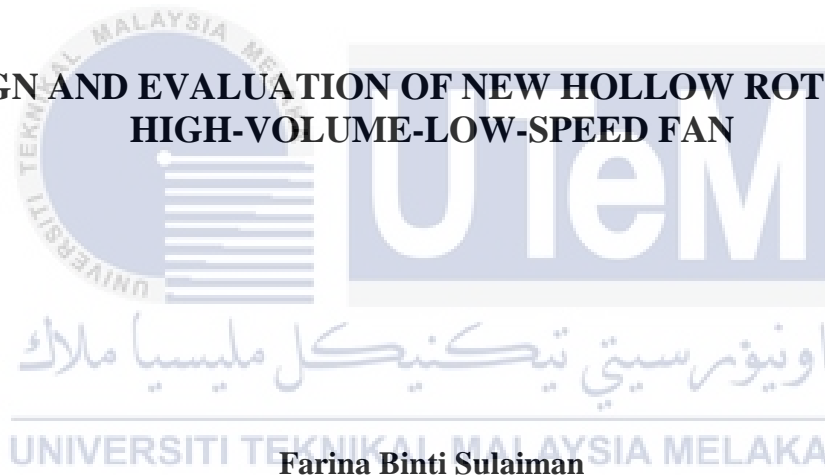




Faculty of Electrical Technology And Engineering

**DESIGN AND EVALUATION OF NEW HOLLOW ROTOR FOR
HIGH-VOLUME-LOW-SPEED FAN**



Farina Binti Sulaiman

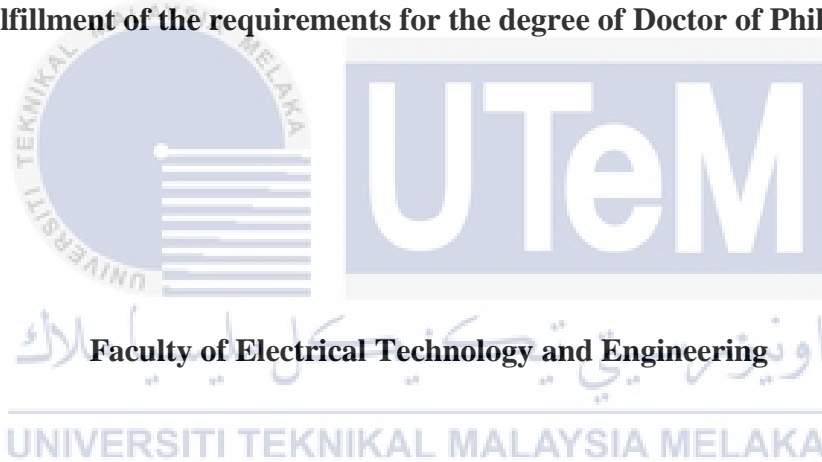
Doctor of Philosophy

2024

**DESIGN AND EVALUATION OF NEW HOLLOW ROTOR FOR
HIGH-VOLUME-LOW-SPEED FAN**

FARINA BINTI SULAIMAN

**A thesis submitted
in fulfillment of the requirements for the degree of Doctor of Philosophy**



UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2024

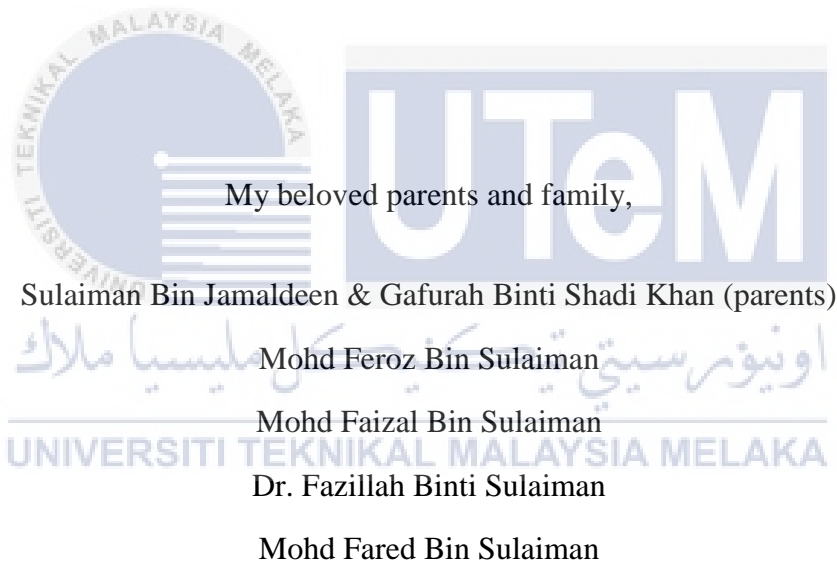
DEDICATION

To my beloved husband and children

Mohd Azam Bin Tumijan (husband)

Khaulah Al-Khansa

Nusaybah Ar-Ramadhani



ABSTRACT

This thesis discussed the design and evaluation of a new hollow rotor for High-Volume-Low-Speed (HVLS) fan application. HVLS fan is commonly used in large areas such as factories, barns, and public places. The research focuses on BLDC motor due to its high efficiency, stability, and high performance. Induction motor is frequently used in HVLS fan industry. The main constraint of the HVLS motor is that it's expensive and requires high maintenance. In this research, four types of BLDC motors are designed by using Permeance Analysis Method (PAM) and Finite Element Method (FEM) for HVLS fan applications. Each motor has been developed based on the same stator design and parameter with different rotor types. These are hollow rotor, spoke rotor, embedded rotor, and surface mount rotor. The PAM method is used to model the sizing equation of the HVLS motor reduced computational time. The PAM formulated the sizing equation to calculate the magnetic flux of the air gap. The FEM measured is used to analyse the characteristics of flux linkage, back emf, cogging torque, inductance, stator flux density and electromagnetic torque. The simulation results from PAM and FEM results are validated for the purpose of choosing the best rotor type design for the fabrication process. The percentage difference for each validation part is below 10 % for back emf, 9.1 % for cogging torque and 7 % for static torque. Based on the validation, a hollow rotor is chosen for prototype fabrication. A hollow rotor can maximise the flux density produced by the permanent magnet and coil by reducing flux leakage. It is confirmed that the implementation of hollow rotor design will optimised the magnetic flux and evenly distribute the air gap. The hollow rotor design was further tested for static and cogging torque characteristics. BLDC driver topology is carried out to analyse the performance of the motor connected with the drivers under loaded condition in the torque speed characterisation. In this characterisation, the value of input voltage, input current, input power, torque, output power and efficiency are measured for each type of commutation which is synchronous commutation, basic commutation and THC, in order to confirm the best topology for BLDC motor. From the topology, it can be seen that by using THC, the detailed result of the hollow rotor could be archived and examined compared to other driver topology. This thesis provides guidelines for designing and analysing BLDC motor for HVLS fan.

