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DEVELOPMENT OF FPGA BASED CONTROL ARCHITECTURE FOR PMSM DRIVES

by

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Certificate of Authorship/Originality

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

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

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ABSTRACT

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The rapid advancement of the very large scale integration (VLSI) technology and electronic design automation techniques in recent years has made a significant impact on the development of complex and compact high performance control architecture for industrial motion systems.

Specific hardware with the field programmable gate array (FPGA) technology is now considered as a promising solution in order to make use of the reliability and versatility of controllers. Indeed, FPGAs have been successfully used in many control applications such as power converter control and electrical machines control. This is because such an FPGA-based implementation can offer an effective reprogrammable capability and overcome disadvantages of microprocessor-based or digital signal processor-based embedded systems.

This thesis aims to provide a proof-of-concept for the control-system-on-chip and a prototype for a fully-implemented FPGA control architecture for permanent magnet synchronous motor (PMSM) drives. In this thesis, a special focus is given on analytical effects, design procedure, and control performance enhancement for PMSM drives under sensor/sensorless vector control using a number of control techniques.

The control schemes include FPGA-based intelligent control and robust cascade control for single axis and multiple axis tracking with PMSMs. An important contribution of this thesis rests with a convincing demonstration of high performance estimation schemes, using sliding mode observers and extended Kalman filters, in terms of accuracy and robustness against noisy and/or perturbed currents for sensor-

less PMSM control based on the FPGA technology. In addition, a sequential finite state machine is developed in this work to result in less logic gate resources, leading to a faster processing time.

Significance of this thesis contribution includes in providing a feasible and effective solution for the implementation of complex control strategies to fully exploit the FPGA advantages in power electronics and drive applications.

List of Publications

1. **Nguyen Khanh Quang**, Nguyen Trung Hieu, Q. P. Ha (2014), *FPGA-Based Sensorless PMSM Speed Control Using Reduced-Order Extended Kalman Filters*, IEEE Transactions on Industrial Electronics, vol.61, no.12, pp.6574-6582.

2. Q. P. Ha, Ying-Hao Yu and **Nguyen Khanh Quang** (2012), *FPGA-based cooperative control of indoor multiple robots*, International Journal of Advanced Mechatronic Systems, vol.4, Nos. 5/6, pp.248-259.

3. **Nguyen Khanh Quang**, Doan Duc Tung and Q. P. Ha (2015), *FPGA-Based Sensorless PMSM Speed Control using Adaptive Extended Kalman Filter*, The 11th IEEE Int. Conf. on Automation Science and Engineering (CASE2015), Gothenburg, Sweden, to be published 2015.

4. **Nguyen Khanh Quang**, Nguyen Trung Hieu and Q. P. Ha (2014), *FPGA Sensorless PMSM Drive with Adaptive Fading Extended Kalman Filtering*, The 13th Int. Conf. on Control, Automation, Robotics and Vision (ICARV2014), Singapore, pp.295-300.

5. **Nguyen Khanh Quang**, Doan Quang Vinh, Nguyen D. That and Q. P. Ha (2013), *Observer-based Integral Sliding Mode Control for Sensorless PMSM Drives using FPGA*, The 2nd International Conference on Control, Automation and Information Sciences (ICCAIS2013), Nha Trang, Vietnam, pp.218-223.

6. **Nguyen Khanh Quang**, Doan Quang Vinh (2013), *Sensorless FPGA-Based PMSM Drives using Improved Sliding Mode Observer*, The 1st Vietnam conference on Control and Automation (VCCA2013), Da Nang, Vietnam, pp.164-170.

7. Tri Tran and **Nguyen Khanh Quang** (2013), *Distributed Model Predictive Control with Receding-Horizon Stability Constraints*, The 2nd Int. Conf. on Control, Automation and Information Sciences (ICCAIS2013), Nha Trang, Vietnam, pp.137-141.

8. Nguyen D. That, **Nguyen Khanh Quang**, Pham Thanh and Q. P. Ha (2013), *Robust Exponential Stabilization of the Pendubot in the Presence of Bounded External Disturbances Using Sliding Mode Control*, The 2nd International Conference on Control, Automation and Information Sciences (ICCAIS2013), Nha Trang, Vietnam, pp.137-141.

