Energy 91 (2015) 630–644

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Techno-economic design of hybrid electric vehicles using multi objective optimization techniques

Zlatina Dimitrova*, François Maréchal

Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

ARTICLE INFO

Article history:
Received 10 April 2015
Received in revised form
20 July 2015
Accepted 15 August 2015
Available online 19 September 2015

Keywords:
Hybrid electric vehicles
Multi objective optimization
Economic models
Driving cycles

ABSTRACT

The improvement of the efficiency of vehicle energy systems promotes an active search to find innovative solutions during the design process. Engineers can use computer-aided processes to find automatically the best design solutions. This kind of approach named "multi-objective optimization" is based on genetic algorithms.

The idea is to obtain simultaneously a population of possible design solutions corresponding to the most efficient energy system definition for a vehicle. These solutions will be optimal from technical and economic point of view.

In this article this kind of "genetic intelligence" is tested for the holistic design of the optimal vehicle powertrain solutions and their optimal operating strategies.

The methodology is applied on D class hybrid electric vehicles, in order to define the powertrain configurations, to estimate the cost of the powertrain equipment and to show the environmental impact of the technical choices. The optimal designs and operating strategies are researched for different vehicle usages – normalized, urban and long way driving.

1. Introduction

With the increasing trend of mobility of the human population, vehicles now face the problem of primary energy resources scarcity. Future regulations for the automotive industry will require a sharp decline in emissions within the next decade. For example in Europe, the regulation of the Tank-to-Wheel CO_2 emissions requires 130 g of CO_2 per kilometer, and by 2020 the CO_2 should be reduced to 95 g of CO_2 per kilometer, for the all car maker vehicle fleet. Therefore higher efficiency and better adaptation to alternative energy sources is required for new vehicles. At the moment the development of hybrid vehicles seems to be the solution chosen from the automotive industry to archive higher Tank-to-Wheel efficiency.

The state of the art today is to consider the "Tank-to-Wheel" energy balance of thermal powertrain. For example Caton in Ref. [1] and Reitz and Duraisamy in Ref. [2] present a review of the efficiency for internal combustion engines. They determine the energy balance of a thermal powertrain on an analytical way. The results show that 30% of the energy is used for the mobility as mechanical power. The other 70% are wastes – waste heat in coolant ~30% and waste heat in exhaust gases ~40%. The hybrid electric vehicles recover the kinetic energy in the vehicle deceleration phases.

The hybrid electric vehicle is seen as a good compromise between increased "Tank-to-Wheel" efficiency, enough long range of autonomy and acceptable cost for the customer [3].

Many researches are performed on the energy conversion balance on the vehicle board. They are based on analytical methods. Katrasnik proposes in Ref. [4] analytically based method to calculate corrected fuel consumption of parallel and series hybrid electric vehicles (HEVs) at balanced energy content of the electric storage devices. The energy conversion phenomena are explained in Ref. [5]. Energy flows and energy conversion efficiencies of commercial plug-in hybrid-electric vehicles (PHEV) are analyzed for parallel and series PHEV topologies. The analysis is performed by a combined analytical and simulation approach.

Various type models and algorithms derived from simulation and experiment are explained in details in Ref. [6]. Most of them are heuristic and based on iterations of designs and energy management strategies. The performances of the various combination of HEV (Hybrid Electric Vehicles) system are summarized. The article provides comprehensive survey of hybrid electric vehicle on their

* Corresponding author.
E-mail addresses: zlatina.dimitrova@epfl.ch (Z. Dimitrova), francois.machechal@epfl.ch (F. Maréchal).

http://dx.doi.org/10.1016/j.energy.2015.08.073
0360-5442/

Nomenclature

f_1	function 1
f_2	function 2
MOO	multi objective optimization
GLPK, Cplex	solvers
SoC	state of charge of the battery in [%]
γ	gear ratio [-]
m	vehicle mass in [kg]
F	force in [N]
w_s	rotation speed of the driving shaft [rpm]
w_w	rotation speed of the wheels in [rpm]
P_s	power of the drive shaft in [kW]
H_r	hybridization ratio in [-]
T_s	torque on the drive shaft in [Nm]
T_{ICE}	torque of the internal combustion engine in [Nm]
T_{EM}	torque of the electric motor in [Nm]
DoH	degree of hybridization
EM	electric motor
ICE	internal combustion engine
PA	power amplifier
BT	high voltage battery
$\dot{V}$	vehicle acceleration or deceleration in [m/s^2]
V	vehicle speed in [m/s]
P_{BT}	power of the battery in [kW]
P_{SC}	power of the supercapacitors in [kW]
$f_{scaling}$	scaling factor for the electric motor [-]
k_1, k_2	structural parameters of the torque coupler [-]
c_{11}, c_{22}, c_3, c_4	high voltage battery coefficients
p_em	power of the electric motor in [kW]
p_th_engine	power of the thermal engine in [kW]
NEDC	New European driving cycle
$\eta_{powertrain}$	powertrain efficiency in [-]

source combination, models, energy management system (EMS) etc.