REKABENTUK DAN PENILAIAN ROTOR BERONGGA BAHARU UNTUK KIPAS BERISIPADU TINGGI BERKELAJUAN RENDAH

ABSTRAK

Tesis ini membincangkan reka bentuk dan penilaian rotor berongga baru untuk aplikasi kipas HVLS. Kipas HVLS biasanya digunakan di kawasan besar seperti kilang, gudang, dan tempat awam. Kajian ini memfokuskan pada motor BLDC kerana kecekapan tinggi, kestabilan, dan prestasi yang tinggi. Motor induksi sering digunakan dalam industri kipas HVLS. Kekangan utama motor HVLS adalah harganya yang mahal dan memerlukan penyelenggaraan yang tinggi. Dalam kajian ini, empat jenis motor BLDC direka menggunakan Kaedah Analisis Permeans (PAM) dan Kaedah Unsur Terhingga (FEM) untuk aplikasi kipas HVLS. Setiap motor telah dibangunkan berdasarkan reka bentuk dan parameter stator yang sama dengan jenis rotor yang berbeza. Ini adalah rotor berongga, rotor berbilah, rotor tertanam, dan rotor dipasang permukaan. Kaedah PAM digunakan untuk memodelkan persamaan saiz motor HVLS yang mengurangkan masa pengiraan. PAM merumuskan persamaan saiz untuk mengira fluks magnet ruang udara. Kaedah FEM digunakan untuk menganalisis ciri-ciri penghubung fluks, emf balik, tork cogging, induktans, ketumpatan fluks stator dan tork elektromagnet. Keputusan simulasi daripada PAM dan FEM disahkan untuk tujuan memilih reka bentuk jenis rotor terbaik untuk proses fabrikasi. Perbezaan peratusan untuk setiap bahagian pengesahan adalah di bawah 10% untuk emf balik, 9.1% untuk tork cogging dan 7% untuk tork statik. Berdasarkan pengesahan tersebut, rotor berongga dipilih untuk fabrikasi prototaip. Rotor berongga dapat memaksimumkan ketumpatan fluks yang dihasilkan oleh magnet kekal dan gegelung dengan mengurangkan kebocoran fluks. Telah disahkan bahawa pelaksanaan reka bentuk rotor berongga akan mengoptimumkan fluks magnet dan mengagihkan ruang udara dengan sekata. Reka bentuk rotor berongga telah diuji lebih lanjut untuk ciri-ciri tork statik dan cogging. Topologi pemacu BLDC dijalankan untuk menganalisis prestasi motor yang disambungkan dengan pemacu di bawah keadaan beban dalam pencirian tork kelajuan. Dalam pencirian ini, nilai voltan input, arus input, kuasa input, tork, kuasa output dan kecekapan diukur untuk setiap jenis komutasi iaitu komutasi sinkron, komutasi asas dan THC untuk mengesahkan topologi terbaik untuk motor BLDC. Dari topologi tersebut, dapat dilihat bahawa dengan menggunakan THC, hasil terperinci rotor berongga dapat dicapai dan diperiksa berbanding dengan topologi pemacu lain. Tesis ini menyediakan garis panduan untuk mereka bentuk dan menganalisis motor BLDC untuk kipas HVLS.

ACKNOWLEDGEMENTS

First and foremost, all praise is to Allah S.W.T for giving me the deen, iman, health, patience and perseverance to complete this research and thesis successfully. I would not have been able to reach this stage without His Grace and Mercy. Secondly, I wish to express my warmest gratitude to my supervisor, Associate Professor Dr. Raja Nor Firdaus Kashfi Bin Raja Othman and my co-supervisor, Dr. Maaspaliza Binti Azri, for their valuable suggestions, guidance and encouragement that have significantly helped me in my work. Working with and learning something valuable from these amazing people has been a great honour. I am greatly indebted to the Ministry of Higher Education and Universiti Teknikal Malaysia Melaka (UTeM) for giving me the opportunity and financial support to pursue my doctoral studies through the Zamalah scheme. Also Ir. Dr. Fairul Azhar Bin Abdul Shukor and Associate Professor Dr. Kasrul Bin Abdul Karim commented on improving my research. There is no way to express how much it meant to me to have been a member of Research Laboratory of Electrical Machine Design (EMD) Lab. These brilliant friends and colleagues who inspired me over many years are Dr. Nor Azizah, Dr. Suhairi, Nur Faezah, Aishah, Ashikin, Norrimah, Abd Rahim and others who I could not possibly mention all of them here for their valuable help, meaningful discussion and insight during my doctoral research. I am eternally grateful to my beloved husband, Mohd Azam Bin Tumijan, for his unconditional love and endless prayers and for being with me through thick and thin throughout this journey. My two wonderful kids, Khaulah Al Khansa and Nusaybah Ar Ramadhani, for their smiles and playful actions, always cheer up

my day, especially when my life is tough. Also, special thanks to my parents, my late father, Sulaiman Bin Jamaldeen and my mom, Gafurah Binti Shadi Khan, my brother and spouse, Mohd Faizal Bin Sulaiman and Roquia Begum Binti Abdul Haq and my dearest sister Dr. Fazillah Binti Sulaiman for their endless affections, prayers and continuous support during my studies. Lastly, it is a great pleasure to thank all those who supported me in completing this research that made this thesis possible.



