

EFFICIENCY OPTIMIZATION OF AN INDUCTION MACHINE USING  
CONSTANT OPTIMAL FLUX CONTROL

NOR KHAIRUNNISA BINTI SIDEK

UNIVERSITI TEKNOLOGI MALAYSIA

EFFICIENCY OPTIMIZATION OF AN INDUCTION MACHINE USING  
CONSTANT OPTIMAL FLUX CONTROL

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requirements for the award of the degree of  
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*This thesis is dedicated to*

My beloved parents, Hj. Sidek bin Jaffar and Hjh. Raja Rohayah binti Raja Abu Bakar

and

all my siblings

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## ABSTRACT

This thesis presents a simulation study of efficiency optimization on Variable-Speed Induction Machine (VSIM) using Constant Optimal Flux (COF) control technique using Matlab/Simulink software. The study covers both motoring and generating modes of a 1.1kW Squirrel-Cage Induction Machine (SCIM) to improve the entire system performance that uses constant  $V/f$  Scalar Control (SC) method. SC method is the pioneer of controlling variable speed IM, thus, it is widely used in most of the IMs applications. However, due to discovery of modern and high performance with complex design of VSIM controllers, the SC method is getting less attention in research and development field of controlling IM. Therefore, in this study, the COF control strategy is proposed to improve the efficiency of conventional SC method to the optimum level by providing optimal flux to the IM. The optimal flux is obtained by implementing the Loss Model based control technique as it could reduce the copper power loss for each of operating speed along the operation. To ensure that the optimal flux has high capability to improve the performance of IM, an approach called as Maximum Torque per Ampere is adapted to ensure that the torque capability of the machine is maximized during the operation. From the simulation results obtained in the study, the proposed COF control technique indicates satisfactory results over the conventional constant  $V/f$  in open-loop and closed-loop SC systems with better dynamic response under transient and steady-state conditions. The findings also show that for the proposed COF control strategy, power loss is successfully reduced and it improves the efficiency of IM in both motoring and generating conditions. Besides, the findings also indicate that the proposed control strategy provides a significant power saving during the high speed operating range. As the implication, a simple design and higher efficiency of SC technique has been developed in order to improve the effectiveness of the existing conventional constant  $V/f$  SC method.

## ABSTRAK

Tesis ini mempersembahkan kajian simulasi untuk pengoptimuman kecekapan Mesin Induksi Kelajuan-Boleh-Ubah (VSIM) menggunakan teknik kawalan Fluks Optimum secara Tetap (COF) menggunakan perisian Matlab/Simulink. Kajian ini meliputi kedua-dua mod iaitu permotoran dan penjanaan sebuah 1.1kW Mesin Induksi (IM) jenis Sangkar Tupai (SCIM) dalam meningkatkan prestasi seluruh sistem menggunakan kaedah Kawalan Skalar (SC) secara nisbah tetap  $V/f$ . Kaedah SC adalah perintis dalam mengawal IM, oleh itu, ia diguna secara meluas dalam kebanyakan aplikasi IM. Walau bagaimanapun, disebabkan oleh penemuan teknik kawalan yang moden dan bercekapan tinggi bersama rekaan teknik kawalan VSIM yang kompleks, kaedah SC semakin kurang mendapat perhatian dalam penyelidikan dan pembangunan bidang teknik kawalan IM. Oleh itu, di dalam kajian ini, teknik kawalan COF telah dicadangkan untuk meningkatkan kecekapan IM ke peringkat yang optimum dengan keupayaan untuk menyediakan fluks yang optimum kepada IM. Fluks yang optimum didapati dengan melaksanakan teknik Model Kawalan Kehilangan Kuasa disebabkan ia berupaya mengurangkan kehilangan kuasa tembaga untuk setiap kelajuan sepanjang operasi. Untuk memastikan bahawa fluks yang optimum tersebut mempunyai keupayaan yang tinggi untuk meningkatkan prestasi IM, satu pendekatan dipanggil Maximum Daya Kilas pada setiap Ampere diadaptasi untuk memastikan bahawa keupayaan daya kilas adalah maximum sepanjang operasi. Daripada keputusan hasil simulasi di dalam kajian ini, teknik kawalan COF yang dicadangkan menunjukkan keputusan yang memberangsangkan berbanding teknik kawalan konvensional secara nisbah tetap  $V/f$  di dalam sistem Kawalan Skalar Gelung-Terbuka dan Kawalan Skalar Gelung-Tertutup dengan menunjukkan prestasi tindak balas dinamik yang lebih baik pada keadaan fana dan stabil. Hasil dapatan juga menunjukkan bahawa dengan kaedah kawalan COF yang dicadangkan, kehilangan kuasa berjaya dikurangkan dan kecekapan kedua-dua mod permotoran dan penjanaan dapat ditingkatkan. Selain itu, hasil dapatan juga menunjukkan kaedah strategi kawalan yang dicadangkan menghasilkan penjimatan kuasa yang ketara ketika berada pada kelajuan yang tinggi. Sebagai implikasi, satu rekaan yang mudah dan teknik kawalan SC yang lebih cekap telah dihasilkan untuk meningkatkan keberkesanan kaedah kawalan konvensional secara nisbah tetap  $V/f$  yang telah sedia ada.

