



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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September 2016

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

- 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  
 $R_w$  - Wheel radius  
 $i_g$  - Gear ratio  
 $CR$  - Coefficient of rolling resistance  
 $g$  - Gravity  
 $\varphi$  - Road incline  
 $C_d$  - 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

$i_{\text{converter}}$	- Torque converter ratio
$\eta_{\text{cvt}}$	- CVT pulley-belt efficiency
$\eta_{\text{converter}}$	- Torque converter efficiency
$P_{\text{loss}}$	- Power losses in gearbox
$\Sigma P_{\text{gear\_mesh}}$	- Power losses in all gear meshing
$P_{\text{con}}$	- Power losses in concentric shaft
$P_{\text{churning}}$	- Power losses in churning and windage
$\Sigma P_{\text{Bearing}}$	- Drag torque in bearings
$P_{\text{disengage\_gear}}$	- Power losses in disengaged gear set
$T_{\text{in}}$	- Gearbox input torque
$T_{\text{con}}$	- Torque lost in concentric shaft viscous shear resistance
$T_{\text{bearing}}$	- Drag torque generated by bearings
$i$	- Gear ratios of 1 <sup>st</sup> , 2 <sup>nd</sup> and final gear
$T_{1\_output\_outer}$	- Output torque of the outer concentric shaft
$T_{\text{gearmesh}}$	- Torque losses in gear pair meshing
$T_{\text{disengage}}$	- Torque consumed in unengaged wet clutch pairs
$T_{\text{churning}}$	- 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

$\beta_w$	- Operating helix angle
$r_{w1}$	- Outside pinion radius
$\alpha_\omega$	- Transverse operating pressure angle
$H_s$	- Sliding ratios at the beginning of approach action
$H_t$	- Sliding ratios at the end of recess action
$r$	- Ratio of currently meshed gear pair
$r_{o1/o2}$	- Pinion outside radius
$r_{w1/w2}$	- 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
$\beta$	- 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 film radius;
$\mu$	- 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 1<sup>st</sup> gear  
 $Brake_{max\_2}$  - Maximum braking force on wheel when vehicle in 2<sup>nd</sup> 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
- $\lambda$  - 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 inevitably 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.