Powertrain Electrification for Jerk Reduction and Continuous Torque Delivery

by Peter Shaker Tawadros

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Completed by:	Peter Shaker Tawadros
Supervisor:	Prof. Nong Zhang
Co-supervisors:	Dr. Paul Walker

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University of Technology Sydney (UTS)
P.O. Box 123, Broadway, Ultimo, N.S.W. 2007
Australia

Certificate of Original Authorship

I, Peter Shaker Tawadros declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Faculty of Engineering and IT at the University of Technology Sydney.

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

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Statement of Contribution

This research project was a collaboration between the Author (Peter Shaker Tawadros) and Mohamed Mahmoud Zakaria Awadallah. Both the Author and Dr Awadallah studied under Prof. Nong Zhang and Dr Paul Walker in the preparation of this project. The project in its entireity required the design, modelling, simulation, verification, construction of a prototype, and experimental validation of a novel P3 mild hybrid vehicle with torque hole elimination.

Mohamed's thesis "A Mild Hybrid Vehicle Control Unit Capable of Torque Hole Elimination in Manual Transmissions", is focused on the development of the control system for the mild hybrid vehicle. It presents the modelling, simulation and hardware-in-the-loop verification of the powertrain and elements of its functionality.

My thesis "Powertrain Electrification for Jerk Reduction and Continuous Torque Delivery", is focused on the development and validation of the physical prototype powertrain. It presents the initial design process, construction of the prototype, experiment design, laboratory testing, and analysis of the data obtained from testing of the physical powertrain prototype.

At all stages of this project both Mohamed and I worked together as a team, collaborating and assisting each other to ensure the project goals were met. For the tasks listed above, where that task is presented in one candidate's thesis, that candidate made the majority contribution to the completion of that task whilst the other provided support as needed.

Signature:

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Peter Shaker Tawadros
28 June 2019

Signature:

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Mohamed Mahmoud Zakaria Awadallah
28 June 2019

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Abstract

A mild-hybrid electric powertrain is proposed for the principal purpose of providing continuous drive torque using a single, dry-plate clutched transmission. The powertrain is optimised to deliver several benefits, in relation to cost, complexity, vibration (jerk), as well as dynamic and emissions performance.

The powertrain proposed is a post-transmission type, with the motor being placed inline with the transmission output shaft, prior to the differential. This allows the powertrain to be controlled for providing continuous drive torque to the wheels during gear shifting and take-off, eliminating the “torque hole” due to disengagement of the clutch plate, and providing a degree of damping during clutch re-engagement. A pressure-based clutch model is used to modulate the electric drive torque to minimise torsional vibration during the gear shifting process, whilst engine speed is controlled proportionally to road speed to minimise discontinuity of rotational velocity during the re-engagement process. The system is designed as a driver assistance function, but can optionally be implemented with automatic clutch and gear actuation units.

A rule-based energy management strategy (EMS) allows the powertrain to be additionally controlled for drive torque supplementation, battery recharging, brake energy recuperation, and electric vehicle (EV) crawl.

System optimization is conducted on several levels. The system architecture is optimized to minimize modification cost from a typical conventional vehicle (CV) by careful consideration of powertrain topology. The selection of the post-transmission (P3) architecture was made to eliminate the cost and complexity of a dual-motor configuration whilst maximising the utility of a single electric motor (EM) using a sophisticated EMS. The

electric power components, primarily the electric motor and battery are optimized for component size and cost based on benchmarking criteria and power needs analysis.

A V-cycle development process using model-based design was followed. A hardware-in-the-loop (HIL) vehicle model was built in a virtual environment, allowing testing of performance and comparison with the CV by running the software model through standard drive cycles in Advanced Vehicle Simulator (ADVISOR). Certain model parameters were tested on a HIL bench and refined, and then the model was downloaded onto a real-time controller (dSPACE MicroAutoBox II) for implementation in the prototype validation stage.

The powertrain is designed to meet the requirements of a typical light vehicle. The prototype powertrain was built into a 1990 Mazda MX-5 (Miata) body, which was modified to fit the additional powertrain components selected through the optimization process. These components include a 1.2 KWh, 96 V $LiFePO_4$ battery pack, a 10 KW cont./30 KW pk. permanent magnet motor, four quadrant 600 A motor controller, battery management system, electronic throttle system, and supervisory controller. The vehicle was instrumented for clutch pedal position, clutch line pressure, gear lever position, brake pedal position, brake line pressure, throttle pedal and butterfly position, engine manifold vacuum, transmission output torque, transmission output speed, and electric motor torque. The battery is also instrumented through the battery management system (BMS) and is capable of logging individual cell voltages and temperatures, as well as pack statistics including state of charge, depth of discharge, current and voltage.

As implemented, the system is designed to suit low-end vehicles typically sold in developing nations, and serves as a way to reduce fossil-fuel dependency, introduce fleet electrification (particularly in areas where access to electricity is unreliable), and improve urban air pollution whilst also improving vehicle driveability through powertrain refinement. In developing the vehicle for such purpose, a tight manufacturing cost control of no more than

105% of the manufacturing cost of the base vehicle is imposed. With changes to the benchmarking criteria and control, the powertrain architecture could also be used for dynamic performance enhancement.

Results of experimental testing of the prototype against the CV are presented and discussed. The experimental testing encompasses acceleration, jerk, torque continuity, and emissions. Results validate the modelled system to a high degree, showing that the powertrain meets its design objectives, effectively providing continuous drive torque, substantially reducing torsional drivetrain vibrations manifested as longitudinal jerk.