TABLE OF CONTENTS

	PAGE
DECLARATION	
APPROVAL	
DEDICATION	
ABSTRACT	i
ABSTRAK	ii
ACKNOWLEDGEMENTS	iii
TABLE OF CONTENTS	v
LIST OF TABLES	ix
LIST OF FIGURES	xi
LIST OF APPENDICES	xxi
LIST OF ABBREVIATIONS	xxii
LIST OF SYMBOLS	xxiv
LIST OF PUBLICATIONS	xxviii
AWARD AND SCHOLARSHIPS	xxix
CHAPTER	
1. INTRODUCTION	1
1.1 Background of HVLS fan	1
1.2 Research motivation	4
1.3 Research problem	6
1.4 Research objectives	9
1.5 Research contribution	9
1.6 Scope of work	11
1.7 Thesis layout	12
2. LITERATURE REVIEW	14
2.1 State of art of HVLS fan	14
2.2 Study on low speed motor application	20
2.2.1 Ventilation	21
2.2.2 Direct drive	27
2.2.3 Electric vehicle	32
2.2.4 Hydraulic motor	36
2.2.5 Motion motor	37
2.3 Overview of BLDC motor	38
2.3.1 Embedded rotor	49
2.3.2 Surface mount rotor	51
2.3.3 Spoke rotor	52
2.3.4 Hollow rotor	54
2.4 Basic equivalent circuit of BLDC motor	56
2.4.1 Resistance	56
2.4.2 Inductance	57
2.4.3 Torque	58
2.4.4 Cogging torque	59

2.4.5	Input and output power	60
2.5	Summary of related research on flux barrier	61
2.6	Selection of low speed motor for comparison	63
2.6.1	Selected low speed motor model from researcher	63
2.6.2	Selected HVLS model from industry	64
2.7	Introduction to finite element method (FEM)	66
2.8	Introduction to permeance analysis method (PEM)	68
2.8.1	Permeance model	69
2.8.2	Magnetic equivalent circuit	70
2.9	Introduction to BLDC driver topology	73
2.9.1	Basic commutation	74
2.9.2	Synchronous commutation	77
2.9.3	Torque hysteresis controller	78
2.9.4	Evaluation of various commutation in the market	79
2.10	Summary	80
3.	METHODOLOGY	83
3.1	Overall research methodology	83
3.2	Modelling of HVLS motor using PAM	85
3.2.1	Development the permeance model	89
3.2.2	Modelling of permeance	90
3.2.2.1	Hollow rotor BLDC motor	91
3.2.2.2	Spoke rotor BLDC motor	94
3.2.2.3	Embedded rotor BLDC motor	97
3.2.2.4	Hollow rotor BLDC motor	100
3.2.3	Permanent magnet operating point	103
3.2.4	Flux calculation	106
3.3	Determination of design sizing parameter	107
3.4	Modelling of HVLS motor using FEM	109
3.4.1	Overall flow chart of FEM modelling	110
3.4.2	Structure modelling	112
3.4.3	Development of mesh	115
3.4.4	Magnetic analysis	117
3.4.5	Coil vectors and winding arrangement	121
3.4.6	HVLS motor magnet arrangement	129
3.4.7	FEM analysis	131
3.5	Validation PAM and FEM model	131
3.6	Prototype fabrication	132
3.7	Experimental verification	136
3.7.1	Static and cogging torque characteristics	137
3.7.2	Torque and speed characteristics	141
3.8	BLDC driver topology	144
3.8.1	Synchronous commutation	145
3.8.2	Basic commutation	146
3.8.3	Torque hysteresis commutation	148
3.9	Summary	149

