DIRECT TORQUE CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTORS (DTC-PMSM)

By

Eng. Shady Mamdouh Sadek Abd Al-Mawla

A Thesis Submitted to the

Faculty of Engineering at Cairo University

In Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

IN

ELECTRICAL POWER AND MACHINES ENGINEERING

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT

2016

DIRECT TORQUE CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTORS (DTC-PMSM)

By

Eng. Shady Mamdouh Sadek Abd Al-Mawla

A Thesis Submitted to the

Faculty of Engineering at Cairo University

In Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

IN

ELECTRICAL POWER AND MACHINES ENGINEERING

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT

2016

DIRECT TORQUE CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTORS (DTC-PMSM)

By

Eng. Shady Mamdouh Sadek Abd Al-Mawla

A Thesis Submitted to the

Faculty of Engineering at Cairo University

In Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

IN

ELECTRICAL POWER AND MACHINES ENGINEERING

Under the Supervision of

Prof. Dr. Mahmoud Mohamed Abd El-Hakim
Professor
Electrical Power and Machines
Faculty of Engineering, Cairo University

Assoc. Prof. Sherif Ahmed Zaid
Associate Professor
Electrical Power and Machines
Faculty of Engineering, Cairo University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT

2016

DIRECT TORQUE CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTORS (DTC-PMSM)

By

Eng. Shady Mamdouh Sadek Abd Al-Mawla

A Thesis Submitted to the

Faculty of Engineering at Cairo University

In Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

IN

ELECTRICAL POWER AND MACHINES ENGINEERING

Approved by the Examining Committee:

_____

Prof. Dr. Mahmoud Mohamed Abd El-Hakim, Thesis Main Advisor
Professor, Faculty of Engineering – Cairo University

_____

Prof. Dr. Adel Diaa El-Deen Shaltout, Internal Examiner
Professor, Faculty of Engineering – Cairo University

_____

Prof. Dr. Mohsen Zaki El-Sherif, External Examiner
Professor, Shubra Faculty of Engineering –Banha University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT

2016

Engineer's Name: Shady Mamdouh Sadek Abd Al-Mawla
Date of Birth: 24/12/1989
Nationality: Egyptian
E-mail: Shady_mamdouh_2011@yahoo.com
Phone: 01111-820-603
Address: Nasr Al-Shorbagy St., Faysal, Giza, Egypt

Registration Date: 1 / 3 / 2012
Awarding Date: / / 2016
Degree: Master of Science
Department: Electrical Power and Machines Engineering

Supervisors:

-Prof. Dr. Mahmoud M. Abd El-Hakim
-Assoc. Prof. Sherif A. Zaid

Examiners:

-Prof. Dr. Mohsen Zaki El-Sherif (External examiner)
Professor, Shubra Faculty of Engineering, Banha University
-Prof. Dr. Adel Diaa El-Deen Shaltout (Internal examiner)
-Prof. Dr. Mahmoud M. Abd El-Hakim (Thesis main advisor)

Title of Thesis:

Direct Torque Control Of Permanent Magnet Synchronous Motors (DTC-PMSM)

Key Words:
Electric Drives, Permanent Magnet Synchronous Motor; Direct Torque Control; Field Oriented Control; Matlab/Simulink

Summary:

DTC of AC drives is considered one of the most important high performance control techniques nowadays. PMSMs are now replacing IMs in wide applications due to their high efficiency and compact size. DTC offers high dynamic responses for torque and flux better than that of FOC with simple control architecture and less parameter sensitivity. Comparisons between DTC and FOC are made via simulations to verify the high dynamics of DTC over FOC. Flux estimation techniques, various switching tables, and the effect of varying the hysteresis bands are studied via simulations to compare between them and show their effects on the drive performance. Torque/Flux ripples and variable switching frequency problems can be solved using SVM, Duty Ratio Control, or Model Predictive Control but complexity will be increased so trade off studies should be done to select the most suitable method according to the used application. The complete description of the experimental DTC-PMSM system is discussed. DSP programming using CACSD is discussed and experimental implementation of six step operation as well as open loop V/F control of PMSM are made and the results are presented and discussed.

Acknowledgments

In the name of Allah, Most Gracious, Most Merciful, Blessing and prayers be upon the Prophet Muhammad (pbuh), a member of the holy family and friends he is elected.

Alhamdulillah, grateful to Allah for giving me the chance to complete this thesis entitled **Direct Torque Control of Permanent Magnet Synchronous Motors (DTC-PMSM)**. First of all I would like to express my sincere gratitude and appreciation to ***Faculty of Engineering Cairo University*** which give me opportunity to gain technical knowledge, soft skills and funding.

Special thanks to Prof. Dr. ***Mahmoud M. Abd Al-Hakim*** and Assoc. Prof. ***Sherif A. Zaid*** for their valuable guidance supervision, knowledge and assistance. The support and supervision under them were truly helpful in my progress through this work.

