite matrices, respectively. The objective of the regulator problem is to bring back as quickly as possible the state in the vicinity of the origin, the solution sought here corresponding well with a compromise between the previous goal. The optimal control of the problem formulated above is given by:[12,14]

$$u_{opt} = -R^{-1}B^T Px \quad (18)$$

Where P is the single positive semi-definite symmetric solution of the differential.

$$-\dot{P} = PA + A^T P + PBR^{-1}B^T P + Q \quad (19)$$

Being observable and controllable, the Riccati equation in steady state can be written as:[12]

$$PA + A^T P + PBR^{-1}B^T P + Q = 0 \quad (20)$$

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

$$u_{opt} = -R^{-1}B^T Px = -Kx \quad (21)$$

By using the LQR algorithm in Matlab, the obtained resulting controller gains : $K = \begin{bmatrix} -5.0915 & 0.7091 \end{bmatrix}^T$
The closed-loop eigenvalues are then: $Poles = [-0.3868 - 162.8825]$

6. 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 in Table 1. The corresponding EV control model is converted into Matlab/Simulink as illustrated in Fig. 2. (a). In order to validate the proposed controller, the simulation was carried out for the stander FTP-75 , the American HWFET and the European NEDC driving cycles as are illustrated in Fig. 2. (b), Fig. 3.(a) and (b) respectively (more details about the used driving cycles in [15]), they are used as an imposed reference velocity for the vehicle. The Fig. 2.(a), 3 and 4 show the responses of the studied EV with control strategies, whereas the vehicle velocity controlled by the States

Table 1. Parameters of the studied EV.

Parameters	Value
$P_{util_{nom}}$	$32kW$
L_{arm}	$0,0065H$
R_{aarm}	$0,35\Omega$
J_m(Rotor inertia)	$0,12kg.m^2$
M_{veh} (vehicle mass)	$1000kg$
l_{veh} (rear wheel track)	$1.6m$
d_{axe} (wheelbase)	$2.4m$
R_{wheel}(Wheel radius)	$0.52m$
J_{weel} (Inertia of wheel)	$4.3Kg.m^2$
A_f (frontal surface of vehicle)	$21.6m^2$
ρ (Density of the air)	$1.2Kg/m^3$

