UNIVERSITY OF TECHNOLOGY SYDNEY
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Control of Motor Drives And Gearshift for a Dual Motor-based Multi-speed Transmission

by

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Certificate of Authorship/Originality

I, Haitao Yang declare that this thesis, is submitted in fulfilment of the requirements for the award of the degree of Doctor of Philosophy, in the Faculty of Engineering and Information Technology 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.

This document has not been submitted for qualifications at any other academic institution. This research is supported by the Australian Government Research Training Program.

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List of Publications

This section shows publications during the research project where Haitao Yang (*H. Yang*) is either the first author or a contributing author. The 1st-8th journal papers and the 1st-2nd conference papers listed here are strongly related to the contents of this thesis, about the control of motor drives and transmissions for the electric vehicle. These papers present the control schemes of motor drives without using the measured rotor speed or position, which can improve the reliability and safety of the drive system due to the fault-tolerant capacity brought by sensorless control strategy. The issue of performance deterioration with low pulse ratio under high-speed operation is also addressed. To improve the efficiency of the drive system, the synchronized PWM schemes are incorporated into the closed-loop current control. Moreover, shift control of the studied transmission and the active damping of torsional vibration are carefully designed to improve the driving comfort. The other papers are about the control of PWM rectifier. The PWM rectifier is used as the active front end to replace the conventional diode bridge rectifier, which guarantees lower stressing of the line supply, i.e. lower harmonics and higher power factor when converting the AC power to DC [1, 2]. However, the battery can directly supply DC voltage to the inverter in a pure electric vehicle. Hence, the work on PWM rectifier is outside the scope of this thesis and will not be included in the main chapters.

Journal Papers

1. ***H. Yang***, Y. Zhang, G. Yuan, P. D. Walker, and N. Zhang, "Hybrid synchronized PWM schemes for closed-loop current control of high-power motor drives," *IEEE Trans. Ind. Electron.*, vol. 64, no. 9, pp. 6920--6929, Sept 2017.

   H. Yang proposes the main ideal and implements the control algorithm in simulation and hardware tests. *H. Yang* writes the paper as the main author with the support of other authors who help to develop test rig and improve the quality of the paper.

2. ***H. Yang***, Y. Zhang, P. D. Walker, N. Zhang, and B. Xia, “A method to start rotating induction motor based on speed sensorless model-predictive control,” *IEEE Trans. Energy Convers.*, vol. 32, no. 1, pp. 359--368, March 2017.

   H. Yang does the main part of the work. *H. Yang* carries out theoretical analysis and proposes a new feedback gain matrix for the adaptive full-order observer aiming at starting a free-running induction motor without a speed sensor. *H. Yang* writes the paper as the main author, and the other authors help to develop test rig, perform the experimental test, and improve the writing quality of the paper.

3. ***H. Yang***, Y. Zhang, P. D. Walker, J. Liang, N. Zhang, and B. Xia, “Speed sensorless model predictive current control with ability to start a free running induction motor,” *IET Electr. Power Appl.*, vol. 11, no. 5, pp. 893--901, 2017.

   H. Yang comes up with the key part of this work and writes the paper as the main author. Theoretical analysis and algorithm implementation are done by *H. Yang*. The other authors help to carry out experimental tests and proofread the manuscript.

4. ***H. Yang***, Y. Zhang, J. Liang, B. Xia, P. D. Walker, and N. Zhang, “Deadbeat control based on a multipurpose disturbance observer for permanent magnet synchronous motors,” *IET Electr. Power Appl.*, vol. 12, no. 5, pp. 708--716, 2018.

   H. Yang completes the main work of this research. *H. Yang* proposes a multipurpose sliding-mode disturbance observer which can either used for rotor position estimation or for improving the robustness of deadbeat predictive control based on the support and discussions with the other authors. B. Xia helps to make the experimental test and Y. Zhang is responsible for the submission and correspondence.