4.	RESULT AND DISCUSSION	151
4.1	Modelling of HVLS motor using PAM	152
4.2	Different sizing of HVLS motor parameters	152
4.3	Modelling and simulation of HVLS motor using FEM meth	154
4.3.1	Hollow rotor BLDC motor	155
4.3.2	Spoke rotor BLDC motor	158
4.3.3	Embedded rotor BLDC motor	160
4.3.4	Surface mount rotor BLDC motor	163
4.3.5	Summary of analysis result for HVLS motor	166
4.4	Comparison between HVLS motor based on FEM results	166
4.4.1	Comparison based on different rotor design : 50 turns	167
4.4.2	Comparison based on different rotor design : 100 turns	170
4.4.3	Comparison based on different rotor design : 150 turns	172
4.4.4	Comparison based on different rotor design : 200 turns	175
4.4.5	Summary of comparison HVLS motor	178
4.5	Simulation results for different types of rotor designs based on FEM method	179
4.6	Result of validation between FEM and PAM methods	181
4.7	Hollow rotor HVLS motor prototype fabrication	189
4.7.1	Prototype for hollow rotor BLDC motor	189
4.7.2	Stator fabrication	190
4.7.3	Rotor fabrication	191
4.7.4	Winding process	193
4.7.5	Bearings and casing mounting	195
4.8	Result of experimental verification	195
4.8.1	Static and cogging torque characteristics	196
4.8.1.1	Back emf	196
4.8.1.2	Cogging and static torque	198
4.8.2	Result of BLDC driver topology	200
4.8.2.1	Synchronous commutation at 15 Hz	200
4.8.2.2	Synchronous commutation at 17 Hz	202
4.8.2.3	Basic commutation	204
4.8.2.4	Torque hysteresis commutation (THC)	206
4.8.2.5	Summary of comparison HVLS driver topology	209
4.8	Summary	211
5.	CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK	213
5.1	Conclusion	213
5.2	Achievement of research objectives	214
5.2.1	To design four types of BLDC motor using permeance analysis method (PAM) and finite element method (FEM) for HVLS fan application	215
5.2.2	To analyse electromagnetic properties of HVLS fan application	215
5.2.3	To verify PAM and FEM with measurement result of designed hollow rotor for HVLS fan	216

5.3	Significant contribution of research output	217
5.4	Recommendation for future work	217
REFERENCES		219
APPENDICES		249



LIST OF TABLES

TABLE	TITLE	PAGE
1.1	Comparison of cost for conventional ventilation and HVLS fan	5
1.2	Research Gap and Contribution	10
1.3	Comparison of motor performance parameter between Literature Review (LR) and desired requirement by Suria Giant Services (SGS)	11
2.1	Reviewed model on flux barrier	62
2.2	Selected BLDC motor from other researcher studies	64
2.3	Selected HVLS fan motor from industry	65
2.4	The states of inverter IGBT related to Hall Effect sensor	76
2.5	The different between commutations	80
2.6	Quantitative result ; Data gathered from 10 industries that sell HVLS fan	81
2.7	Qualitative result ; Study on low speed motor	81
3.1	Permeance equation for different model (Deshpande et al., 1995; Zhu et al., 2005)	87
3.2	Permeance equation for different configuration of poles (continue)	88
3.3	Fixed parameter for HVLS motor	91
3.4	HVLS motor unknown parameter	91
3.5	HVLS motor Fixed Parameters	108
3.6	Mesh material configurations for HVLS motor	116
3.7	Fundamental winding factor for different slot and pole combinations	121
3.8	HVLS motor coil arrangements	124

3.9	Specifications of variable HVLS motor parameter	131
3.10	Winding connection	138
4.1	HVLS motor parameter based on PAM modeling for different types of rotor designs	152
4.2	Specifications of variable HVLS motor parameter	154
4.4	HVLS motor magnetic flux	181
4.5	HVLS motor flux linkage and back emf	182



LIST OF FIGURES

FIGURE	TITLE	PAGE
1.1	HVLS Fan	9
	(a) HVLS component (b) Proposed solution	
2.1	HVLS fan that been used in various places	15
2.2	Market demand of HVLS fan	17
	(a) Power of the motor over total hanging weight of HVLS fan (b) Speed of the motor over total hanging weight of HVLS fan	
2.3	Flux density of 30 W BLDC hub motor by Rajagopal (2007)	23
	(a) Flux density of proposed model (b) Parametric analysis	
2.4	Improve BLDC motor design by Liu (2009)	23
2.5	Two cogging torque reduction technique by Saxena (2015)	25
	(a) Variation of air gap in stator tooth (b) Magnet skewing	
2.6	Design parameters of BLDC motor by Zulkarnain (2016)	26
2.7	Geometry of FSCW PMSM with CP rotor by Chung (2012)	29
2.8	Magnet core combination of BLDC motor by Nakamura (2012)	30
2.9	Schematic diagram of a single hybrid rotor by Jiu (2019)	31
2.10	Radial section of Low speed and high torque dual Permanentmagnet motor by Zhang (2020)	32
2.11	Axial excited hybrid reluctance motor structure by Qianfan (2007)	33
2.12	Magnet combination and CMMF motor model by Shigeta (2010)	34

