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Modelling and control of hybrid electric vehicles (A comprehensive review)

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ABSTRACT

The gradual decline in global oil reserves and presence of ever so stringent emissions rules around the world, have created an urgent need for the production of automobiles with improved fuel economy. HEVs (hybrid electric vehicles) have proved a viable option to guaranteeing improved fuel economy and reduced emissions. The fuel consumption benefits which can be realised when utilising HEV architecture are dependent on how much braking energy is regenerated, and how well the regenerated energy is utilised. The challenge in developing an HEV control strategy lies in the satisfaction of often conflicting control constraints involving fuel consumption, emissions and driveability, without over-depleting the battery state of charge at the end of the defined driving cycle.

As a result, a number of power management strategies have been proposed in literature. This paper presents a comprehensive review of these literatures, focusing primarily on contributions in the aspect of parallel hybrid electric vehicle modelling and control. As part of this treatise, exploitable research gaps are also identified. This paper prides itself as a comprehensive reference for researchers in the field of hybrid electric vehicle development, control and optimisation.

1. Introduction

The gradual decline of global oil reserves, in addition to stringent emission regulations around the world, has made even more critical the need for improved vehicular fuel economy [1–3]. In recent years, the scientific community and industries alike have proposed a variety of innovations to face this challenge, coming up with new solutions from the viewpoint of hybrid powertrain architectures. Hybrid electric vehicles (HEVs) are able to address this problem by introducing a powertrain with an additional propulsion system, which consists in its simplest form of an electrical energy storage unit (an electric battery), an electric torque actuator (an electric motor) and a device which couples together the electric driveline and the thermal driveline. The additional driveline allows for greater flexibility in engine use while ensuring fulfilment of the power request at the wheels.

In comparison to conventional vehicles, HEVs offer a number of advantages. The most popular of such advantages is the possibility of downsizing the original internal combustion engine whilst meeting the power demand at the wheels. This advantage is brought about by the capability of the hybrid powertrain to deliver power to the wheels from both the internal combustion engine and the electric motor at the same time, thus resulting in reduced fuel consumption [4,5]. The introduction of an electric driveline in an HEV also allows for the regeneration of kinetic braking energy, which would otherwise be lost to mechanical brakes in conventional vehicles.

Crucial to achieving the aforementioned advantages is a real time control strategy capable of coordinating the on-board power sources in order to maximise fuel economy and reduce emissions. To date, a number of energy management strategies have been proposed in literature. This treatise presents a comprehensive review of these literatures, focusing primarily on contributions in the aspect of parallel hybrid electric vehicle modelling and control. As part of this treatise, exploitable research gaps are also identified.

The contributions in this paper are elucidated as follows: First, investigations are made in to emergence of HEVs with particular emphasis on: the factors driving its development, its industrial evolution and advantages. Next, several HEV configurations are discussed in light of their characteristics and applications. Thereafter, HEV modelling techniques are briefly discussed with a view to highlighting the relative importance of each approach. Afterwards, HEV control strategies are reviewed at depth on two main tiers: HEV offline control strategies and HEV online control strategies. This detailed appraisal is aimed at highlighting the control structure of the reviewed techniques, its novelty, as well as contributions towards the satisfaction of several optimisation objectives, which includes but are not limited to: reduction of fuel consumption and emissions, charge sustenance, optimisation of braking energy regeneration, and improvement of vehicle driveability. Finally, exploitable research gaps within the research area are identified and discussed.