## TABLE OF CONTENTS

<b>CHAPTER</b>	<b>TITLE</b>	<b>PAGE</b>
	<b>DECLARATION</b>	ii
	<b>DEDICATION</b>	iii
	<b>ACKNOWLEDGMENT</b>	iv
	<b>ABSTRACT</b>	v
	<b>ABSTRAK</b>	vi
	<b>TABLE OF CONTENTS</b>	vii
	<b>LIST OF TABLES</b>	x
	<b>LIST OF FIGURES</b>	xii
	<b>LIST OF SYMBOLS</b>	xiv
	<b>LIST OF ABBREVIATIONS</b>	xvii
	<b>LIST OF APPENDICES</b>	xix
 <b>1</b>	 <b>INTRODUCTION</b>	
	1.1 Background of Study	1
	1.2 Problem Statement	3
	1.3 Objectives of Study	3
	1.4 Scope of Study	4
	1.5 Major Contribution of Study	4
	1.5 Thesis Outline	5
 <b>2</b>	 <b>LITERATURE REVIEW</b>	
	2.1 Introduction to Squirrel-Cage Induction Machine (SCIM)	6

	2.1.1	Dynamic Equations of SCIM in d-q Frames	12
	2.2	Induction Machine (IM) Scalar based Control	17
	2.3	Efficiency Optimization of IMs using Type 1	18
	2.3.1	Maximum Torque per Ampere (MTA)	19
	2.3.2	Field Weakening (FW) and Maximum Torque per Ampere (MTV)	20
	2.4	Efficiency Optimization of IMs using Type 2	22
	2.4.1	Displacement Power Factor (DPF)	23
	2.4.2	Search Control Algorithm (SCA)	24
	2.4.3	Loss Model based Control (LMC)	25
	2.5	Summary of the IM's Efficiency Optimization Approaches	27
	2.6	Summary	29
<b>3</b>		<b>MODEL DEVELOPMENT OF SCIM AND CONVENTIONAL CONSTANT V/F SCALAR CONTROLS</b>	
	3.1	Introduction	30
	3.2	Modelling Framework	32
	3.3	Direct Supply Model	34
	3.3.1	“Voltage supply block”	34
	3.3.2	“Primary Supply Block”	35
	3.4	Model Development of SCIM Model	37
	3.4.1	“Unit vector block”	39
	3.4.2	“3-to-2 phase block”	39
	3.4.3	“SCIM d-q model”	40
	3.4.4	“2-to-3 phase model”	44
	3.5	The Conventional Constant V/f Control Method	45
	3.5.1	Open-Loop Scalar Control (OLSC)	47
	3.5.1.1	The Development of OLSC Simulink Model	48
	3.5.2	Closed-Loop Scalar Control (CLSC)	53
	3.5.2.1	The Development of CLSC Simulink Model	54
	3.5.2.2	PI Controller Tuning Method	56
	3.6	Summary	60