2.13	Machine configuration of IPM motor by Wang (2021)	35
	(a) IPM (b) FI-PM (c) Parametric structure of FI-PM motor	
2.14	Spherical induction motor by Fernandez (2016) in an electrical wheelchair	38
2.15	DC brushed motor structure	39
2.16	BDC motor configuration	39
2.17	Rotor shaped optimisation of IPM motor by Hur and Kim (2010)	42
	(a) Stator (b) Rotor	
2.18	Low noise external BLDC Andres (2002)	43
2.19	IPM BLDC by Hong Seok Kim et al. (2017)	44
	(a) Configuration of IPM BLDC (b) Notch shape of the rotor	
	(c) Chamfer shape of the stator teeth	
2.20	A hollow shaft PMSM by Zingerli and Kolar (2012)	45
2.21	Neodymium free spoke type motor by Rahman (2014)	46
2.22	Flux barrier demagnetisation endurance in BLDC Motor by Kim (2014)	47
2.23	Spoke type BLDC motors with high power density by Lee (2004)	48
2.24	Embedded rotor	49
	(a) Embedded rotor motor model	
	(b) Embedded motor PM configuration	
2.25	Surface mount rotor	51
	(a) Surface mount motor model	
	(b) Surface mount motor PM configuration	
2.26	Spoke rotor	53
	(a) Spoke rotor motor model	
	(b) Spoke rotor PM configuration	
2.27	Hollow rotor	54
	(a) Hollow rotor	
	(b) Hollow rotor	

	motor model	PM configuration	
2.28	BLDC motor equivalent circuit		56
2.29	Magnetic circuit model		57
2.30	2D mesh		66
2.31	Configuration of cylindrical shape permeance		69
2.32	Magnetic equivalent circuits		71
	(a) Series connection	(b) Parallel connection	
2.33	Permeance area configurations		72
	(a) Series	(b) Parallel	
2.34	Position of Hall Effect Sensor		73
2.35	Stator phase voltage and current wave's indication the converter conducting devices		75
2.36	Six step driver basic		76
	(a) Hall sensor phase voltage wave form	(b) Three phase inverter	
2.37	Rotating magnetic field produced by three-phase current in a three-pole synchronous motor		78
2.38	Structure of Torque Hysteresis Controller (THC) drive for Brushless DC (BLDC) Motor		79
3.1	Overall research methodology		84
3.2	Flowchart of hollow rotor modelling using PAM		89
3.3	Flux flow and permeance model for hollow rotor		91
3.4	Permeance consideration dimension for hollow rotor		92
3.5	Magnetic equivalent circuit of hollow rotor		92
	(a) Non simplified	(b) Simplified	
3.6	Flux flow and permeance model for spoke rotor		95
3.7	Permeance consideration dimension for spoke rotor		95

3.8	Magnetic equivalent circuit of spoke rotor	95
	(a) Non-simplified (b) Simplified	
3.9	Flux flow and permeance model for embedded rotor	98
3.10	Permeance consideration dimension for embedded rotor	98
3.11	Magnetic equivalent circuit of embedded rotor	98
	(a) Non simplified (b) Simplified	
3.12	Flux flow and permeance model for surface mount rotor	101
3.13	Permeance consideration dimension for surface mount rotor	101
3.14	Magnetic equivalent circuit of surface mount rotor	101
	(a) Non simplified (b) Simplified	
3.15	Hysteresis loop for a magnetic material	104
3.16	B-H curve and operating point of permanent magnet	105
3.17	Sizing parameter of HVLS motor	108
	(a) Hollow rotor (b) Spoke rotor	
	(b) Embedded rotor (d) Surface mount rotor	
3.18	FEM modelling	112
3.19	Flowchart of hollow rotor structure modelling for ANSYS	113
3.20	Stator modelling process in Solidwork	114
	(a) Sketch of stator (b) Stator feature created	
3.21	HVLS complete assembly model	114
	(a) Hollow rotor (b) Spoke rotor	
	(c) Embedded rotor (d) Surface mount rotor	
3.22	The mesh generated in HVLS motor	116
	(a) Hollow rotor (b) Spoke rotor	

