Energy xxx (2015) 1–12

Contents lists available at ScienceDirect

Energy

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

Energy integration on multi-periods and multi-usages for hybrid electric and thermal powertrains

Zlatina Dimitrova [a, b, *], François Maréchal [b]

[a] PSA Peugeot Citroën, Vélizy, France
[b] Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

ARTICLE INFO

Article history:
Received 21 October 2014
Received in revised form
16 February 2015
Accepted 18 February 2015
Available online xxx

Keywords:
Energy vehicle balance
Energy integration
Driving profiles
ICE efficiency
Multi-periods
ORC

ABSTRACT

The improvement of the efficiency of vehicle energy systems promotes an active search to find innovative solutions during the design process. This requires more accurate modeling of complex systems, which offers new ways to improve the design efficiency of energy systems.

The vehicle is a highly dynamic system. The size and the efficiency of the convertors are dependent on the dynamic driving profile. In order to increase the energy efficiency, using energy integration techniques, an adapted methodology is required to choose the best points for the integrated system design. The idea is to clusterize the dynamic profile on typical multi-periods of the vehicle use. The energy system design is then optimized for these typical multi-periods.

In this article a new methodology is applied on hybrid electric vehicles, in order to define the energy integrated powertrain configuration of the vehicle. The energy recovery potential of a single stage Organic Rankine Cycle for a thermal engine in combination with a hybrid electric powertrain is assessed for different drive cycles profiles and comfort situations.

After the energy integration, a multi-objective optimization is applied to define the optimal design of a hybrid electric vehicle with a waste heat recovery system.

1. Introduction

1.1. Dynamic driving cycles

In order to compare fairly passenger cars performance, thay are evaluated in standardized test cycles. In Europe, NEDC (new European drive cycle) is currently used, and only the energy needed for the propulsion is considered. So it is defined the Tank-to-Wheel efficiency. This cycle is constituted from two parts: UDC – Urban Driving Cycle and EUDC – Extra Urban Driving Cycle (Fig. 1):

In practice these cycles are conducted in laboratory conditions with precisely controlled environment (temperature and humidity) and follow very strict test procedure, the velocity profile is followed in a strict error band [1] with a limited numbers of accessories working (air conditioning is off for example).

In the every day use of the cars, the operating conditions can vary a lot, then certain robustness of the efficiency gain of the fuel saving technologies on the driving profiles and the comfort demands is then needed. From this need comes the idea to define a vehicle energy system with integrated energy services for mobility and comfort. Once the system defined, an energy integration methodology is needed. The energy integration should occur on the dynamic and comfort profiles, through technologies allowing to recover energy and to use it to satisfy the integrated energy system as a function of the customers' drives and comfort demands. Fig. 2 presents the energy system definition for hybrid electric vehicle application. The hybrid electric vehicles are briefly introduces in the following section.

1.2. Hybrid electric vehicles

Hybrid electric vehicles have two or more prime movers (internal combustion engine – ICE or fuel cell and electric machine) and power sources (fuel tank and electrochemical battery) on their board. Supercapacitors may be also used to increase the power

* Corresponding author. EPFL SCI-STI-FM, ME A2 402 (Bâtiment ME), Station 9, CH-1015 Lausanne, Switzerland.
E-mail addresses: zlatina.dimitrova@mpsa.com, zlatina.dimitrova@epfl.ch (Z. Dimitrova), francois.machechal@epfl.ch (F. Maréchal).

http://dx.doi.org/10.1016/j.energy.2015.02.060
0360-5442/

Nomenclature

ICE	internal combustion engine
HEV	hybrid electric vehicle
ORC	organic Rankine cycle
NEDC	new European drive cycle
UDC	urban driving cycle
EUDC	extra urban driving cycle
MGB	Manuel gear box
CVT	continuously variable transmission
BMEP	break mean effective pressure
MILP	mixed integer linear programming
EGS	enhanced geothermal systems
MOO	multi objective optimization
TES	thermo-economic simulation
EI	energy integration
TEE	thermo economic evaluation
EMOO	evolutionary multi objective optimization
MER	minimum energy requirement

storage capacity on the vehicle board. One of the main motivations for HEV (hybrid electric vehicle) developments is the efficiency increase of the powertrain in comparison to the thermal powertrain and long ranges of autonomy comparable to thermal vehicles.