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Nomenclature

Abbreviations description, units

A-ECMS	Adaptive Equivalent Consumption Minimisation Strategy [dimensionless]
ANN	Artificial Neural Network [dimensionless]
CIDI	Compression Ignition Direct Ignition [dimensionless]
CPU	Central Processing Unit [dimensionless]
CVT	Continuous Varying Transmission [dimensionless]
DB	Data Base [dimensionless]
DEV	Deviation in Percentile [dimensionless]
DIP	Driver's Intention Predictor [dimensionless]
DIRCOL	Direction Cosine Linkage [dimensionless]
DPR	Driving Pattern Recognition [dimensionless]
DP	Dynamic Programming [dimensionless]
DOH	Degree of Hybridisation [dimensionless]
ECMS	Equivalent Consumption Minimisation Strategy [dimensionless]
EDR	Energy-to-Distance Ratio [dimensionless]
EFCOCS	Equivalent Fuel Consumption Optimal Control Strategy [dimensionless]
EIL	Engine in Loop [dimensionless]
EM	Electric Motor [dimensionless]
EM-TFL	Electromagnetic-Team Fuzzy Logic [dimensionless]
ES	Extremum Seeking [dimensionless]
etc	Et Cetera [dimensionless]
EU	European Union [dimensionless]
EV	Electric Vehicle [dimensionless]
EVT	Electric Variable Transmission [dimensionless]
FC	Fuel consumption [dimensionless]
FE	Fuel Economy [dimensionless]
FHDS	Federal Highway Driving Schedule [dimensionless]
FLC	Fuzzy Logic Control [dimensionless]
FNN	Fuzzy Neural Network [dimensionless]
FPIDF	Flexible complexity reduced PID-like Fuzzy controller [dimensionless]
GA	Genetic Algorithm [dimensionless]
GPS	Global Positioning System [dimensionless]
HC	Hydro Carbons [dimensionless]
HEV	Hybrid Electric Vehicle [dimensionless]
HEVs	Hybrid Electric Vehicles [dimensionless]
HIL	Hardware in the Loop [dimensionless]
HJB	Hamilton-Jacobi-Bellman [dimensionless]
HWFET	Highway Fuel Economy Test [dimensionless]
ICE	Internal Combustion Engine [dimensionless]
IEMA	Intelligent Energy Management Agent [dimensionless]
JP	Japan [dimensionless]
MOGA	Multi-objective Genetic Algorithm [dimensionless]
MOS	Multi-objective solutions [dimensionless]
MOSADE	Multi objective Self Adaptive Differential Evolution [dimensionless]
MPC	Model Predictive Control [dimensionless]
MPG	Miles Per Gallon [dimensionless]
NEDC	New European Driving Cycle [dimensionless]
NDP	Neuro-Dynamic Programming [dimensionless]
NSGA	Non-Dominated Sorting Genetic Algorithm [dimensionless]
NYCC	New York City Cycle [dimensionless]
PBC	Power Balance Controller [dimensionless]
PCA	Principal Component Analysis [dimensionless]
PD	Proportional-Derivative [dimensionless]
PFC	Power Follower Control Strategy [dimensionless]
PI	Proportional-Integral [dimensionless]
PID	Proportional-Integral-Derivative [dimensionless]
PIDF	PID-like Fuzzy [dimensionless]
PHEV	Plug in Hybrid Electric Vehicle [dimensionless]
PM	Particulate Matter [dimensionless]
PMP	Pontryagin's Minimum Principle [dimensionless]
PNGV	Partnership for a New Generation of Vehicles [dimensionless]
PSAT	PNGV System Analysis Toolkit [dimensionless]
PSO	Particle Swarm Optimisation [dimensionless]
SDP	Stochastic Dynamic Programming [dimensionless]
SDP-ES	Stochastic Dynamic- Extremum Seeking programming [dimensionless]
SIL	Software in the Loop [dimensionless]
SMPC	Stochastic Model Predictive Control [dimensionless]
SOC	State of Charge [dimensionless]
SOE	State of Energy [dimensionless]
SOGA	Single Objective Genetic Algorithm [dimensionless]
SP-SDP	Shortest Path Stochastic Dynamic Programming [dimensionless]
TDNN	Time Delay Neural Network [dimensionless]
TCS	Thermostat Control Strategy [dimensionless]
THS	Toyota Hybrid System [dimensionless]
UDDS	Urban Dynamometer Driving Schedule [dimensionless]
UDDSHDV	Urban Dynamometer Driving Schedule for Heavy Duty Vehicles [dimensionless]
US	United states [dimensionless]

Symbols description, units

CO	Carbon monoxide [dimensionless]
CO_2	Carbon dioxide [dimensionless]
g	Grams [dimensionless]
Km	Kilometers [dimensionless]
NOx	Oxides of nitrogen [dimensionless]

2. Emergence of hybrid electric vehicles

In recent years, several determinants including stringent emission regulations and limitation in conventional vehicles have created an eminent and urgent need for the production of automobiles such as hybrid electric vehicles with improved fuel economy.

To contextualise the transition from conventional vehicles to HEVs, this section investigates the emergence of HEVs with particular emphasis on: the factors driving its development, its industrial evolution and advantages.

2.1. Vehicle emission regulations

Increasing concerns about fossil fuels availability in the long term and environmental pollution have focused considerable attention on the problem of efficient energy utilisation in automobiles [6–10]. In response to these concerns, regulators around the world have set out various stringent emissions targets to curb regulated emissions (hydrocarbons, nitrogen oxides, carbon monoxide and particulate matter). Fig. 1 provides a comparison of the EU CO_2 passenger car standards with similar regulations around the world. This chart converts all