9. **Nguyen Khanh Quang**, Nguyen D. That, Nguyen Hong Quang and Q. P. Ha (2012), *FPGA-based Fuzzy Sliding Mode Control for Sensorless PMSM Drive*, The 8th IEEE International Conference on Automation Science and Engineering (CASE2012), Seoul, Korea, pp.172-177.

10. **Nguyen Khanh Quang**, N. T. Hieu, G. P. Hunter, and Q. P. Ha (2012), *FPGA-based Sensorless PMSM Drive Using Parallel Reduced-Order Extended Kalman Filter*, The 1st Int. Conf. on Control, Automation and Information Sciences (ICCAIS2012), Ho Chi Minh, Vietnam, pp.164-169.

11. **Nguyen Khanh Quang**, Tri Tran (2012), *Dissipativity Criterion for Linear Systems with a Coupling Delay and Asymptotically Positive Realness Constraint*, The 1st Int. Conf. on Control, Automation and Information Sciences (ICCAIS2012), Ho Chi Minh, Vietnam, pp.60-65.

12. Nguyen D. That, **Nguyen Khanh Quang**, Raja M. T. Raja Ismail, Phan T. Nam and Q. P. Ha (2012), *Improved reachable set bounding for linear systems with discrete and distributed delays*, The 1st Int. Conf. on Control, Automation and Information Sciences (ICCAIS2012), Ho Chi Minh, Vietnam, pp.137-141.

13. **Nguyen Khanh Quang**, Y.-S. Kung, and Q. P. Ha (2011), *FPGA-Based Control Architecture Integration for Multiple-Axis Tracking Motion Systems*, IEEE/SICE International Symposium on System Integration (SII2011), Kyoto, Japan, pp.591-596.

14. Y.S. Kung, **Nguyen Khanh Quang** and Le Thi Van Anh (2009), *FPGA-based neural fuzzy controller design for PMLSM drive*, The 8th Int. Conf. on Power Electronics and Drive Systems (PEDS2009), Taipei, Taiwan, pp.222-227.

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Quang Nguyen Khanh

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Nomenclature and Notation

List of abbreviations

- ADC : Analog digital converter
- ASIC : Application-specific integrated circuit
- CCCT : Current controller and coordinate transformation
- EDA : Electronic design automation
- EKF : Extended Kalman filter
- EMF : Electromotive force
- EPROM : Programmable read-only memory
- FC : Fuzzy control
- FPGA : Field programmable gate array
- FSM : Finite state machine
- HF : High frequency
- IDE : Integrated development environment
- IP : Intelligent property
- IR : Interrupt service routine
- LE : logic element
- LPM : Library parameterized module
- LUT : Look up table
- PLD : Programmable logic device
- PMSM : Permanent magnet synchronous motor
- PMLSM : Permanent magnet linear synchronous motor
- PI : Proportional integral controller
- QEP : Quadrature encoder pulse

- RBF : Radial basis function
- SoPC : System-on-programmable-chip
- SRAM : Static random access memory
- SVPWM : Pulse-width-modulation
- VHDL : Very high speed integrated hardware description language
- VLSI : Very large scale integration

List of symbols

- θ : Rotor position
- F_e : Motor thrust force
- F_L : External load force
- B_m : Viscous friction coefficient
- K_t : Force constant
- J : Inertia
- λ : Permanent magnet flux linkage
- p : Pairs of poles of a motor
- τ : Pole pitch
- ω_e : Electrical speed (rad/s)
- r_s : Stator resistance
- v : Voltage
- i : Current
- T_s : Sampling period
- x : State space vector
- u : Input vector
- y : Output vector
- $\nu; \xi$: The discrete forms of system and measurement noise
- K : Kalman matrix
- $P; P0$: State error covariance matrix, Initial state error covariance matrix
- $Q; R$: Covariance state noise and covariance measurement noise matrices

- $F; H; \Phi$: Jacobian, output matrix, and state transition matrices

- s : Laplace operator

Indexes

- $d - q$: Rotating reference frame indexes

- $\alpha - \beta$: Stationary reference frame indexes

- $a; b; c$: Three phase reference frame indexes

- $*$: Reference quantity

- $\hat{}$: Estimated quantity

- n : Sampling index

- $n/n-1$: Predicted quantity

- n/n : Optimal estimated quantity