Thus, with this occasion I would like to express my gratitude to many people who helped me in this work. Especially to the teaching assistances of ***Electrical Power and Machines Department at Cairo University*** and others who helped me with opinions and knowledge to achieve the aim of this work.

Thousands of thanks and appreciations are given to my friends: Eng. ***Mostafa Hassan,*** *Eng.* ***Ahmed Abd Al-Rahman,*** *Eng.* ***Ahmed Kamal,*** *Eng.* ***Mohamed Gamal Gouda,*** *Eng.* ***Eslam Abd Al-Nabi,*** *Eng.* ***Mahmoud Al-Nahhas,*** *Eng.* ***Wael Abd Al-Aziz,*** *Eng.* ***Mostafa Samir,*** *Eng.* ***Ahmed Mohammed,*** *Eng.* ***Hossam Salah,*** *and Eng.* ***Shaaban Shaaban*** for their technical helps and encouragements till the work has been finished.

Thousands of thanks and appreciations are given to anyone whom involved either directly or indirectly for helping me in this work.

Last but not least privileges of appreciation and great thanks to my parents for their support and encouragements till the work has been completed.

Table of Contents

ACKNOWLEDGEMENTS…… I
TABLE OF CONTENTS…… II
LIST OF TABLES……..... V
LIST OF FIGURES……..... VI
LIST OF ABBREVIATIONS ……..…….. X
LIST OF SYMBOLS……..…… XII
Abstract …….. XIV
Chapter 1 " Introduction "……...……..….. 1
1.1. Motivation..……...……..…….. 1
1.2. History of Permanent Magnet Machines……...…...…...…… 3
1.3. Permanent Magnet Materials……. 3
1.4. Permanent Magnet Electric Machines……... 3
1.5. Classifications of PM Electric Machines……...……..….. 4
1.6. Permanent Magnet Synchronous Machines Configurations…….…...…. 5
1.7. Permanent Magnet Rotor Types……..... 6
1.7.1. Surface-Mounted PMSM (SPMSM)……..…….... 6
1.7.2. Surface-Inset PMSM (SIPMSM)……..……. 6
1.7.3. Interior PMSM (IPMSM)…….…..…. 7
1.7.4. Interior PMSM with Circumferential Orientation……..…… 8
1.8. Control Techniques of Permanent Magnet Synchronous Motor…….…….…..... 8
1.8.1. Scalar Volts/Hertz Control…….…..…….. 9
1.8.2. Field Oriented Control…….…..…. 10
1.8.3. Direct Torque Control…….…..…... 11
1.9. Outline of the Thesis……..... 12
Chapter 2 "Modeling of Permanent Magnet Synchronous Motor"…….…..…… 15
2.1. Introduction……..……...…..…… 15
2.2. Axes transformation……..….. 15
2.2.1. Stationary Reference Frame (D-Q plane)……..…… 15
2.2.2 Rotating Reference Frame (d-q plane)…… 18
2.3. Machine Dynamic Model…….. 20
2.3.1. Dynamic Model in the Stationary Reference Frame…….……. 20
2.3.2. Dynamic Model in the Rotating Reference Frame…….… 21
2.4. Electromagnetic Torque Equation…….…..... 22
2.5. Mechanical System Model……. 23
2.6. Simulink Model of PMSM in the Stationary Reference Frame…… 23
Chapter 3 "Direct Torque Control of Permanent Magnet Synchronous Motor"…… 27
3.1. Introduction…….…….. 27
3.2. Space Vector PWM Technique……...…….. 27
3.3. Concept of DTC as applied to PMSMs……. 31
3.3.1. Control of Stator Flux-Linkage Space Vector Magnitude……..... 33
3.3.2. Control of Stator Flux-Linkage Space Vector Rotational Speed……..…….... 35
3.4. Different Building Blocks of PMSM-DTC……..... 36
3.4.1. Flux and Torque Controllers……..……..…… 37
3.4.1.1. Flux Controller (2-Level Hysteresis Comparator)……...…….…..... 37

