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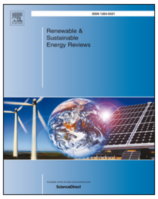

A review of power management strategies and component sizing methods for hybrid vehicles

Yanjun Huang[a], Hong Wang[a,*], Amir Khajepour[a], Bin Li[b], Jie Ji[c,*], Kegang Zhao[a,d], Chuan Hu[e]

[a] *Department of Mechanical and Mechatronics Engineering, University of Waterloo, Waterloo, ON, Canada N2L 3G1*
[b] *Department of Mechanical and Industrial Engineering, Concordia University, Montreal, Canada H3G 1M8*
[c] *College of Engineering and Technology, Southwest University, Chongqing 400715, China*
[d] *School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou, Guangdong 510640, China*
[e] *Department of System Design Engineering, University of Waterloo, Waterloo, ON, Canada N2L 3G1*

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ABSTRACT

This paper comprehensively reviews power management strategies (PMS) and component sizing (CS) methods for hybrid vehicles with more than one energy storage system (ESS). The PMS aims to coordinate the power flow among different ESSs while meeting the drive commands and other constraints; whereas, CS is used to optimize the combination of the components to compose a cost-effective powertrain. However, these two aspects are usually coupled such that it is not reasonable to discuss them separately from a system-level design perspective. Therefore, this review briefly discusses the popular PMS, followed by a detailed CS review in different aspects, including the classic and optimization-based with their own subtypes. In addition, several case studies belonging to different optimization structures are also reviewed in detail to demonstrate the features and the main conclusions of each method. As the comparison results show that with the proper CS methods, the hybrid powertrain witness a large fuel saving compared to their conventional counterparts. Furthermore, factors or issues that affect the performance of the PMS and CS methods are discussed. Meanwhile, the future research trends in PMS and CS are elaborated. This study intends to help researchers to have an overview of the state-of-the-art in PMS and CS methods and more importantly, to provide directions for optimal powertrain and power management controller designs for cost-effective and environmental-friendly vehicles.

1. Introduction

The Energy Information Administration (EIA) in the U.S. has predicted that petroleum and other liquid fuels will dominantly contribute to energy consumption in the transportation sector, although it can witness a slightly decrease (i.e. from 89% to 80%) from 2010 to 2040 [1]. In other words, fossil fuels are the main energy sources in most current vehicles by means of the internal combustion engine (ICE). Consequently, the CO2 emissions produced by the transportation sector accounts for 22% globally, which leads to the climate change issues such as the global warming [2]. In order to deal with issues like air pollution, climate change, and a shortage of petroleum, automotive researchers and policymakers are seeking sustainable alternatives that pollute less and are less dependent on oil. These alternatives are classified and shown in Table 1.

Alternative energy resources include solar, wind, hydroelectric, nuclear, and hydrogen, which can be converted to electricity via the onboard (e.g. solar photovoltaics and fuel cell) or offshore devices (e.g. the large-scale generator). For the corresponding energy storage devices, some of them can be adopted as the primary energy sources in vehicles (e.g. battery) due to their relatively high energy density. Whereas, the others can only be used as supplementary energy sources (e.g. ultracapacitor, hydraulic accumulator, air tank, and flywheel) to assist the main ones. Most of the energy sources require their own energy conversion devices such as the electric motor/generator, hydraulic motor/pump, and the air motor/compressor installed onboard to transfer the primary energy to mechanical energy for driving the vehicle. In terms of vehicles, by combining the aforementioned energy sources as well as their conversion devices mutually or with the conventional internal combustion engine, the HVs can be designed at the configuration level. Such HVs are the results of the desire to produce vehicles with lower emissions and better fuel economy to satisfy the requirements of environmental policies and energy saving.

When it comes to the HVs, after the configurations being

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* Corresponding authors.
E-mail addresses: wanghongbit@gmail.com (H. Wang), jijiess@163.com (J. Ji).

