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Multiphysics modeling and optimization of the driving strategy of a light duty fuel cell vehicle

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ARTICLE INFO

Article history:
Received 4 August 2016
Received in revised form
22 May 2017
Accepted 21 June 2017
Available online 21 August 2017

Keywords:
Fuel-cell powertrain
Multi-physics modeling
Optimization
Eco-marathon

ABSTRACT

This paper presents the optimization of the driving strategy of a high efficiency fuel cell based power train. This power train is developed to equip a light duty urban-concept vehicle that runs energetic races. The objective is to go the furthest with the lowest quantity of fuel. A comprehensive dynamical model is presented, including the mechanical requirement, the thermal behavior of the fuel cell stack and the various losses and consumptions of the power train devices. This model is next integrated into a global optimization algorithm, to determine the best race strategy to be adopted. These results are validated on experimental measurements, obtained during a real race at the Shell Eco-Marathon, in 2015.

Introduction

Given the new economic and ecological issues, car manufacturers should focus on alternative energy sources, such as electric batteries or fuel cells [8,10,27,32,33,35,36,38]. Although still young and hard to handle, fuel cells, and particularly Proton Exchange Membrane Fuel Cells (PEMFCs), remain a promising way. Indeed, a hydrogen fuel cell vehicle has naturally a better performance than a diesel car (usually 30% against 22% of efficiency at the wheel). Moreover, the energy supplied by the fuel cell is electric, which allows propulsion chains more flexible with high performances [11,37]. For several years, a prototype vehicle with extremely low energy consumption has been developed by researchers and electrical engineering students, to run energetic races [28,34,39]. The energy source of this vehicle is a PEMFC. From 2010 to 2012, this vehicle has been recognized by the Shell group (through the 2010 edition of the Shell Eco-marathon competition, on the EuroSpeedway race track, Germany) as the world most energy efficient car, with an equivalent consumption of only 0.02 L of unleaded gasoline 95 per 100 km, at a minimum average speed of 30 km/h.

Since 2013, a new car with extremely low energy consumption is developed (see Fig. 1). It comes under the urban-

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http://dx.doi.org/10.1016/j.ijhydene.2017.06.243

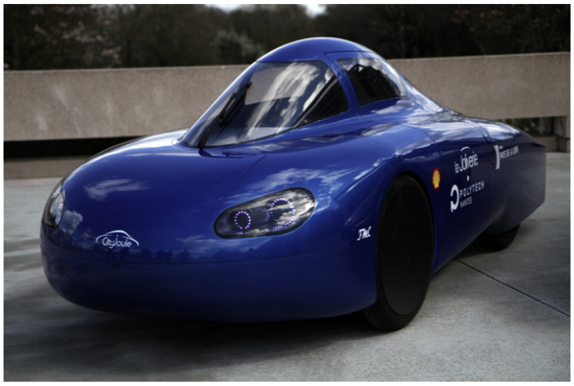

Fig. 1 – The Urban-Concept vehicle Cityjoule.

concept category, which aims to promote the development of vehicles closest to true city cars. The energy source of this vehicle is also a PEMFC. To achieve an energy consumption as low as possible, each element of the vehicle must be optimized, from the mechanical angle (drag coefficient, frontal area, slop, road-wheel friction, weight) to the electrical architecture (power converter, motor efficiencies and fuel cell peripheral elements consumption). This optimization has been done in previous works, but without taking into account the driving strategy [34]. In this paper, the optimal driving strategy that minimizes the car energy demand is presented. It is based on a multi-physics modeling of the power train, taking into account the road profile and the race constraints (average speed, stop at each turn, etc.) [1,5,7,31]. This model is then integrated into a global optimization algorithm, which lead to the best velocity profile, motor current and gearbox ratio.

The paper is structured as follows: In section Presentation of the race and vehicle characteristics, the vehicle specifications and the race characteristics are presented. A focus is made on power train architecture from the fuel cell stack to the mechanical needs. In section Multi-Physics modeling of the powertrain, a dynamical and multi-physics model is developed. In this section, each part of the power train is presented. An originality of this work is the addition of a thermal modeling of the PEMFC, in order to take into account the auxiliary stack consumption in energy balance, including the air feeding and cooling systems. The optimization results are given in Section Results, which allow to achieve a driving strategy minimizing the final energy consumed by the vehicle. Simulations and experimental results are compared to a real race, recorded during the previous edition of the Shell eco-marathon, in Rotterdam, Netherlands. Conclusions are given in Section Conclusions.

Presentation of the race and vehicle characteristics

The urban-concept car and its associated fuel cell power train were both designed and built to participate in the Shell Eco Marathon energetic race (Rotterdam, Netherlands). The principle of such a competition is to drive a vehicle with one pilot the furthest with the lowest quantity of fuel at a minimum average speed of 25 km/h. A minimum weight of 70 kg is imposed for the pilot. Each competitor will have to travel 10 laps of the race track corresponding to 16.1 km in less than 40 min. In the urban-concept category, a stop is mandatory during at each lap. To evaluate prototype car efficiency, the fuel quantity carried on board is measured before and after the attempt. Wide range of fuels can be used (Unleaded gasoline; diesel; LPG; GTL; fatty acid methyl ester; ethanol E100 and hydrogen). In the fuel cell category, an official flow meter is used to measure the volume of hydrogen consumed during the attempt. This amount of energy is converted into kilometers per kWh. It is important to notice that in the fuel cell category, battery is not allowed in the car except for safety purposes, i.e. to power the car-horn and the hydrogen sensor.

Multi-physics modeling of the powertrain

In this section, a dynamical model of the vehicle is proposed. For a set of input parameters (e.g. motor current, road slope, ambient temperature, …), this model calculates the evolution of the various system states, the losses and the consumption of each subsystem (see Fig. 2).

This model is organized around six main blocks: The mechanical part, the propulsion motor, the power converter, the fuel cell, the stack accessories coupled to a thermal model, and the control laws and supervision. This dynamical model is oriented towards the optimization and must be solved quickly. Thus, only the velocity v and the stack temperature T_{st}, which are the slowest state variables, are taken into account. All other dynamics are considered fast enough to be regarded as instantaneous (see Fig. 3).

The urban-concept *Cityjoule* presented in this paper is made of two identical power trains, each supplying one of the two rear wheels. In the next sections, only one power train is studied.

Fuel cell

The fuel-cell stack has a power rate of 800 W and is composed of 28 cells connected in series, each of them having an active area of 60 cm^2. A PEMFC is mainly described by its polarization curve. It gives the voltage level U_{st} according to the supplied current I_{st}. The electrochemical equations give a relation

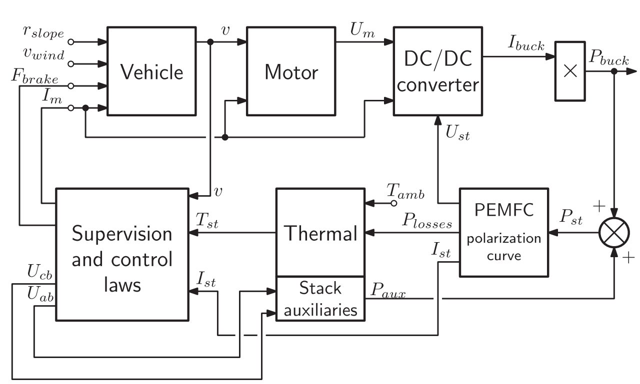

Fig. 2 – Tank-to-wheel model.