Design and development of a virtual model of an electric vehicle of category L7

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Abstract. This study is aimed at creating an accurate mathematical model, developed in Matlab-Simulink through the Simscape library, concerning an electric vehicle of class L7. To this end, a mechanical model with three degrees of freedom is used. The degrees of freedom are advancement, vertical displacement, and pitch. Two degrees of freedom are also added to this dynamical model in order to model the stiffness and the damping of the tires, whose behavior is described by the "Magic Formula". The propulsion unit is modeled in a standard design configuration. The vehicle can be controlled by supplying the driver's inputs, by controlling the cruising speed, or by ensuring that the vehicle has a driving cycle. The proposed model allows for identifying the critical aspects of the selected design solution, thereby reducing the time required in the design phases.

1. Introduction

This paper deals with the virtual design and the computer development of a dynamical model of an electric vehicle of category L7. This section provides background information on the problem addressed in this paper and the organization of the manuscript. Currently, one of the technologies with the greatest potential in the field of sustainability is electric propulsion [1,2,3]. Electric Vehicles (EV) do not emit polluting substances. However, the energy that feeds them generates different emissions globally based on the way in which the same amount of energy is produced. If this energy is obtained through the use of fossil fuels, the result is simply to transfer the emissions from the city to the production plant. On the other hand, if the energy required to power electric vehicles is produced using any renewable form of energy generation, a significant impact on the sustainability of the means of transportation can be achieved. It is, therefore, necessary to globally enhance the synergy between EV and renewable energy production. If these systems were used globally, there would be ideally zero emissions. The remaining part of this manuscript is structured as follows. Section 2 provides a short literature review on the topic addressed in this paper. In Section 3, the background materials and the computational methods employed in this research project are described. Section 4 and 5 proposes the developments of the virtual prototype of the electric vehicle of category L7 that represents the main object of the present paper. Section 6 offers a summary of the work and the conclusions reached in this paper.

2. Literature Review

Several recent research works are devoted to the virtual prototyping of electric vehicles. To obtain a general overview of electric vehicles, one can consult the journal paper [4], which illustrates the most used technologies, comparing the models on the market with the impact of electric vehicles on the environment, the economy, and the electricity grid. The theme of the impact of electric vehicles is dealt with in the detailed paper, in which the in-depth analysis proposed concerns vehicles of category L [5]. For the study of vehicle performance, an excellent reference is the vehicle dynamics textbook by Guiggiani [6]. Also, useful references are the journal publications [7,8], in which the half-body model of an electric vehicle is analyzed in particular. The longitudinal tire model was developed using Pacejka's well-known "Magic Formula" described in the book [9]. The model developed in this work uses the Simulink model as a basis [1]. Furthermore, as far as the vehicle models developed in Matlab/Simulink is concerned, the reference papers [10-12] are recommended. For a review on the electrical motor drivelines in electric vehicles, the literature survey [13] is recommended. The suspension system suitable also for the vehicle of category L7 considered in this work are studied in the journal paper [14].

3. Materials and Methods

In the development of the present work, a systematic approach is used. Firstly, the object of study is analyzed, therefore analyzing the various existing components for EVs, such as batteries, charging stations, engines, and the different possible configurations. Subsequently, for the creation of the mathematical model, a systematic approach is used, dividing the whole system into simpler problems. Once solved the individual problems, the complete system is assembled creating a general vehicle model. However, the main focus of the paper is on the development of a structured dynamical model which couples the mechanical aspects and the electric aspects of the vehicle. For the development of the vehicle model, the Matlab/Simulink software was used, an application included in the Matlab calculation program and which constitutes, in large part, a powerful and intuitive graphic interface aimed at simplifying its use by the user. Using Simulink it is possible to program the execution of calculations in the Matlab environment in a much faster and error-free way compared to the writing of the long and complex m-files that are necessary, for example, to program the numerical integration of a system of high order differential equations. Through the visual tools available in the Simulink environment it is possible to simulate even very complex systems with an effort by the user that is limited to the tracking, on an electronic worksheet, of a block diagram representative of the system under examination. Simulink consists of a series of libraries that contain elementary blocks, which, properly interconnected, form the block diagram representing the desired functionality. The library most used to conduct this study is Simscape, in which the blocks represent physical elements having different levels of fidelity relative to the different levels of the system being analyzed, and the lines, which connect these components, correspond to physical connections in the system real that transmits power. This method thus allows us to describe the physical structure of a system rather than the underlying mathematics. The electrical and mechanical connections are represented by different colors that indicate the physical domain. This software was used in order to carry out a preliminary simulation of the behavior of the electric vehicle in a more economical and efficient way compared to hardware prototypes.