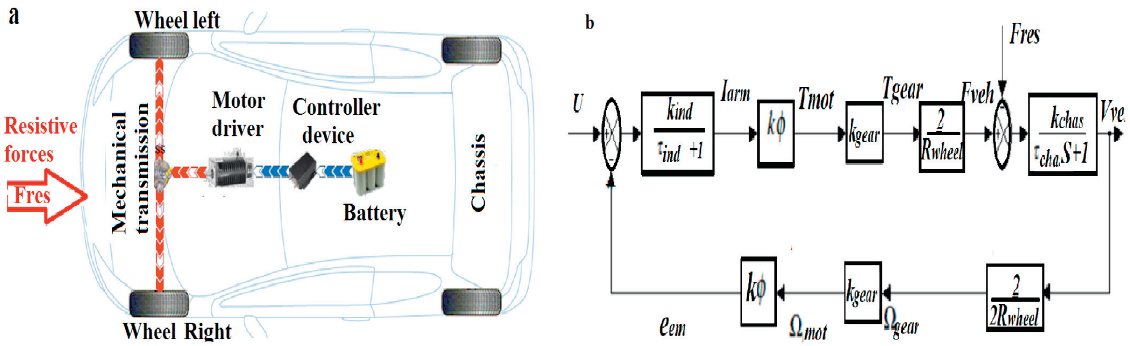

Fig. 1. (a) Components of the studied architecture (b) Bloc diagram of the EV

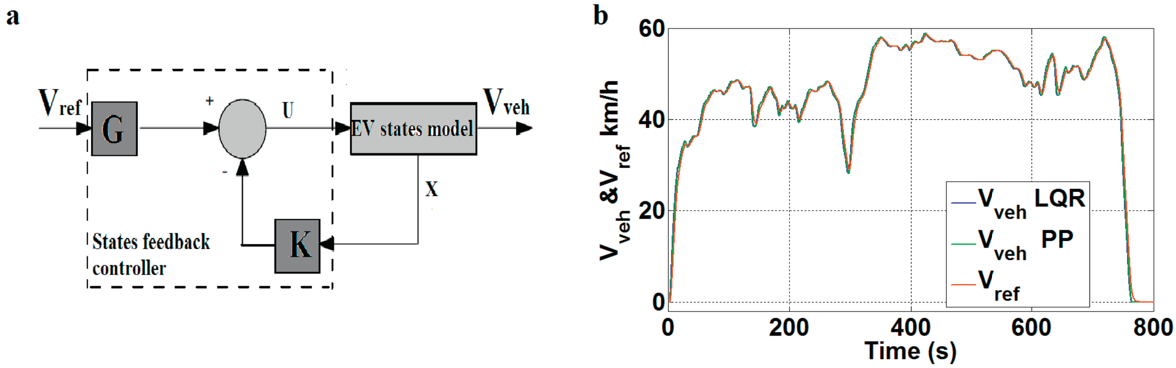

Fig. 2. (a) Structure of state feedback control of studied EV (b) Reference and vehicle speed with HWFET

Feedback Regulator using Pole Placement and the Linear Quadratic Regulator (LQR). The Fig. 3. (a) shows the reference and vehicle velocities of EV, where simulation was carried out to standard European driving cycles (NEDC is suitable for both urban and highway, medium and high speed). It is clearly seen that the response of the system has good dynamic behaviour and tracks very well its reference without steady error or overshoot.

At 65s the vehicle makes a turn during 3.46 s as 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 (22), where the left wheel speed v_{veh_left} slow down and the right wheel speed v_{veh_right} up for the turn but that does not effect on the vehicle speed as illustrated

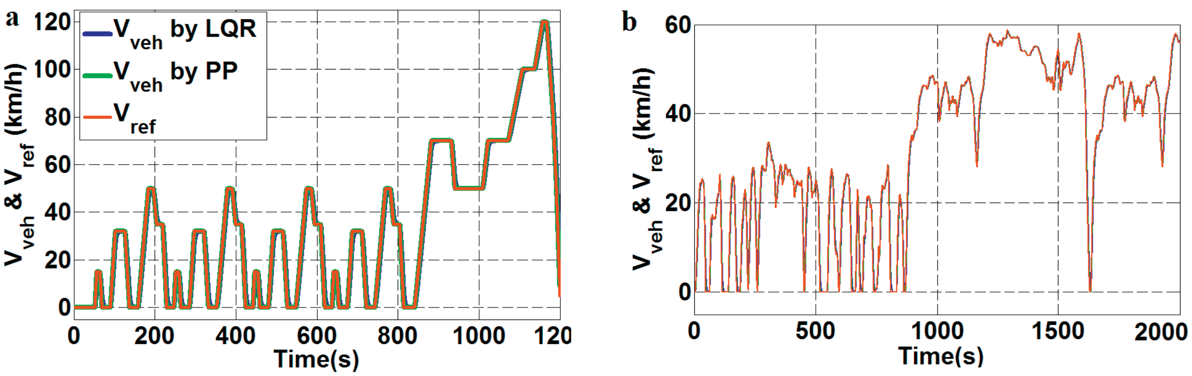

Fig. 3. (a)Reference and vehicle speed with NEDC (b)Reference and vehicle speed with FTP-75