3.4.1.2. Torque Controller (3-Level Hysteresis Comparator)…… 39
3.4.2. Basic Voltage Switching Look-up Table…… 40
3.4.3. Stator Flux Linkage Space Vector Estimation…… 40
3.4.3.1. Flux Estimation Using the Voltage Machine Model…… 41
3.4.3.2. Flux Estimation Using the Current Machine Model…… 42
3.4.3.3. Flux Estimation Using the Hybrid Machine Model…… 43
3.4.4. Torque Estimation…… 44
3.4.5. Voltage and Current Measurements and Transformations…… 44
3.5. Simulation of the PMSM-DTC model using MATLAB Simulink…… 45
3.5.1. Some References Simulation Comparison…… 45
3.5.2. Some References Experimental Results Comparison…… 51
3.6. Comparison between Direct Torque Control and Field Oriented Control of PMSM 55
3.7. Analysis of Direct Torque Controlled Permanent Magnet Synchronous Motor Drive…… 58
3.7.1. Estimation of the Stator Flux Various Designs Considering Their Problems and Suitable Solutions…… 60
3.7.1.1. Pure Integrator…… 60
3.7.1.2. Low Pass Filter…… 63
3.7.1.3. Modified Integrators…… 63
3.7.1.4. Tunable Low Pass Filter…… 65
3.7.2. Various Switching Table Designs and Effect of Adding Zero Voltage Vectors 66
3.7.2.1.Takahashi's Switching Table…… 66
3.7.2.2. 2-Level Hysteresis Comparator with Using Zero Voltage Vectors Switching Table…… 67
3.7.2.3. 2-Level Hysteresis Comparator Without Using the Zero Voltage Vectors Switching Table…… 68
3.7.2.4. 2-Level Hysteresis Comparator With Only One State Zero Voltage Vector Switching Table…… 69
3.7.2.5. 3-Level Hysteresis Comparator with Modified Sectors…… 69
3.7.3. Effect of Hysteresis Band Width of Torque and Flux Comparators on the Drive Performance…… 72
3.7.3.1. Effect of Flux Hysteresis Band Amplitude…… 72
3.7.3.2. Effect of Torque Hysteresis Band Amplitude…… 75
3.7.4. High Ripple Content in Torque and Flux & Variable Switching Frequency Problems and Their Remedies…… 76
3.7.4.1. Increased Number of Voltage Vectors…… 76
3.7.4.2. Pulse Width Modulation (PWM) Techniques…… 79
3.7.4.2.1. Space Vector Modulation (SVM) Technique (SVM-DTC)…… 79
3.7.4.2.2. Sinusoidal Pulse Width Modulation Technique (SPWMDTC)…… 80
3.7.4.2.3. Discrete Space Vector Modulation Technique (DSVM-DTC)…… 81
3.7.4.3. Duty-Ratio Control…… 81
3.7.4.4. Model Predictive Control (MPC)…… 82
Chapter 4 " Simulation Results"…… 84
4.1. Introduction…… 84
4.2. Comparisons between Various Methods of Flux Estimation via Simulations…… 85
4.2.1. Pure Integrator…… 85
4.2.2. Low Pass Filter…… 87
4.2.3. Modified Integrators…… 89
4.2.4. Tunable Low Pass Filter…… 91
4.3. Comparison between the Various Switching Tables via Simulations…… 93

4.3.1. Torque Response of the Different Switching Tables (0 ➔0.2 sec)…… 94
4.3.2. Torque Response of the Different Switching Tables (0.04 ➔0.06sec)..... 95
4.3.3. Torque Response of the Different Switching Tables (Zooming View)……... 96
4.3.4. Torque Ripples of the Different Switching Tables (0.04➔0.05 sec)…… 97
4.3.5. Flux Responses of the Different Switching Tables…… 98
4.3.6. Flux Ripples of the Different Switching Tables…… 99
4.3.7. D-Q Flux Responses of the Different Switching Tables…… 100
4.3.8. Speed Responses of the Different Switching Tables…… 101
4.3.9. Switching Pattern of the Different Switching Tables……... 102
4.4. Effects of Flux / Torque Hysteresis Band Amplitudes Via Simulation…… 106
4.4.1. Effect of Flux Hysteresis Band Amplitude Via Simulations……..... 106
4.4.2. Effect of Torque Hysteresis Band Amplitude Via Simulations…… 109
Chapter 5: "Experimental Work"…… 113
5.1. Introduction…… 113
5.2. System Architecture…… 115
5.2.1. Power Circuit…… 115
5.2.1.1. Three Phase Inverter Board…… 115
5.2.1.2. Three Phase Motor (PMSM)…… 116
5.2.1.3. Mechanical Load…… 116
5.2.2. Control Circuit…… 117
5.2.2.1. Control Circuit Hardware Requirements…… 117
5.2.2.2. Programming using Computer Aided Control System Design…… 119
5.2.2.3. Control Board Selection…… 119
5.2.2.3.1. TI TMS320F28335 Digital Signal Processor…… 120
5.2.3. Measurements and Signal Conditioning…… 120
5.2.3.1. Optocoupler Isolation Circuit…… 121
5.2.3.2. Position and Speed Measurement…… 122
5.2.3.3. Current Measurement…… 122
5.2.3.3.1. Current Signal Conditioning Circuit…… 123
5.3. Experimental Works…… 124
5.3.1. 180^{o}-Conduction Six Step Operation…… 124
5.3.2. Open Loop V/Hz Operation…… 129
Chapter 6: "Conclusions and Future Work"…… 134
6.1. Thesis Conclusions…… 134
6.2. Recommendations for Future Work…… 137
Appendix (A)…… 138
Appendix (B)…… 141
References…… 142
Extracted Paper…… 148