UNIVERSITY OF TECHNOLOGY, SYDNEY

Faculty of Engineering and Information Technology

Design and Verification of Novel Powertrain Management for Multi-Geared Battery Electric Vehicles

A thesis submitted for degree of

Doctor of Philosophy

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Student:

Date: 30 September 2016

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY OF TERMS AND NOTATIONS

ABBREVIATIONS USED IN THESIS

EV - Electric Vehicle

BEV - Battery Electric Vehicle

HEV - Hybrid Electric Vehicle

ICE - Internal Combustion Engine

DCT - Dual Clutch Transmission

AT - Automatic Transmission

AMT - Automated Manual Transmission

CVT - Continuously Variable Transmission

PM - Permanent Magnet Motor

IM - Induction Motor

SRM - Switched Reluctance Motor

DC - Direct Current

VCU - Vehicle Control Unit

ABS - Anti-Lock Brake System

EBD - Electro Control Brake Distribution

BAS - Brake Assistance System

RBS - Regenerative Brake System

SOC - State of Charge

RSP - Relative selling price

ECE cycle - United Nations Economic Commission for Europe (UNECE) urban driving

NEDC - New European driving cycle

UDDS - Urban dynamometer driving schedule

LA-92 - Los Angeles 92 / Unified cycle driving schedule

HWFET- Highway fuel economic test

JP1015 - Japan 1015 emission test cycles model

KPK - Driving kilometres per kilowatt hour

MPC - Mileage per cycle

CPK - Consumed energy per km

RPK - Braking energy recovered per km

CHAPTER 4 NOTATIONS

m - Vehicle mass

Rw - Wheel radius

i_g - Gear ratio

CR - Coefficient of rolling resistance

g - Gravity

φ - Road incline

Cd - Drag coefficient

A - Vehicle frontal area

u - Vehicle speed

V_{bat} - Battery voltage

C_{bat} - Battery capacity

E_{bat} - Battery energy content

i_m - Main reduction ratio

i_{cvt} - CVT ratio varying range

$i_{converter}$ - Torque converter ratio

η_{cvt} - CVT pulley-belt efficiency

$\eta_{converter}$ - Torque converter efficiency

P_{loss} - Power losses in gearbox

$\sum P_{gear\_mesh}$ - Power losses in all gear meshing

P_{con} - Power losses in concentric shaft

$P_{churning}$ - Power losses in churning and windage

$\sum P_{Bearing}$ - Drag torque in bearings

$P_{disengage\_gear}$ - Power losses in disengaged gear set

T_{in} - Gearbox input torque

T_{con} - Torque lost in concentric shaft viscous shear resistance

$T_{bearing}$ - Frag torque generated by bearings

i - Gear ratios of 1st, 2nd and final gear

$T_{1\_output\_outer}$ - Output torque of the outer concentric shaft

$T_{gearmesh}$ - Torque losses in gear pair meshing

$T_{disengage}$ - Torque consumed in unengaged wet clutch pairs

$T_{churning}$ - Drag torque generated by churning

P_m - Power losses in gear meshing

f_m - Friction coefficient

v^j - Temperature based kinematic viscosity of lubricant in transmission

V^h - Tangential velocity of pitch line

K^g - K-factor

T_1 - pinion torque

n_1 - Pinion rotational speed

β_w	-	Operating helix angle
r_{w1}	-	Outside pinion radius
α_ω	-	Transverse operating pressure angle
H_s	-	Sliding ratios at the beginning of approach action
$\mathrm{H_t}$	-	Sliding ratios at the end of recess action
r	-	Ratio of currently meshed gear pair
$\mathrm{r_{o1/o2}}$	-	Pinion outside radius
$\mathrm{r_{w1/w2}}$	-	Pinion operating pitch radius
$z_{1/2}$	-	Gear teeth and pinion teeth.
R_f	-	Roughness factor
M_t	-	Transverse tooth module
f_g	-	Gear dip factor
D	-	Outside diameter of gear
F	-	Face width
L	-	Length of the gear in mm
β	-	Generated helix angle
R_{con_o}	-	Inner radius of the outer shaft
R_{con_i}	-	Outer radius of the inner shaft
$\Delta\ \omega$	-	Relative speed between two concentric shafts
$R_{i/o}$	-	Inner and outer oil firm radius;
μ	-	Viscosity of the lubricant oil
h_c	-	Clearance of clutch plate;
$v_n \uparrow$	-	Upshift speed threshold
$v_{n+1} \downarrow$	-	Downshift speed threshold.