<b>4</b>	<b>THE PROPOSED COF CONTROL STRATEGY AND PERFORMANCE ASSESSMENT</b>	
4.1	Introduction	61
4.2	Description of the Proposed COF Control Strategy	62
4.3	Implementation of LMC Technique	63
4.4	Adaption of MTA Approach	68
4.5	Model Development of COF Control Model	73
4.6	Performance Measure	76
	4.6.1 Starting Behaviour	77
	4.6.2 Performance	77
	4.6.2.1 Power Losses Reduction	78
	4.6.2.2 Efficiency Evaluation	79
	4.6.2.3 Power Saving	80
	4.6.3 Operation Modes	81
4.7	Summary	82
<b>5</b>	<b>SIMULATION RESULTS AND DISCUSSIONS</b>	
5.1	Introduction	83
5.2	Results for tuning PI controller in CLSC System	84
5.3	Starting Behavior	89
5.4	Performance of the Proposed COF Control Strategy	95
	5.4.1 Motoring Condition	96
	5.4.2 Generating Condition	101
	5.4.3 Power Loss	106
	5.4.4 Efficiency	108
	5.4.5 Potential of Power Saving	111
5.5	Summary	112
<b>6</b>	<b>CONCLUSIONS &amp; RECOMMENDATIONS</b>	
6.1	Introduction	114
6.2	Conclusions	114
6.3	Recommendations	116
	<b>REFERENCES</b>	117
	Appendices A-D	122-129

## LIST OF TABLES

TABLES NO.	TITLE	PAGE
2.1	The summary of reviewed loss minimization techniques.	28
3.1	The parameters of 1.1kW SCIM [37].	33
3.2	The information of Look-up Table.	51
3.3	The determination of gain in PI controller.	57
3.4	Effects of retuning the parameter independently using Visual Loop tuning rules [44].	59
5.1	Tuning the Proportional gain, $K_p$ for PI controller.	86
5.2	The $P_{critical}$ and $\tau_{critical}$ values.	86
5.3	The PI controller gains using Ziegler-Nichols tuning method.	87
5.4	The PI controller gains After Tuning (AT) using Ziegler-Nichols method.	88
5.5	The PI controller gains before and after retuning process using Visual Loop tuning rules.	88
5.6	The transient response before and after retuning the PI controller gains using Visual Loop tuning rules.	89
5.7	The initial stator current, $I_s$ and the terminal voltage, $ V $ values of the proposed COF system.	92
5.8	The value of line resistance, $R_c$ in “primary supply block”.	93

5.9	The dynamic performance of OLSC, CLSC and the proposed COF system during starting condition: stator current.	94
5.10	The dynamic performance of OLSC, CLSC and the proposed COF system during starting condition: electromagnetic torque.	95
5.11	The dynamic performance of SCIM model in form of rotor speed, $\omega_r$ during motoring condition.	98
5.12	The dynamic performance of SCIM model in form of electromagnetic torque, during motoring condition.	99
5.13	The dynamic performance of SCIM model in form of stator current, during motoring condition.	100
5.14	The dynamic performance of SCIM model in form of rotor speed, during generating condition.	104
5.15	The dynamic performance of SCIM model in form of electromagnetic torque, $T_e$ during generating condition.	105
5.16	The dynamic performance of SCIM model in form of stator current, during generating condition.	106
5.17	The efficiency for OLSC, CLSC and the proposed COF system.	108

## LIST OF FIGURES

FIGURES NO.	TITLE	PAGE
1.1	Loss distributions for 4-poles 0.75kW IM [3].	3
2.1	Assembly construction of typical AC induction motor [10].	8
2.2	The equivalent circuit of ideal transformer [11].	9
2.3	The per-phase equivalent circuit of an IM [11].	9
2.4	Torque-speed curve of induction machine [11].	12
2.5	The stationary frame $as-bs-cs$ to $ds-qs$ axes transformation [11].	13
2.6	Dynamic $de-qe$ equivalent circuit of 2-phase stationary frames (a) q-axis (b) d-axis [11].	15
2.7	The optimization techniques.	18
3.1	Study milestones.	31
3.2	Modelling work.	32
3.3	The complete simulation model of SCIM.	33
3.4	Simulink model of the “voltage supply block”.	35
3.5	Simulink model of the “primary supply block”.	37
3.6	The complete simulation model of the developed SCIM model.	38
3.7	Simulink model of the “unit vectors block”.	39