	(d) Embedded rotor	(d) Surface mount rotor	
3.23	Flux distribution of surface mount rotor at no load condition		119
	(a) Flux lines of hollow rotor	(b) Flux density of hollow rotor	
	(c) Flux lines of spoke rotor	(d) Flux density of spoke rotor	
	(e) Flux line of embedded rotor	(f) Flux density of embedded rotor	
	(g) Flux line of surface mount rotor	(h) Flux density of surface mount rotor	
3.24	B-H curve of M250-35A silicon steel		120
3.25	Coil vectors of HVLS motor in mechanical degree		123
3.26	Coil vectors and winding arrangement of HVLS		125
	(a) Coil vectors in electrical degree	(b) Group of coil vectors	
3.27	Winding arrangement of HVLS motor		127
3.28	Winding arrangement of HVLS motor		127
	(a) Phase A		
	(b) Phase B		
	(c) Phase C		
3.29	Final winding arrangement of HVLS motor		128
3.30	Coil consideration area between the slots for HVLS motor		129
3.31	HVLS rotor magnet arrangement		130
	(a) Hollow rotor	(b) Spoke rotor	
	(c) Embedded rotor	(d) Surface mount rotor	
3.32	Flowchart of hollow rotor prototype fabrication and assembly		133
3.33	Flowchart for overall measurement setup		136

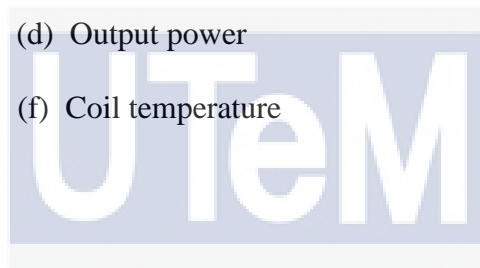
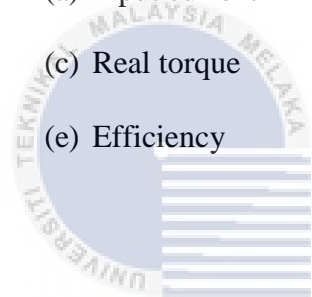
3.34	Equipment setup for static and cogging torque measurement	137
3.35	Connection diagram	138
	(a) Winding_1	
	(b) Winding_2	
	(c) Winding_3	
3.36	Construction of hollow rotor	139
3.37	Actual measurement setup for static and cogging torque experiment	139
3.38	Flowchart for electromagnetic measurement	140
3.39	Measurement setup for dynamic characteristic	142
	(a) Equipment setup for torque and speed measurement	
	(b) Actual setup for torque and speed measurement	
3.40	Flowchart for torque speed measurement setup	143
3.41	Matlab simulink of synchronous commutation	145
3.42	Synchronous commutation controller Dspace	146
3.44	Basic commutation controller Dspace	147
3.46	Torque Hysteresis Controller using Dspace	149
4.1	Basic structure of HVLS motor	153
4.2	Simulation results for hollow rotor design during no load condition	156
	(a) Back emf	(b) Cogging torque
	(c) Flux linkage	(d) Inductance
4.3	Simulation results for hollow rotor design during loaded condition	156
	(a) Stator flux density	(b) Torque
4.4	Simulation results for spoke rotor design during no load condition	159
	(a) Back emf	(b) Cogging torque