CHAPTER 5 NOTATIONS

a_0 - Rolling coefficient in dynamometer

a_1 - Grading coefficient in dynamometer

a_2 - Acceleration coefficient in dynamometer

n - Dynamometer input speed

I - Coefficient of rotation parts translational equivalent inertia

G_f - Rolling resistance

G_i - Grading resistance

CHAPTER 6 NOTATIONS

$C_{capacity\_SR}$ - Required battery capacity for 158km range in single reduction powertrain

$C_{capacity\_DCT}$ - Required battery capacity for 158km range in single DCT powertrain

$C_{capacity\_CVT}$ - Required battery capacity for 158km range in single CVT powertrain

$E_{SR\_lifetime}$ - Lifetime electricity consumption for single reduction based BEV

$E_{DCT\_lifetime}$ - Lifetime electricity consumption for two-speed DCT based BEV

$E_{CVT\_lifetime}$ - Lifetime electricity consumption for simplified CVT based BEV

CHAPTER 7 NOTATIONS

$Brake_{\max\_1}$ - Maximum braking force on wheel when vehicle in 1st gear

$Brake_{\max\_2}$ - Maximum braking force on wheel when vehicle in 2nd gear

F_{bf} - Braking force on front axle

F_{br} - Braking force on rear axle

f_{regen} - Regenerative braking force

$f_{caliper}$ - Friction braking force

λ - Wheel slip ratio

$Regen_{min}$ - Minimum available motor braking force at full brake pedal

$Friction_{max}$ - Maximum available friction braking force at full brake pedal

CHAPTER 8 NOTATIONS

Q_{re} - Energy recovery rate

ABSTRACT

Despite the long-term benefit of battery electric vehicles (BEVs) to customers and the environment, the initial cost and limited driving range present the significant barriers for wide spread commercialization. The integration of multi-speed transmission to BEVs' powertrain systems, which is in place of fixed ratio reduction transmission, is considered as a feasible method to improve powertrain efficiency and extend limited driving range for a fixed battery size. Additionally, regenerative braking also extends the mileage by recapturing the vehicle's kinetic energy during braking, rather than dissipating it as heat. Both of these two methods reduce the requirement of battery pack capacity of BEVs without loss of performance. However, the motor-supplied braking torque is applied to the wheels in an entirely different way compared to the hydraulic friction braking systems. Drag torque and response delay may be introduced by transmitting the braking torque from the motor through a multi-speed transmission, axles and differential to the wheels. Furthermore, because the motor is usually only connected to one axle and the available torque is limited, the traditional friction brake is still necessary for supplementary braking, creating a blended braking system. Complicated effects such as wheel slip and locking, vehicle body bounce and braking distance variation, will inevitability impact on the performance and safety of braking. The aim of this thesis is to estimate if the multi-speed transmission and the mechanic-electric blended braking system are worthwhile for the customers, in terms of the price/performance relationship of others' design solutions;

To do so a generic battery electric vehicle is modelled in Matlab/Simulink® to predict motor efficiency, braking performance of different strategies, energy consumption and recovery for single reduction, two-speed Dual Clutch Transmission (DCT) and simplified Continuous Variable Transmission (CVT) equipped BEVs. Braking strategies for different purposes are proposed to achieve a balance between braking performance, driving comfort and energy recovery rate. Special measures are taken to avoid any effects of motor failure. All strategies are analysed in detail for various braking events. Advanced driver assistance systems (ADAS), such as Anti-Lock Brake System (ABS) and Electro Control Brake Distribution (EBD), are properly integrated to work harmoniously with the regenerative braking system (RBS). Different switching plans during braking are discussed. The braking energy recovery rates and brake force distribution details for different driving cycles are simulated.

A credible conclusion is gained, through experimental validation of single speed and two-speed DCT scenarios and reasonable assumptions to support the CVT scenario, that both two-speed DCT and simplified CVT improve the overall powertrain efficiency, save battery energy and reduce customer costs, although each of the configurations has unique cost and energy consumption related trade-offs. Results for two of the cycles in an ‘Eco’ mode are measured on a drive train testing rig and found to agree with the simulated results to within approximately 10%. Reliable conclusions can thus be gained on the economic and dynamic braking performance. The strategies proposed in this thesis are shown to not only achieve comfortable and safe driving during all conditions but also to significantly reduce cost in both the short and long terms.