5. ***H. Yang***, J. Liang, P. D. Walker, J. Ruan and N. Zhang, "Gearshift Control and Active Damping of Torsional Vibrations for a Dual Motor-Based Multi-Speed Transmission," *Mechatronics*, MECH-D-18-00517, under review.

   H. Yang completes the main part of the work. *H. Yang* proposes a discrete-time sliding-mode torque observer, based on which, the smooth and fast gearshift is achieved. Additionally, a simple but very effective active damping scheme is developed to suppress torsional vibrations during and after shifting process. P. D. Walker proofreads the manuscript and holds responsible for the correspondence of this paper. J. Liang helps to develop the simulation model and check the correctness of the equations. The other authors offer the suggestions on the control system design.

6. Y. Zhang, Y. Bai, and ***H. Yang****, "A universal multiple-vector-based model predictive control of induction motor drives," *IEEE Trans. Power Electron.*, vol. 33, no. 8, pp. 6957--6969, Aug 2018.

   H. Yang is responsible for revision, submission and correspondence of this paper. *H. Yang* contributes with the theoretical proof to justify the effectiveness of the main ideal presented in this paper. Y. Zhang comes up with the key ideal, develops the test rig and proofreads the manuscript. Y. Bai carries out experimental tests and write the first draft.

7. Y. Zhang, Y. Bai, ***H. Yang****, and B. Zhang, "Low switching frequency model predictive control of three-level inverter-fed IM drives with speed sensorless and field-weakening operation," *IEEE Transactions on Industrial Electronics*, pp. 1--1, 2018.

   H. Yang is responsible for revision, submission and correspondence of this paper, and *H. Yang* contributes with the field-weakening strategy. Y. Zhang and Y. Bai develop the test rig, carry out experimental tests and write the first draft. B. Zhang offers some help in the experimental test.

8. J. Liang, ***H. Yang***, J. Wu, N. Zhang, and P. D. Walker, "Power-on shifting in dual input clutchless power-shifting transmission for electric vehicles," *Mech. Mach. Theory*, vol. 121, pp. 487 -- 501, 2018.

   The main part of the work is done by J. Liang, and the other authors help him in different areas. *H. Yang* helps to develop the simulation model and provide some suggestions on the shifting algorithm.

9. J. Liang, ***H. Yang***, J. Wu, N. Zhang, and P. D. Walker, "Shifting and power sharing control of a novel dual input clutchless transmission for electric vehicles," *Mech. Syst. Sig. Process.*, vol. 104, pp. 725 -- 743, 2018.

   J. Liang does the main part of the work. J. Wu provides an example of the code for power-sharing scheme. *H. Yang* helps to set up the simulation model for the dual input clutchless transmission and proofread the whole manuscript.

10. ***H. Yang***, Y. Zhang, J. Liang, J. Gao, P. D. Walker, and N. Zhang, "Sliding-mode observer based voltage-sensorless model predictive power control of PWM rectifier under unbalanced grid conditions," *IEEE Trans. Ind. Electron.*, vol. 65, no. 7, pp. 5550--5560, July 2018.

    H. Yang proposes the main ideal of the work and writes the paper as the main author. *H. Yang* does theoretical analysis and implements the control algorithm in the simulation test. Y. Zhang is responsible for the correspondence of the paper and does experiments with the help from J. Gao.

11. ***H. Yang***, Y. Zhang, J. Liang, J. Liu, N. Zhang and P. D. Walker, "Robust Deadbeat Predictive Power Control With a Discrete-Time Disturbance Observer for PWM Rectifiers Under Unbalanced Grid Conditions," *IEEE Trans. Power Electron.*, vol. 34, no. 1, pp. 287--300, Jan 2019.

    H. Yang proposes a discrete-time disturbance observer for improving the robustness of deadbeat predictive power control. *H. Yang* performs theoretical analysis and algorithm implementation. Y. Zhang is responsible for the correspondence of the paper and carries out experiment tests with J. Liu.

Conference Papers

1. ***H. Yang***, Y. Zhang, J. Liang, N. Zhang, and P. Walker, "Robust digital current control based on adaptive disturbance estimation for PMSM drives with low pulse ratio" in *2018 21st International Conference on Electrical Machines and Systems (ICEMS)*, Oct 2018, pp. 1252–1257.