4. Electrical Model of the Vehicle

The electrical system is powered by a lithium-ion battery consisting of 10 parallels composed of 50 series of cells each. In the representation of the battery, the equivalent circuit of the cell is created, and by multiplying it appropriately, the entire generator is obtained. There is a DC-DC converter to bring the current from the battery voltage to the motor voltage. The electric motor is synchronous with permanent magnets with closed-loop torque control, which means that the input voltage and power adjust according to the torque required by the control system. Therefore, having at the motor input the electric current, regulated by the controller, the rotation of the rotor and the heat generated are obtained. Furthermore, in the case of negative torque and positive speed, the electric machine operates like a current generator recharging the batteries. The electric system is shown in Figure 1.

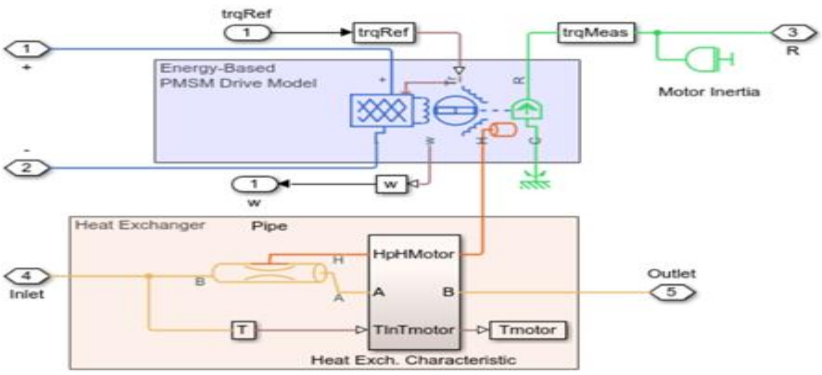

Figure 1. Electric motor.

5. Mechanical Model of Vehicle

The mechanical part of the electric vehicle of interest is modeled considering a simplified multibody approach [15,16]. To this end, the system uses a half-car vehicle model with three degrees of freedom: advancement, vertical displacement (bouncing), and pitching, in order to consider the different forces acting on the car such as viscous friction with the air, the elastic ones and the damping ones due to the suspensions [17]. The behavior of the tires was also examined using the well-known Pacejka “Magic Formula” and considering their stiffness and damping [18]. The propulsion unit has been modeled according to a standard configuration consisting of a central engine, with a fixed transmission ratio and a mechanical differential that distributes the driving torque to the wheels [19,20]. In the design configuration chosen, the rotation obtained by the motor is first reduced by a fixed gear, then distributed by a mechanical differential to the two driving wheels, from whose model, finally, the longitudinal force acting on the axis is calculated, and which affects the dynamic model as shown in Figure 2. In electric vehicles, it is possible not to use the speed change, since the electric motors, compared to traditional internal combustion engines, have a high starting torque, much higher maximum RPMs and good efficiency for a wide speed range.

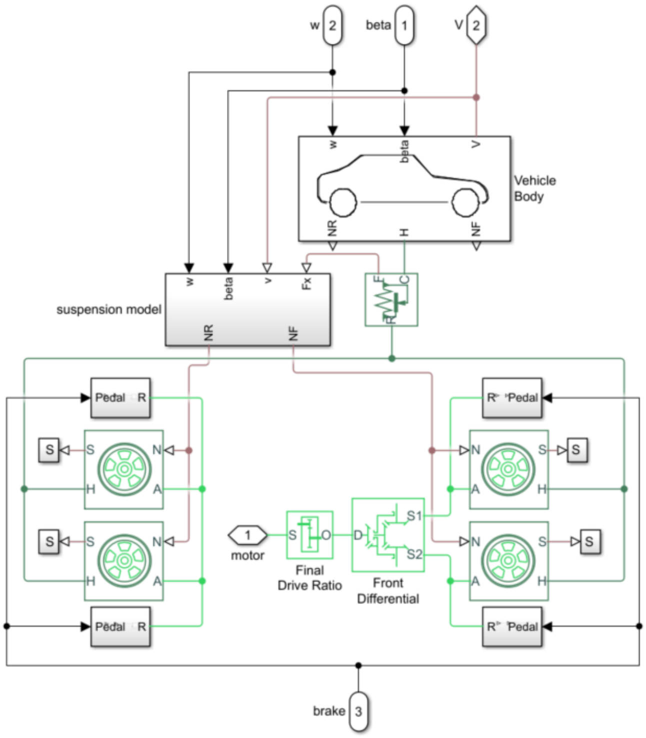

Figure 2. Matlab/Simulink model of the design configuration.

A dynamic half-car model with three degrees of freedom was used: advancement, vertical displacement (bouncing), and pitching, to which two degrees of freedom are added, giving stiffness and damping to the tires as shown in Figure 3.