The HEV combines the advantages of an electric powertrain with a kinetic recovery system, possible zero tank-to-wheel emissions till certain vehicle speeds in urban drive. On the other side, the HEV also combines the advantages of the ICE based vehicles, represented by high power and energy density, high range in extra-urban drives and rapidly recharging of the fuel tank. Hybrid electric vehicles proliferate under current technical developments and on the markets [3], because they are considered as a powerful technology to promote the change from conventional mobility to e–mobility [4]. In the recent past years, automotive industry focusses on the reduction of the imperfections of HEVs such as higher cost, added weight of batteries and limited range [5]. The HEV propulsion system is complex and the energy consumption benefits are possible through an adapted design and size of the powertrain components and efficient energy management systems, according to the drive modes and cycle's power demands. Many researches are performed on the energy conversion balance on the vehicle board. They are based on analytical methods [6], explaining the energy conversion phenomena [7] and coupled to modern simulation tools and optimization algorithms [8]. The design of the

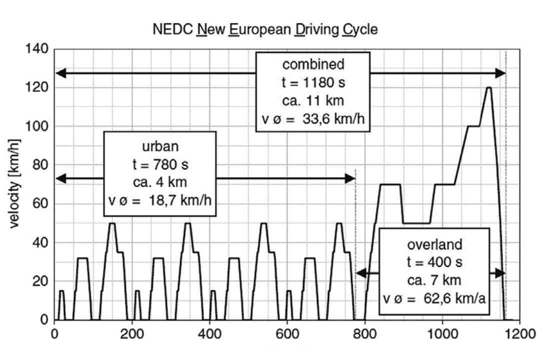

Fig. 1. NEDC characteristics.

convertors and the stockers is optimized for global best tank-to-wheel efficiency. Finesso et al. present in Ref. [9] the optimized design of a complex parallel HEV for different driving missions. Bayindir et al. present in Ref. [10] an overview of HEV with a focus on hybrid configurations, energy management strategies and electronic control units. In Ref. [11] Poullikkas details vehicle battery technologies and associated charging mechanisms. Genetic algorithms are mostly used for the design optimizations [5,12], and dynamic mathematical programming is applied to the energy management optimization, including heuristic management strategies. For example, Khayyam present in Ref. [13] an intelligent energy management system for HEV, based on adaptive neuro-fuzzy inference system. Torres study in Ref. [14] an energy management strategy for Plug-in HEV based on a rule based optimal controller selecting the appropriate operating mode. Tribioli et al. present in Ref. [15] a methodology to design a heuristic controller to be used online, based on rules extracted from the analysis of the powertrain behavior under the optimal control solution. The application is on HEV 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 Refs. [3,6,16], and predictive control modes are researched for the fuel reduction robustness are presented in Refs. [13,17].

Hybrid-electric vehicles are classified into parallel, series or series-parallel (combined) hybrid main types, according to the architecture between the prime movers. Hybrid-electric vehicles differ also according to the degree of hybridization of the powertrain (Fig. 3).

To sum up, the efficiency improvement of the HEVs is researched on best adapted designs and energy management strategies for the vehicle usages. Hybrid vehicles can use energy storage systems to disconnect the engine from the driving wheels of the vehicle. This enables the engine to be run closer to its optimum operating condition, but fuel energy is still wasted through the exhaust system as heat. The use of a turbo generator on the exhaust line addresses this problem by capturing some of the otherwise wasted heat and converting it into useful electrical energy. Briggs [18] applied that on a diesel hybrid electric bus. The idea of combination of kinetic energy recovery and waste heat energy recovery comes. The energy requirements for comfort are investigated and analyzed in Refs. [6,19]. Some researchers [11,20], are extending the energy system till the electrical grid and the HEVs are considered as grid related vehicles offering an additional possibilities for the electric grid power and energy storage capacities.

The novelty of this article is to consider simultaneously the vehicles energy services for mobility and comfort and to propose a methodology for their energy integration. The methodology uses a generic multi-objective optimization structure, applied for optimal HEV powertrain design and optimal comfort systems. The article studies the impact of an energy recovery technology, such as the organic Rankine cycle on the mobility and comfort performances of HEV energy system. After integration of the energy services, a sensitivity analysis on the fuel benefits is done for different customers' representative driving cycles.

The present article applies the k-means algorithms in an energy integration approach. The organic Rankine cycle utility is sized on the representative clusters for a hybrid electric vehicle. After that the energy recovery potential of this utility is assessed for different dynamic usages of the vehicle – urban, peri-urban and long way drives. Multi-objective optimization is applied on a hybrid electric vehicle, including the waste heat recovery technology, to give the optimal size of the powertrain components and to estimate their cost.