   H. Yang proposes a digital current controller based on sliding-mode disturbance observer with low pulse ratio. *H. Yang* performs theoretical analysis and algorithm implementation. *H. Yang* writes the paper and presents it at the conference in South Korean. The other authors offer some useful suggestions and help in making experimental tests.

2. ***H. Yang***, Y. Zhang, and N. Zhang, "Two high performance position estimation schemes based on sliding-mode observer for sensorless SPMSM drives," in *2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia)*, May 2016, pp. 3663–3669.

   H. Yang introduces two position estimation schemes for SPMSM drives in this paper. *H. Yang* performs theoretical analysis, algorithm implementation and experimental tests. *H. Yang* writes the paper and Y. Zhang presents it at the conference in China.

3. ***H. Yang***, Y. Zhang, J. Liang, N. Zhang, and P. Walker, "A robust deadbeat predictive power control with sliding mode disturbance observer for PWM rectifiers" in *2017 IEEE Energy Conversion Congress and Exposition (ECCE)*, Oct 2017, pp. 4595–4600.

   H. Yang comes up with the key ideal and makes theoretical analysis, algorithm implementation and experimental tests. *H. Yang* writes the paper and presents it at the conference in the USA. The other authors help to develop the test rig and make the experiments.

Contents

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Abbreviation

AFO	Adaptive full-order observer
AT	Automatic transmission
AMT	Automated manual transmission
BBCS	Basic bus clamping strategy
CHMPWM	Current harmonic minimum pulse width modulation
CVT	Continuous variable transmission
CCS-MPC	Continuous control set-model predictive control
DCT	Dual clutch transmission
DEKF	Dual extended Kalman filter
DSP	Digital signal processor
DTC	Direct torque control
DT-CVPI	Discrete-time complex-vector proportionality-integral
DMMT	Dual motor based multi-speed transmission
DSMTO	Discrete-time sliding mode torque observer
DPCC	Discrete-time predictive current controller
DO-PCC	Disturbance observer based-predictive current control
EKF	Extended Kalman filter
EMF	Electromotive force

EV	Electric vehicle
FCS-MPC	finite control set-model predictive control
FOC	Field oriented control
HEV	Hybrid electric vehicle
HPF	High pass filter
JEKF	Joint extended Kalman filter
KF	Kalman filter
LQG	Linear-quadratic-Gaussian
MPC	Model predictive control
MPFC	Model predictive flux control
MST	Multi-speed transmission
MTPA	Maximum torque per ampere
MT	Manual transmission
ICE	Internal combustion engine
IM	Induction motor
IPMSM	Interior permanent magnet synchronous motor
PI	Proportional-integral
PID	Proportional-integral-derivative
PMSM	Permanent magnet synchronous motor
PWM	Pulse width modulation
SHEPWM	Selective harmonic elimination pulse width modulation
SMO	Sliding-mode observer

SMTO	Sliding-mode torque observer
SPMSM	Surface-mounted permanent magnet synchronous motor
SPWM	Sinusoidal pulse width modulation
SRM	Switched reluctance motor
SVM	Space vector modulation
TCU	Transmission control unit
THD	Total harmonic distortion
WTHD	Weighted total harmonic distortion
ZOH	Zero-order hold

Nomenclature and Notation

Capital letters denote complex vectors or matrices.

The symbol ˆ is used to denote an estimated variable.

The superscript ref represents the reference.

The superscript k denotes a kth instant variable.

