UNIVERSITY OF TECHNOLOGY SYDNEY

Faculty of Engineering and Information Technology

A Comprehensive Study on Energy Management Strategy Design of an Extended-Range Electric Vehicle

A thesis submitted for the degree of

Doctor of Philosophy

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 # CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Boyi Xiao declare that this thesis, is submitted in fulfilment of the requirements for the award of a Doctor of Philosophy degree, in the School of Mechanical and Mechatronic Engineering/Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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Publications

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[1] B. Xiao, P. D. Walker, N. Zhang, Performance Analysis of A Electric Vehicles Energy Flow and Regenerative Braking Strategy, Intern. Conf. on Adv. Veh. Powert. (ICAVP), 2019.

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Abbreviations

BEV - Battery Electric Vehicle

EREV - Extended Range Electric Vehicle

ERLV - Extended Range Logistics Vehicle

FCV - Fuel Cell Vehicles

HEV - Hybrid Electric Vehicle

PHEV - Plug-in Hybrids Electric Vehicles

APU - Auxiliary Power Unit

ICE - Internal Combustion Engine

ISG - Integrated Starter Generator

Li-Ion - Lithium-Ion

NiMH - Nickel-metal Hydride

SC - Supercapacitor

SOC - State of Charge

SOH - State of Health

NEDC - New European Driving Cycle

CLTC - China Light-duty Vehicle Test Cycle

WLTC - Worldwide Harmonized Light Vehicles Test Cycle

PMP - Pontryagin's Minimum Principle

MPC - Model Predictive Control

MDP - Markov Decision Process

DP - Dynamic Programming

DL - Deep Learning

DRL - Deep Reinforcement Learning

RL - Reinforcement Learning

DQN - Deep Q Network

DDPG - Deep Deterministic Policy Gradient

A3C - Asynchronous Advantage Actor Critic

TD3 - Twin Delayed DDPG

SAC - Soft Actor-Critic

BMS - Battery Management Strategy

EMS - Energy Management Strategy

CD - Charge-depleting

CS - Charge-sustaining

ESS - Energy Storage System

HESS - Hybrid Energy Storage System

HIL - Hardware in the Loop

TCO - Total Cost of Ownership

Abstract

The extensive usage of conventional internal combustion engine vehicles (ICEVs) is responsible for a large amount of greenhouse gas emissions. However, the battery electric vehicle can not substitute for the traditional vehicle due to its limited energy storage ability. To moderate this issue, the extended range electric vehicle (EREV) provides a solution by providing a satisfactory driving range and lower production cost than battery electric vehicle (BEV). An EREV is characterized by having an auxiliary power unit (APU) to provide electric power to the traction motor and the energy storage system, and its battery pack can meet a majority of pure-electric driving needs. To distinguish from the other vehicle structures, the potential of the EREV platform should be further studied/presented on a full scale, and novel control strategies can be designed to improve the power performance of the vehicle. In this thesis, a research on the development process of an extended range logistics vehicle is conducted in the automobile theory and vehicle control points of view. The research priority of the study consists of three parts: the background review and the vehicle structure design, the consumption and cost analysis and the innovation on its control strategy.

First of all, a comprehensive background investigation and literature review are conducted and discussed. The investigation systematically introduces the current developments of EREV in terms of the powertrain structure, energy management and vehicle performance, while the two key focus areas of the auxiliary power are the unit (APU) charging control and hybrid energy storage system (HESS) power management. A case analysis on a typical EREV is presented along with a general

manufacturing cost analysis for different types of vehicles, showing the EREV as one of the cheapest options for long term usage.

Secondly, an extended range mathematical platform for a logistics van is proposed. Suitable configurations for the sizing of the APU, ESS and the traction motor are selected for a standardized mid-size van. This study presents a thorough energy consumption and Total cost of ownership (TCO) analysis for an Extended range logistics van (ERLV). Both EREV and BEV mathematical models are constructed and compared, and their dynamic long-term battery degradation comparison is conducted. Dynamic programming (DP) algorithm is adopted in the energy management strategy optimization, and the global result reveals the optimal energy consumption of the EREV. Comparative results demonstrate that the ERLV has a relatively long drive distance, slower battery aging trend and cheaper TCO (6.6%) when compared to the BELV.

Thirdly, a novel auxiliary power unit (APU) charging strategy with multi-object optimization is proposed on the ERLV platform to achieve high fuel conversion efficiency while maintaining battery charging health. The state-of-the-art algorithm, Soft Actor-Critic (SAC) is applied to perform a better exploration of the possible APU behaviour, and its performance is further verified by the results of the Deep Deterministic Policy Gradient (DDPG) algorithm and DP. Three targets are selected as the RL rewards for optimization: the engine fuel rate, SOC charging trajectory, and the battery charging rate (C-rate). The comparative results show that the SAC had a 36% faster convergence speed than DDPG while providing a smoother and more stable action space. The fuel consumption with SAC also outplays DDPG by around 3%, which achieves almost 90% of the global optimization result. The successful deployment of the SAC algorithm as an EMS indicates its standout ability in dealing with wide-range actions and states with high randomness, revealing the practical potential compared with the existing RL strategies.