The design of the converters and the stockers is optimized for global best tank-to-wheel efficiency. Finesso et al. focuse in Ref. [7] on the design, optimization and analysis of a complex parallel hybrid electric vehicle, equipped with two electric machines on both the front and rear axles. Bayindir et al. present in Ref. [8] an overview of HEVs with a focus on hybrid configurations, energy management strategies and electronic control units. Poullikkas presents in Ref. [9] an overview regarding electric vehicle technologies and associated charging mechanisms is carried out. The review covers a broad range of topics related to electric vehicles, such as the basic types of these vehicles and their technical characteristics, fuel economy and CO_2 emissions, the electric vehicle charging mechanisms and the notions of grid to vehicle and vehicle to grid architectures. In particular three main types of electric vehicles, namely, the hybrid electric vehicles (HEVs), the plug-in electric vehicles (PHEVs) and the full electric vehicles (FEVs) are discussed in details.

Genetic algorithms are mostly used for the optimizations of the HEV components design. Eren et al. in Ref. [10] deal with optimal sizing of HEV and propose a methodology for the optimization of HEV components using the multi-objective approach considering the minimization of operating cost, weight and volume simultaneously. To optimize the sizing of HEV components, the mixed integer linear programming (MILP) model is tested and optimization processes are performed for different range of drive cycles. Song et al. used in Ref. [11] a multi-objective optimization of a semi-active battery/supercapacitor energy storage system for electric vehicles. Dynamic mathematical programming is applied to the energy management optimization, including heuristic management strategies. In Ref. [12] Khayyam et al. propose a soft computing based intelligent management system developed using three fuzzy logic controllers. The fuzzy engine controller within the intelligent energy management system is made adaptive by using a hybrid multi-layer adaptive neuro-fuzzy inference system. Torres et al. present in Ref. [13] the development of an energy management strategy of a plug-in hybrid electric vehicle (PHEV). In this case, a rule-based optimal controller selects the appropriate operation mode. Tribioli et al. study in Ref. [14] a real time energy management strategy for Plug-in hybrid electric vehicles based on optimal control theory and the optimal problem is solved with the Pontryagin's Minimum Principle. The robustness of the fuel economy as a function of the different customers behaviors are measured and analyzed. In Ref. [15] Santiangeli et al. do experimental analysis of the auxiliaries' consumption in the energy balance of a pre-series Plug-in hybrid-electric vehicle. Davies et al. study in Ref. [16] the implications for energy and emissions impacts of plug-in hybrid electric vehicles. Predictive control modes are researched for the fuel reduction robustness in Ref. [17] where Cost analysis of plug-in hybrid electric vehicles using GPS-based longitudinal travel data is presented.

Sakti et al., perform in Ref. [18] a techno-economic analysis and optimization of Li-ion batteries for light-duty passenger vehicle electrification. They conduct a techno-economic analysis of Li-ion prismatic pouch battery and pack designs for electric vehicle applications. They develop models of power capability and manufacturing operations to identify the minimum cost cell and pack designs for a variety of plug-in hybrid electric vehicle (PHEV) and battery electric vehicle (BEV) requirements.

Mock et al. propose in Ref. [19] techno-economic assessments of battery and fuel cells. A detailed assessment of past progress of key technological parameters and their technical limits enables judgment of the probability of reaching target values set for the future. Examination of production costs using a combination of a top-down learning curve approach and a bottom-up mass production costs approach identifies potentials for future cost reductions. The method of techno-economic assessment is applied to the technologies of fuel cells and batteries, illustrating past developments and resulting in an outlook on a likely future introduction of both technologies, with focus on the market for passenger car propulsion systems.

Wu et al. study in Ref. [20] a component sizing optimization of plug-in hybrid electric vehicles. This paper describes a methodology for the optimization of PHEVs component sizing using parallel chaos optimization algorithm. In this approach, the objective function is defined so as to minimize the drivetrain cost. In addition, the driving performance requirements are considered as constraints. Finally, the optimization process is performed over three different all electric range (AER) and two types of batteries.

Hung et al. in Ref. [21] present an integrated optimization approach for a hybrid energy system in electric vehicles. They develop a simple integrated optimization approach for deriving the best solutions of component sizing and control strategies of a hybrid energy system which consists of a lithium battery and a supercapacitor module.