A	Vehicle frontal area
C_s	Viscous coefficient
C_v	Rolling resistance coefficient
d	Duty ratio
$\boldsymbol{d}_p$	Disturbance resulted from parameter mismatches
$\boldsymbol{e}_i$	Current estimation error
$\boldsymbol{e}_\psi$	Flux estimation error
f_s	Switching frequency
f_e	Fundamental frequency
f_{ratio}	Frequency ratio
J	Inertial
L_m	Mutual inductance
L_s	Stator inductance
L_r	Rotor inductance

$L_{d,q}$	dq-axis inductance
m_v	Vehicle mass
M^{ref}	Modulation index
n_p	Pole pairs
N	Pulse ratio
i_d	d-axis current
i_q	q-axis current
$\boldsymbol{i}_r$	Rotor current vector
$\boldsymbol{i}_s$	Stator current vector
k_h	Coefficient of the hysteresis loss
k_{ec}	Coefficient of the eddy current loss
k_{ex}	Coefficient of the excess loss
k_d	Controller gain
$\boldsymbol{k}_u$	Voltage compensation gain
$p_{1,2}$	Poles of the system
P_{iron}	Iron loss
$r_{1,2}$	Gear ratios
r_f	Gear ratio of the final drive
r_w	Tire radius
R_s	Staotr resistance
R_r	Rotor resistance
s	Laplace operator

T_e	Electromagnetic torque
T_L	Load torque
T_M	Motor torque
T_D	Dog clutch torque
T_{sc}	Control period
T_r	Rotor time constant
T_{pwm}	PWM period
U_{dc}	DC-link voltage
$\boldsymbol{u}_s$	Stator voltage vector
$\boldsymbol{u}_s$	Extended electromagnetic force
V_{lim}	Maximum voltage available from the inverter
ω_r	Rotor speed
ω_e	Electrical speed
z	Delay operator
$Z()$	Boundary switching function
ψ_{pm}	Permanent magnetic flux
ψ_{ext}	Extended flux
$\boldsymbol{\psi}_s$	Stator flux vector
$\boldsymbol{\psi}_r$	Rotor flux vector
$\alpha_{1,2,3}$	Reduced variables
ρ	Air density
γ	Percentage of the throttle opening

τ	Time constant
θ	Phase angle
Δ	Estimation Error
$\otimes$	Cross product of two complex variables
$\int$	Integral
sign()	Sign function

Abstact

Currently, most pure electric vehicles (EVs) in the commercial market are equipped with a single-speed transmission. However, this configuration presents some disadvantages such as compromised driveability performance and lower overall efficiency due to the limited freedom in determining optimal states for motor drives. Therefore, using multi-speed transmission (MST) in EVs is regarded as a viable scheme to improve the EV performance further. This thesis focuses on the control of a dual motor-based multi-speed transmission. More specifically, the thesis centres on the following three research topics: 1) powertrain modelling and model-based torque observer design; 2) high-performance motor control including position/speed sensorless operation, controller and observer design under low pulse ratio, and closed-loop control based on synchronized pulse width modulation; 3) gearshift control including coordinated torque and speed control of two motors, speed synchronization and active vibration damping control.

The first part of this thesis introduces the configuration of the studied MST, its advantages and the issues need to be addressed. Additionally, the detailed transmission and motor models are developed for theoretical analysis and controller design. The requirement of the motor drive in an EV involves more than the satisfactory steady-state performance but also fast dynamic response and high battery-to-motor efficiency. The control of motor drive is the fundamental based on which an EV can be driven efficiently, comfortably and safely. Therefore, the second part of this thesis work develops control schemes for the induction motor (IM) and permanent magnet synchronous motor (PMSM) which are currently the main choices for EVs. The

improved observers are designed to achieve position/speed sensorless control. The impact of discrete-time implementation is investigated to ensure stability and fast dynamic response under low pulse ratio. Simulation, experimental tests and comparative studies with the prior methods were carried out to validate the superiority of the proposed methods. Finally, a closed-loop torque control scheme along with active vibration damping is proposed to achieve high-quality gearshift. Considering the measurement of shaft torque is not feasible in practical application, a discrete-time sliding-mode torque observer is further designed to provide the feedback signal for the proposed controller.

Owing to the sophisticated structure design and advanced control schemes, not only the driving comfort but also the reliability and efficiency of the whole system can be greatly improved. The feasibility and effectiveness of the proposed methods are confirmed by simulation and/or experimental tests.