

بسم الله الرحمن الرحيم





شبكة المعلومات الجامعية التوثيق الالكتروني والميكرو فيلم



جامعة عين شمس

التوثيق الإلكتروني والميكرو فيلم

قسم

نقسم بالله العظيم أن المادة التي تم توثيقها وتسجيلها
على هذه الأقراص المدمجة قد أعدت دون أية تغييرات



يجب أن

تحتفظ هذه الأقراص المدمجة بعيدا عن الغبار





ELECTROMAGNETIC AND MECHANICAL ANALYSIS AND INVESTIGATIONS OF AXIAL FLUX SYNCHRO- NOUS MACHINES EQUIPPED WITH DIFFERENT PM CONFIGURATIONS

By

Amr Ahmed Abbas Abdelaziz Khader

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
2021

ELECTROMAGNETIC AND MECHANICAL ANALYSIS AND INVESTIGATIONS OF AXIAL FLUX SYNCHRO- NOUS MACHINES EQUIPPED WITH DIFFERENT PM CONFIGURATIONS

By

Amr Ahmed Abbas Abdelaziz Khader

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

Associate Professor

Hanafy Hassan Hanafy

Electrical Power and Machines Department
Faculty of Engineering, Cairo University

Assistant Professor

Ahmed M. Hemeida

Electrical Power and Machines Department
Faculty of Engineering, Cairo University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2021

ELECTROMAGNETIC AND MECHANICAL ANALYSIS AND INVESTIGATIONS OF AXIAL FLUX SYNCHRO- NOUS MACHINES EQUIPPED WITH DIFFERENT PM CONFIGURATIONS

By

Amr Ahmed Abbas Abdelaziz Khader

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

Assoc. Prof. Hanafy Hassan Hanafy

Thesis Main Advisor

Prof. Amr A. Adly

Internal Examiner

Prof. Ayman Samy Abdel-Khalik
Faculty of Engineering, Alexandria University

External Examiner

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2021

Engineer's Name: Amr Ahmed Abbas Abdelaziz Khader
Date of Birth: 6/5/1994
Nationality: Egyptian
E-mail: mm.ame94@gmail.com
Phone: 01066327792
Address: Giza
Registration Date: 1/10/2018
Awarding Date: .../.../2021
Degree: (Master of Science)
Department: Electrical Power and Machines Engineering



Supervisors:

Assoc. Prof. Hanafy Hassan Hanafy
Asst. Prof. Ahmed M. Hemeida

Examiners:

Assoc. Prof. Hanafy Hassan Hanafy (Thesis main advisor)
Prof. Amr A. Adly (Internal examiner)
Prof. Ayman Samy Abdel-Khalik (External examiner)
Faculty of Engineering, Alexandria University

Title of Thesis:

ELECTROMAGNETIC AND MECHANICAL ANALYSIS AND INVESTIGATIONS OF AXIAL FLUX SYNCHRONOUS MACHINES EQUIPPED WITH DIFFERENT PM CONFIGURATIONS

Key Words:

Axial flux machine; Halbach arrays; Analytical model; Finite element model; Optimization routine.

Summary:

This thesis presents a comparison between using conventional permanent magnet (PM) and Halbach PM array configurations in yokeless and segmented armature axial flux permanent magnet synchronous machines. An analytical model is adopted to carry out the study and finite element models are used to verify the results. A sensitivity analysis is carried out to investigate the effects of motor parameters on performance. An optimization routine is introduced to achieve some performance requirements and fully optimize the machine. The rotor disk design is studied from electromagnetic and mechanical points of views for the conventional PM and Halbach array configurations. From electromagnetic point of view, the rotor flux density is reduced. This allows the reduction of the rotor thickness and improvement the power density of the machine. However, from mechanical point of view, the air gap flux density increases. Therefore, the rotor thickness needs to be larger to support the rotor fixation for the same rotor displacement.

Disclaimer

I hereby declare that this thesis is my own original work and that no part of it has been submitted for a degree qualification at any other university or institute.

I further declare that I have appropriately acknowledged all sources used and have cited them in the references section.

Name: Amr Ahmed Abbas Abdelaziz Khader

Date: .../.../2021

Signature:

Acknowledgments

All praise is due to almighty ALLAH who bestowed success on me and gave me the guidance of several people who advise, assist and help me throughout the completion of this thesis.

I would like to express my sincere thanks and gratitude to my supervisors, Dr. Hanafy H. Hanafy and Dr. Ahmed Hemeida for their guidance and help throughout the accomplishment of this work.