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Nomenclature

APSO	accelerated particle swarm optimization
BA	bee algorithm
BBA	branch and bound algorithm
CAHV	compressed air hybrid vehicle
CAPSO	Chaotic APSO
COA	chaos optimization algorithm
CS	component sizing
DP	dynamic programming
ECMS	equivalent consumption minimization strategy
EIA	energy information administration
ESS(s)	energy storage system(s)
EUDC	extra urban driving cycle
EV(s)	electric vehicle(s)
FC	Fuel consumption
FCHV	fuel cell electric vehicle
FHEV	Fuel-cell hybrid electric vehicle
FTP	federal test procedure
GA	genetic algorithm
GSM	global search method
HEV(s)	hybrid electric vehicle(s)
HHV	hydraulic hybrid vehicle
HV(s)	hybrid vehicle(s)
HWFET	highway fuel economy test
ICE	internal combustion engine
MILP	mixed integer linear programming
MPC	model predictive control
NEDC	new European driving cycle
NN	Neural Network
PCOA	parallel chaos optimization algorithm
P.F.	Power Follower
PHEV	plug-in hybrid electric vehicle
PMS	power management strategies
PSAT	Powertrain system analysis toolkit
PSO	particle swarm optimization
SA	simulated annealing
SDP	statistic dynamic programming
SFTP	supplemental federal test procedure
SQP	sequential quadratic programming
UDDS	urban dynamometer driving schedule
V2G	Vehicle-to-grid
V2I	Vehicle-to-infrastructure
WLTP	worldwide light vehicles test procedure

Table 1
Alternatives to the new energy vehicles.

Energy resources	Energy storage device	Energy conversion devices	Hybrid vehicles
Solar/wind/hydroelectric/nuclear	Battery/Ultracapacitor	Motor/generator	HEV, Plugin HEV and EV
Hydrogen, etc.	Hydrogen Tank	Fuel cell, motor/generator	FCHV [3]
N/A	Hydraulic accumulator	Hydraulic motor/pump	HHV
N/A	Air tank	Air motor/compressor	Compressed-air hybrid vehicle (CAHV) [4]
N/A	Flywheel	N/A	FHEV [5]

determined, the remaining challenges are component sizing and developing an efficient PMS to satisfy the desired objective without diminishing vehicle performance [6]. In other words, CS and PMS are the two major factors that determine the costs (i.e. initial and operating costs) and the pollution contributions of the HVs. To pursue low costs and emissions, these two aspects should be dealt with properly. Specifically, the results of the CS relies heavily on how the components operate and cooperates with each other, which is decided by the PMS. Meanwhile, without appropriate CS methods or results, the PMS cannot optimally coordinate each component for a high holistic efficiency or even cannot satisfy other requirements (e.g. dynamics).

In current literature, most of them focus on the PMS in terms of both comprehensive review [6] ~ [13] and individual algorithm design. For example, the author in [7] discussed the development, classification, comparison and future trends of the PMS in HEVs, where the PMSs were sorted into rule-based and optimization-based types with their own subclasses. Ref. [8] presented an extensive review of the powertrain configurations as well as the PMSs, where the similar categories were used to classify the powertrain control techniques. A review of the architecture and PMS of HEVs was conducted in [6] with an emphasis on the plug-in HEVs and the through-the-road HEVs with in-wheel motors. Both the lower-level (i.e. component-level) and supervisory control strategies were studied in [9]. The PMSs were comprehensively surveyed for each type of the powertrain configuration (e.g. series, parallel, and power-split) in HEVs [10]. The research status regarding the PMS for HEVs was quantitatively analyzed and evaluated based on bibliometric data in [11]. Thanks to the popularity of the model predictive control (MPC), the MPC-based PMSs in HEVs were elaborated upon in several aspects (e.g. the acquisition ways of the future driving information and the types of the system model), and future research directions were also pointed out [12].

Although the CS is such obviously significant, none of the available literature regarding CS methods categorizes and summarizes the existing approaches in a systematic way. Only a few of them briefly discusses the limited CS methods in their introduction section. For instance, Ref. [14] points out that one of the existing CS methods is to choose an optimization algorithm and apply it to the vehicle modeling and simulation software tools for the sake of the CS task. The CS methods are classified depending on the consideration or the types of the power management strategy in [15], where the authors also briefly discussed each category. In addition, the authors also put forth the necessity to optimize component sizes and PMS together.

Therefore, to solve the aforementioned issue, this study conducts a comprehensive survey on the existing component sizing methods in a systematical way by categorizing into different subtypes, such as the traditional and optimization-based, and then the pros and cons of each method are elaborated and compared via several cases from the current literature. In addition, the design process of some common methods used in the literature is presented in detail. Furthermore, the existing problems and the research trends in terms of the CS and PMS are summarized, which will be beneficial to active researchers in this area. As the core of this study, these three points will be definite contributions to the current literature related to the design of the HVs. However, as stated above, in the process of the CS, PMSs should be properly taken into consideration. As a result, according to the related papers and from a real-world application point of view, this study reviews PMSs in two main aspects (i.e. offline and online) to differentiate the PMS methods by whether it can be used in real time. The review puts more efforts on the features and purposes of each category at a higher level instead of comparatively studying each of them. Besides that, the different PMSs are also compared and analyzed when working with CS methods in different ways.