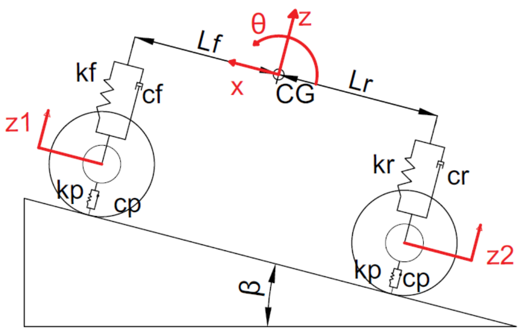

Figure 3. Scheme of the dynamical model.

$$
\begin{cases}
m\ddot{x} = F_x - F_{d,x} - F_{g,x} \\
m\ddot{z} = F_{d,z} + F_{sz,F} + F_{sz,R} - F_{g,z} \\
I_{yy}\ddot{\theta} = -L_f F_{sz,F} + L_r F_{sz,R} + hF_x - M_{d,y} \\
m_w \ddot{z}_1 = -F_{sz,F} + F_{s1} \\
m_w \ddot{z}_2 = -F_{sz,R} + F_{s2}
\end{cases}
\tag{1}
$$

In these equations:

- F_x is the longitudinal force applied on the wheel axis;
- $M_{d,y}; F_{d,z}; F_{d,x}$ are respectively the drag moment, the longitudinal drag force, and the vertical drag force;
- $F_{sz,F;} F_{sz,R;}$ are the elastic and damping force of the front and rear axle suspensions;
- $F_{gx}; F_{gz}$ are the components of the gravity force;
- $L_f; L_r$ are respectively the longitudinal distances from the center of mass to the front and rear axle;
- h is the normal distance between the CG and the wheel axis.

The viscous friction force between the air and the vehicle is therefore directly proportional to the square of the difference between vehicle speed and wind speed:

$$
\begin{cases}
F_{d,x} = \dfrac{1}{2} C_d \rho A(\dot{x} - w)^2 \\
F_{d,z} = \dfrac{1}{2} C_l \rho A(\dot{x} - w)^2 \\
M_{d,y} = \dfrac{1}{2} C_{pm} \rho A(\dot{x} - w)^2 (L_r + L_f)
\end{cases}
\tag{2}
$$

The elastic and damping force of the suspensions and of the tires is given by the equations:

$$
\begin{cases}
F_{sz,F} = -2k_f (z - z_1 - L_f \vartheta) - 2C_f (\dot{z} - \ddot{z}_1 - L_f \dot{\vartheta}) \\
F_{sz,R} = -2k_r (z - z_2 + L_r \vartheta) - 2C_r (\dot{z} - \ddot{z}_1 + L_r \dot{\vartheta})
\end{cases}
,\quad
\begin{cases}
F_{s1} = -k_p x_1 - c_p \dot{x}_1 \\
F_{s2} = -k_p x_2 - c_p \dot{x}_2
\end{cases}
\tag{3}
$$

The advancement equation is independent of the other ones, therefore it is resolved independently with the use of the “Vehicle body” block. The remaining equations are instead coupled and are solved with the use of Matlab Simulink blocks. The values used for the simulation refer to a generic vehicle of category L7, in particular the damping and stiffness coefficients of the suspension, and of the tires, are those present in the paper [15] in which a vehicle with a mass comparable to that chosen by us is analyzed. To model the tire using the Simulink pakage “Tire block (magic formula)”, which describes the longitudinal behavior, using an empirical formula based on four adaptation coefficients. The block models the dynamics of the tire considering it a rigid set with the wheel, both in constant and variable road conditions and evaluating its inertia, rolling resistance and slip. Moreover, this block considers the longitudinal stiffness and damping of the tire. The model used is based on the Pacejka Magic Formula [9], obtained through experimental tests. The general formula is:

$$
F_x = F_z D \sin(C \arctan\{B\kappa - E[B\kappa - \arctan(B\kappa)]\})
\tag{4}
$$

The coefficients B, C, D, E are obtained graphically where the function passes through the origin of the Cartesian system, reaches a maximum and then tends to a horizontal asymptote. The slip is given by the ratio between the speed of slip and the speed of progress in the case in which there is no slip, therefore:

$$\kappa = \frac{V_{sx}}{|V_x|} = \frac{r_w\Omega - V_x}{|r_w\Omega|}, \quad \kappa = \frac{2V_{sx}}{V_{th} + \frac{V_x^{\,2}}{V_{th}}} \tag{5}$$

where the second equation is valid at low speeds.

6. Summary and Conclusions

The authors focus their research mainly on the dynamics of multibody systems [21-25], on the optimal control techniques [26-30], and on the algorithms of system identification [31-35]. Based on this research background, this paper deals with the design and the developments of a virtual prototype of an electric vehicle. This work is focused on the design of a mathematical model representing the engineering relevant aspects of an electric vehicle of class L7. In order to be able to carry out an analysis that takes into account the different forces acting on the system, a standard dynamic model with three degrees of freedom referred to as the half-car model is implemented. This mechanical model is further extended including also the longitudinal displacement of the vehicle in order to simulate appropriate driving cycles. The computer simulations are performed in Matlab-Simulink environment, using the Simscape library. A proportional-integrative control is used for the system motion, which allows the vehicle to follow the standard WLTP class 1 driving cycle. The electric system of the vehicle is also modeled in Matlab-Simulink environment in order to determine the energy consumption. The proposed dynamic model allows for effectively performing the virtual prototyping of the electric vehicle of interest.

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