	(c) Flux linkage	(d) Inductance	
4.5	Simulation result for spoke rotor design during loaded condition		159
	(a) Stator flux density	(b) Torque	
4.6	Simulation results for embedded rotor design during no load condition		162
	(a) Back emf	(b) Cogging torque	
	(c) Flux linkage	(d) Inductance	
4.7	Simulation results for embedded rotor design during loaded condition		162
	(a) Stator flux density	(b) Torque	
4.8	Simulation results for surface mount rotor design during no load condition		164
	(a) Back emf	(b) Cogging torque	
	(c) Flux linkage	(d) Inductance	
4.9	Simulation results for surface mount rotor design during loaded condition		164
	(a) Stator flux density	(b) Torque	
4.10	Comparison of simulation results for different type of rotor designs during no load (50 turns)		168
	(b) Back emf	(b) Cogging torque	
	(c) Flux linkage	(d) Inductance	
4.11	Comparison of simulation results for different type of rotor designs during load (50 turns)		168
	(a) Stator flux density	(b) Torque	
4.12	Comparison of simulation results for different types of rotor designs during no load (100 turns)		171
	(d) Back emf	(b) Cogging torque	
	(c) Flux linkage	(d) Inductance	
4.13	Comparison of simulation results for different type of rotor designs during load (100 turns)		171

	(a) Stator flux density	(b) Torque	
4.14	Comparison of simulation results for different type of rotor designs during no load (150 turns)		174
	(a) Back emf	(b) Cogging torque	
	(c) Flux linkage	(d) Inductance	
4.15	Comparison of simulation results for different type of rotor designs during load load (150 turns)		174
	(a) Stator flux density	(b) Torque	
4.16	Comparison of simulation results for different type of rotor designs during no load (200 turns)		177
	(a) Back emf	(b) Cogging torque	
	(c) Flux linkage	(d) Inductance	
4.17	Comparison of simulation results for different type of rotor designs during load (200 turns)		177
	(a) Stator flux density	(b) Torque	
4.18	Example of FEM analysis (Hollow rotor)		180
	(a) Back emf	(b) Cogging torque	
	(c) Flux linkage	(d) Inductance	
	(e) Stator flux density	(f) Torque	
4.19	Comparison of PAM and FEM for hollow rotor		184
	(a) Flux linkage	(b) Back emf	
4.20	Comparison of PAM and FEM for spoke rotor		185
	(a) Flux linkage	(b) Back emf	
4.21	Comparison of PAM and FEM for embedded rotor		186
	(a) Flux linkage	(b) Back emf	
4.22	Comparison of PAM and FEM for surface mount		187
	(a) Flux linkage	(b) Back emf	

4.23	Flux leakage distribution for different of HVLS rotor designs	188
	(a) Hollow rotor (b) Spoke rotor	
	(c) Embedded rotor (d) Surface mount rotor	
4.24	Complete assembly of hollow rotor development	190
	(a) Exploded view	
	(b) Cross sectional view (c) Full assembly view	
4.25	Stator fabrication and assembly process	191
	(a) Pieces of laminated steel (b) Compressed of stator	
4.26	Rotor of the hollow rotor	192
	(a) Pieces of laminated steel (b) Rotor slotted bracket	
	(c) Rotor assemble	
4.27	Completed winding of stator hollow rotor	194
4.28	Complete assemble of hollow rotor	195
	(a) Front view (b) Back view	
4.29	Result of maximum back emf by FEM, PAM and measurement	197
	(a) Back emf at 100 rpm	
	(b) Back emf during different operating speed	
4.30	Result of cogging torque and static torque	199
	(a) Cogging torque	
	(b) Static torque at 2 A	
4.31	The experimental result of synchronous commutation at 15 Hz	201
	(a) Input current (b) Input power	
	(c) Real torque (d) Output power	
	(e) Efficiency (f) Coil temperature	

4.32	The experimental result of synchronous commutation at 17 Hz	203
	(a) Input current (b) Input power	
	(c) Real torque (d) Output power	
	(e) Efficiency (f) Coil temperature	
4.33	The experimental result of basic commutation	205
	(b) Input current (b) Input power	
	(d) Real torque (d) Output power	
	(e) Efficiency (f) Coil temperature	
4.34	The experimental result of THC	207
	(a) Input current (b) Input power	
	(c) Real torque (d) Output power	
	(e) Efficiency (f) Coil temperature	



اونيورسيتي تيكنيكل مليسيا ملاك

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Hollow rotor technical drawing	249
B	HVLS Fan specification from Suria Giant	259
C	Equation for percentage different %	260
D	Matlab Simulink figure	260
E	Ceiling fan price in Malaysia	261