I would like to thank Dr. Hanafy for his valuable time in guidance and reviewing the work with valuable comments and edits. I would like to thank Dr. Ahmed for his countless effort and time to get this work. They gave me lots of their time and knowledge.

I would like to thank my colleagues in electrical power department especially eng. Mostafa El-Sayed, eng. Ramadan Ragab and eng. Emad Fathy for their support and help.

Finally, I would like to thank my mother and father. Without their sacrifices and support, I could not achieve any valuable thing in this life. Special thanks to my wife for her support and encouragement. Thanks to my sisters and brother. Thanks to everyone try to help me.

Amr Ahmed Abbas Abdelaziz Kader

Table of Contents

List of Tables	v
List of Figures	viii
List of Abbreviations	x
List of Symbols	xiii
Abstract	xiii
CHAPTER 1: Introduction	1
1.1 Axial and Radial Flux Machine Topologies	1
1.2 Why Axial Flux Machine?	2
1.3 AFM Topologies	3
1.3.1 Single Stator Single Rotor - SSSR	3
1.3.2 Double Stator Single Rotor - DSSR	3
1.3.3 Single Stator Double Rotor - SDDR	4
1.3.4 Multi Stator Multi Rotor - MSMR	6
1.3.5 Topology Selection	6
1.4 Halbach Array PM Configuration	7
1.5 Scope of the Thesis	10
1.6 Objectives of the Thesis	10
1.7 Outline of the Thesis	10
CHAPTER 2: Electromagnetic Modeling of YASA AFPMSM with Halbach Array PM Configuration	13
2.1 Introduction	13
2.2 Finite Element Models Description	13
2.2.1 3D Finite Element Model	14
2.2.2 2D Multi-Slice Finite Element Model	14
2.3 Magnetic Equivalent Circuit Model Description	17
2.3.1 Permanent Magnets Modeling	18
2.3.2 Reluctance Network Construction	21
2.3.3 System Matrices Construction	21
2.4 Iron Loss Model	24
2.5 MEC Model Verification	25
2.5.1 Linear Material Simulation	25
2.5.2 Non-Linear Material Simulation	29
CHAPTER 3: YASA Machine Rotor Disk Mechanical Analysis	33
3.1 Introduction	33
3.2 Electromagnetic Constraint	33
3.3 Mechanical Constraint	33
3.4 Dynamic Stability Constraint	35

CHAPTER 4: Sensitivity Analysis and Parameters Optimization	37
4.1 Introduction	37
4.2 Sensitivity Analysis	37
4.2.1 PM Span Ratio Sweeping Study	37
4.2.2 PM Thickness Sweeping Study	38
4.3 Optimization Routine	40
CHAPTER 5: Optimization Routine Results	43
5.1 Introduction	43
5.2 Electromagnetic Results	43
5.3 Axial Force Effect on Rotor Thickness	46
CHAPTER 6: Conclusions and Recommendations for Future Work	49
6.1 Conclusion	49
6.2 Recommendations for Future Work	50
References	50

List of Tables

Table 2.1	Coefficients of (2.23) based on PM configuration and magnetization direction	20
Table 2.2	Power loss fitting parameters	24
Table 2.3	Test machine parameters	25
Table 2.4	Performance comparison between 3D FE, 2D FE and MCE models for linear material at no-load and rated load conditions	28
Table 2.5	35CS300 steel BH curve fitting parameters	30
Table 2.6	3D FE, 2D FE and MCE models results comparison with non-linear material	30
Table 2.7	Linear and non-linear simulations' comparison for the three models at rated load condition only	32
Table 4.1	Routine predefined constraints' values	41
Table 5.1	Demonstration machine parameters	46