Based on the test results of the prototype, a number of refinements, optimizations, and further works are suggested. Principally, the major system improvements include the implementation of an auto-clutch system (ACS), computerized gear selection, or the combination of both in the form of an automated manual transmission (AMT). These improvements eliminate the need for predictive algorithms required to fill the torque hole, as the target speed and torque are known at all stages during the gear selection process. Further refinements include optimization of the traction battery, new approaches to motor control, and further cost reductions in the transmission componentry through the use of electronic synchronization control.

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Acronyms and abbreviations

4WD	Four-Wheel-Drive
5MT	5-speed Manual Transmission
A/D	Analog-to-Digital
ABB	ASEA Brown Boveri (company name)
AC	Alternating Current
ACG	Automatic Code Generation
ACIM	Alternating Current Induction Motor
ADC	Analog-to-Digital Converter
ADVISOR	ADvanced VehIcle SimulatOR
AER	All-Electric Range
AMT	Automated Manual Transmission
AT	Automatic Transmission
BEV	Battery Electric Vehicle
BLDC	BrushLess Direct Current
BMEP	Brake Mean Effective Pressure
BMS	Battery Management System
BOL	Beginning Of Life
BSFC	Brake-Specific Fuel Consumption
CAN	Controller Area Network
CARB	California Air Resources Board
CD	Coast Down
CRAC	Computer Room Air Conditioning
CSHVR	City-Suburban Heavy Vehicle Route
CTM	Cost To Manufacture
CV	Conventional Vehicle
D/A	Digital-to-Analog
DAC	Digital-to-Analog Converter
DAQ	Data AcQuistion
DC	Direct Current
DCT	Dual-Clutch Transmission
DHT	Dedicated Hybrid Transmission
DOF	Degrees Of Freedom
ECE/UNECE	United Nations Economic Commission for Europe
ECU	Electronic Control Unit
EM	Electric Motor
EMF	ElectroMotive Force
EOL	End Of Life
EPA/US EPA	United States Environmental Protection Authority
EPS	Electric Propulsion System
ESM	Engine Simulation Motor
EV	Electric Vehicle
FE	Fuel Economy
FF	Front-engine/Front-wheel-drive
FOC	Field Orientation Control
FR	Front-engine/Rear-wheel-drive
HAMT	Hybridized Automated Manual Transmission

HAP	Hazardous Air Pollutants
HC	Hydrocarbons
HEV	Hybrid Electric Vehicle
HIL	Hardware-In-the-Loop
HPEVS	Hi-Performance Electric Vehicles
HSD	Hybrid Synergy Drive
HWFET	HighWay Fuel Economy Test
I/O	Input/Output
I2V	Infrastructure-to-Vehicle
I4	Inline 4-cylinder
ICE	Internal Combustion Engine
IGBT	Integrated Gate Bipolar Transistor
IoT	Internet of Things
ISC	Idle Speed Control
KERMIT IV	Kinetic Energy Recovery and Motor Infill Torque Investigation Vehicle
LiFePO4	Lithium Iron Polymer
Li-ion	Lithium-Ion
LSB	Load Simulation Brake
MAHA	MAHA Maschinenbau Haldenwang Gmbh & Co. KG (company name)
MBD	Model-Based Design
MHEV	Mild Hybrid Electric Vehicle
MR	Mid-engine/Rear-wheel-drive
MT	Manual Transmission
N/C	Normally Closed
N/O	Normally Open
n-D	n-Dimensional
NEDC	New European Driving Cycle
NEMA	National Electrical Manufacturers' Association
NI	National Instruments (company name)
NiMH	Nickel Metal Hydride
NOVC	Non Off-Vehicle Charging
NOx	Nitric Oxide
NVH	Noise, Vibration and Harshness
NYCC/NYCDDS	New York City Cycle/New York City Dynamometer Drive Schedule
OBD/OBDI/OBDII	On-Board Diagnostics (version I/II)
OEM	Original Equipment Manufacturer
OTA	Over-the-Air
OVC	Off-Vehicle Charging
PC	Personal Computer
PCB	Printed Circuit Board
PEMS	Portable Emissions Measurement System
PESTEL	Political, Economic, Social, Technological, Environmental, Legal
PHEV	Plug-in Hybrid Electric Vehicle
PID	Proportional Integral Differential
PIL	Processor-In-the-Loop
PM2.5	Particle Matter <2.5um
PMSM	Permanent Magnet Synchronous Motor

PMSRM	Permanent Magnet Switched Reluctance Motor
PPF	PowerPlant Frame
PSI	Pounds per Square Inch
PTO	Power Take-Off
RCP	Rapid Control Prototyping
REEV/BEVx	Range-Extended Electric Vehicle/Battery Electric Vehicle - Extended Range
RHS	Rectangular Hollow Section
RLD	Road Load Determination
RON	Research Octane Number
RPM	Revolutions Per Second
RR	Rear-engine/Rear-wheel-drive
RTI	Real Time Interface
SAE	Society of Automotive Engineers
SIL	Software-In-the-Loop
SOC	State-Of-Charge
SPDT	Single-Pole Double-Throw
SRM	Switched Reluctance Motor
TCO	Total Cost of Ownership
TCO	Total Cost of Ownership
THS/THS-II/THS-III	Toyota Hybrid System (I/II/III)
TTR	Through-the-Road
UDDS	Urban Dynamometer Drive Cycle
UN	United Nations
UTS	University of Technology Sydney
UUT	Unit Under Test
V&V	Verification and Validation
V2I	Vehicle-to-Infrastructure
VDV	Vibration Dose Value
VFD	Variable Frequency Drive
VI	Virtual Instrument
VOC	Volatile Organic Compounds
WHO	World Health Organization
WLTP	World-harmonized Light-duty Test Procedure
ZEV	Zero Emissions Vehicle