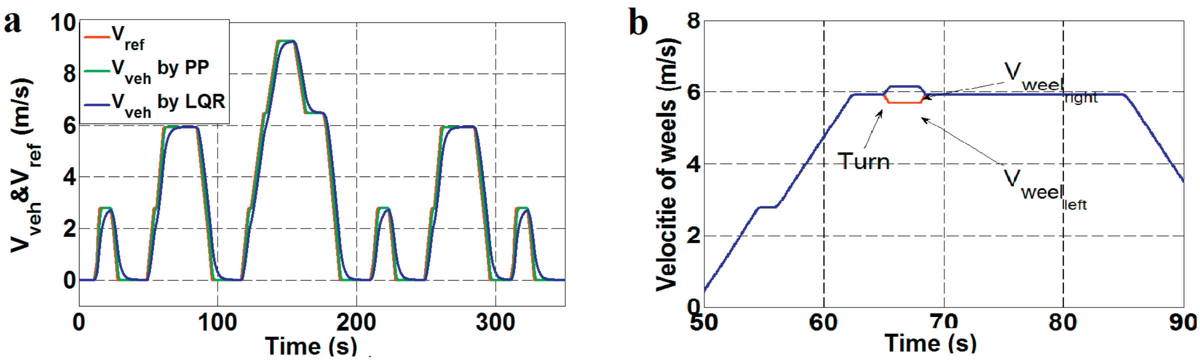

Fig. 4. (a) Left and right wheels velocity (b) Reference and vehicle speed SOC(0)=75%

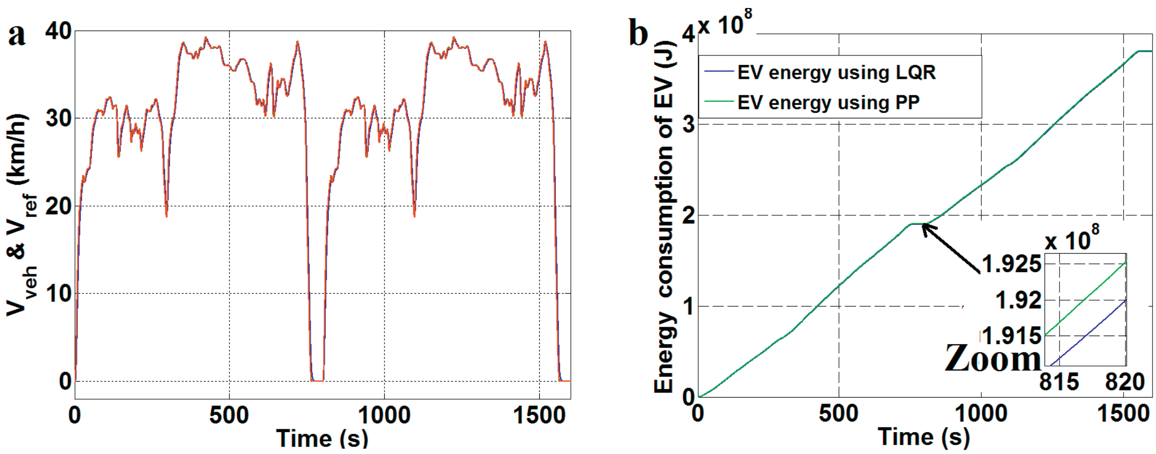

Fig. 5. (a) Reference and vehicle speed with double FTP-75 (b) Energy consumption of EV

in the Fig. 4. (a).

$$\begin{cases} v_{veh_{left}} = \frac{R_{courb} + \frac{l_{left}}{2}}{R_{courb}} v_{veh} \\ v_{veh_{right}} = \frac{R_{courb} - \frac{l_{left}}{2}}{R_{courb}} v_{veh} \end{cases} \quad (22)$$

Under the same driving cycles and simulation conditions, Fig. 5 presents a comparison between the EV energy consumption of two different control strategies. One is a the developped LQR, the second is the State Feedback controller using Poles Placement (PP), as it is indicated in Fig. 5. (b) the energy consumption of the EV using LQR is less than the energy consumption of the EV using PP and the average difference between them equals $4416.9kJ$, The closed loop Eigenvalues of system using Pole placement and LQR technique are real and negatives, then EV system is stable and robust in presence of perturbation on the road such as the case of the turn.

7. Conclusions

This paper contains a study and simulation of the electromechanical model and control strategies of an electric vehicle. Using an electrical and dynamical laws, the EV is presented by a linear dynamic model expressed by state space representation. The states feedback controller based on linear quadratic regulator and poles placement are designed to reduce the energy consumption of the EV and increase system stability. The proposed controllers are validated by simulation results. The LQR results showed that the energy consumption of the EV is significantly minimized. The approach makes it possible in practice to conserve material and energy resources for many applications, Therefore the proposed control method is simple, accurate, and robust. This study demonstrates the robustness and the dynamic performance of the state feedback control of the traction drive for Electric Vehicles.

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