List of Figures

Figure 1.1	Faraday disk, the first generator created by Michael Faraday.	1
Figure 1.2	Radial and axial machines flux paths. a)Radial path b)Axial path	2
Figure 1.3	AFPMSM topologies	3
Figure 1.4	SSSR topology of 12 slots 8 poles machine with surface mounted PMs. a) 3D view b) 2D view at constant radius with flux path.	4
Figure 1.5	DSSR topology of 12 slots 8 poles machine with surface mounted PMs. a) 3D view b) 2D view at constant radius with flux path.	4
Figure 1.6	TORUS-NN topology of 12 slots 8 poles machine with surface mounted PMs. a) 3D view b) 2D view at constant radius with flux path using core wound winding type.	5
Figure 1.7	TORUS-NS topology of 12 slots 8 poles machine with surface mounted PMs. a) 3D view b) 2D view at constant radius with flux path using tooth wound winding type.	5
Figure 1.8	YASA topology of 12 slots 8 poles machine with surface mounted PMs. a) 3D view b) 2D view at constant radius with flux path.	6
Figure 1.9	3D view of MSMR AFPMSM topology	7
Figure 1.10	Conventional PMs configuration	7
Figure 1.11	Ideal Halbach array	7
Figure 1.12	Two segment Halbach array formation from conventional PMs. a) vertical (radial) PMs b) horizontal (azimuthal) PMs c) the resultant Halbach array.	8
Figure 1.13	Higher segment number Halbach array. a) Three segments array b) Four segments array.	9
Figure 2.1	3D FE models of YASA machine. a) Full machine b) Axial symmetry c) Poles and teeth number symmetry.	14
Figure 2.2	2D multi-slice model formation. a) 3D machine geometry with axial symmetry b) Machine at slice number i in 3D c) Machine slicing in 2D d) 2D planner machine. (1)Neumann BC (2)Dirichlet BC (3)Periodic BC (4)Stator teeth (5) Winding (6)Rotor disk (7) PMs	15
Figure 2.3	Conventional PM magnetization vector	18
Figure 2.4	Hal90 PM magnetization vector	19
Figure 2.5	Hal45 PM magnetization vector	19
Figure 2.6	MEC Regions	21
Figure 2.7	Reluctance network basic element	22
Figure 2.8	Curve fitting of iron losses coefficients. a) dc hysteresis loss curve b)higher frequency loss curves.	24
Figure 2.9	Flux density distribution. a) 3D FE model b) 2D FE model c) MEC model.	26

Figure 2.10	The axial air-gap flux density for the three models. a) no-load condition b) full load condition.	26
Figure 2.11	The circumferential air-gap flux density for the three models. a) no-load condition b) full load condition.	27
Figure 2.12	The phase voltage comparison for the three models. a) no-load b) full load.	27
Figure 2.13	Torque comparison for the three models. a) cogging torque b) full load torque.	28
Figure 2.14	Effect of changing circumferential discretization elements on the voltage and torque percentage error and CPU time.	29
Figure 2.15	Effect of changing axial discretization elements on the percentage voltage and torque error and CPU time.	29
Figure 2.16	35CS300 steel BH curve.	30
Figure 2.17	Phase voltage waveforms for the three models	31
Figure 2.18	Non-linear simulation air-gap flux density. a) axial b) Circumfer- ential	31
Figure 2.19	Output Torque with non-linear model	31
Figure 2.20	3D FE model linear and non-linear simulation comparison. a) load EMF b) torque	31
Figure 2.21	2D FE model linear and non-linear simulation comparison. a) load EMF b) torque.	32
Figure 2.22	MEC model linear and non-linear simulation comparison. a) load EMF b) torque	32
Figure 3.1	Rotor flux path in case of CPM configuration	34
Figure 3.2	Rotor deflection due to axial force. r is the point at which axial force starts to apply.	34
Figure 3.3	Eigen frequency deformation for various rotor configurations. a) Circular disk rotor ($f_n = 1684.2\text{Hz}$) b) Circular disk rotor with shaft hole ($f_n = 1614\text{Hz}$) c) Rotor disk with shaft ($f_n = 2018\text{Hz}$). . .	36
Figure 4.1	PM span ratio sweeping effects on: a) mean torque b) efficiency c) mass d) rotor iron maximum flux density	38
Figure 4.2	PM thickness sweeping effects on: a) mean torque b) efficiency c) cost d) rotor iron maximum flux den- sity	39
Figure 4.3	Optimization routine structure	40
Figure 5.1	Optimization routine geometrical outputs. a) slot width b) tooth axial length c) rotor iron thickness d) ma- chine mass	43
Figure 5.2	Optimization routine performance output. a) mean torque b) efficiency c) rotor maximum flux density d) power density.	44
Figure 5.3	Required electromagnetic and mechanical rotor thickness.	45
Figure 5.4	Mechanical FE model. a) rotor deflection b) sample of the stress contours in 3D.	45

Figure 5.5	Machine performance. a) average air gap flux density per pole b) axial force.	46
Figure 5.6	Demonstration machine performance. a) average air gap flux density per pole b) axial force.	47
Figure 5.7	Required electromagnetic and mechanical rotor thickness for demonstration machine	47
Figure 5.8	Demonstration machine rotor deflection from mechanical FE model	47
Figure 5.9	Comparison between electromagnetic and total mass for machine two	48
Figure 5.10	Demonstration machine. a) total cost b) power density.	48