3.8	Simulink model of the “3-to-2 phase block”.	40
3.9	Simulink model of the configuration inside the “SCIM d-q model block”.	41
3.10	Simulink model of the configuration inside Column 1.	42
3.11	Simulink model of the configuration inside column 2.	42
3.12	Simulink model for Column 3.	43
3.13	Simulink model for Column 4.	43
3.14	Simulink model for Column 5.	44
3.15	Simulink model of the “2-to-3 phase block”.	45
3.16	Constant $V/f$ ratio profile.	46
3.17	Torque-speed curve of tested 1.1kW SCIM with constant $V/f$ control.	47
3.18	Open-loop with constant $V/f$ ratio SC system.	48
3.19	The schematic diagram of OLSC system in Simulink model.	49
3.20	The complete Simulink model of OLSC system.	50
3.21	The “open loop constant $V/f$ control block” in OLSC system.	51
3.22	Simulink model of the “calculate dynamic $i_s$ block”.	52
3.23	Simulink model of the “calculate $I_r$ block”.	52
3.24	Closed-loop with constant $V/f$ ratio SC system.	53
3.25	The schematic diagram of CLSC system.	54
3.26	The complete Simulink model of CLSC system.	55
3.27	The “closed-loop constant $V/f$ control block” in CLSC system.	56
3.28	The determination of critical-oscillation, $\tau_{critical}$ .	57
3.29	Tuning rules of PI controller using Ziegler-Nichols method.	58

4.1	The proposed COF system.	62
4.2	Implementation of LMC technique in the proposed work.	64
4.3	Total copper power loss, $P_{copper}$ as function of synchronous speed, $\omega_e$ under various selections of $V/f$ ratio at $\omega_r = 100$ rad/s and $T_e = 2.9$ Nm.	67
4.4	The plots of optimal $V/f$ ratios at each of operating speeds from (a) the proposed COF control strategy (b) the previous work in [37].	72
4.5	The schematic diagram of the proposed COF control strategy.	73
4.6	The complete Simulink model of COF system.	75
4.7	The “COF controller block” in COF system.	76
4.8	The SCIM simulation model with performance evaluation blocks.	77
4.9	Simulink model of “ $P_{copper}$ block”.	78
4.10	Simulink model of “(total) block”.	79
4.11	Simulink model of “ $P_{in}$ block”.	80
4.12	Simulink model of “Efficiency block”.	80
4.13	Torque-speed curve of (a) the developed 1.1 kW SCIM (b) NEMA classification of IMs [11].	81
5.1	The input of reference operating speed, $\omega_{r(ref)}$ .	84
5.2	The rotor speed, $\omega_r$ response of CLSC system after tuning the PI controller gains using Ziegler-Nichols method.	87
5.3	The rotor speed, $\omega_r$ response of CLSC system after retuning the PI controller gains using Visual Loop tuning rules.	89
5.4	The stator current, $I_s$ response of OLSC and CLSC systems during the starting condition.	90
5.5	The electromagnetic torque, $T_e$ response of OLSC and CLSC systems during the starting condition.	91

5.6	The stator voltage, $V_s$ supplied from “COF control block”	92
5.7	The stator current, $I_s$ response of OLSC, CLSC and the proposed COF system during the starting condition.	93
5.8	The electromagnetic torque, $T_e$ response of OLSC, CLSC and the proposed COF system during the starting condition.	94
5.9	The input variables profile for motoring mode (a) reference operating speed, ( $ref$ ) and (b) load torque, $T_{load}$ .	96
5.10	Results of rotor speed, for motoring condition dynamic response.	97
5.11	Results of electromagnetic torque, for motoring condition dynamic response.	99
5.12	Results of stator current, for motoring condition dynamic response.	100
5.13	The input variables profile for motoring mode (a) reference operating speed, ( $ref$ ) (b) load torque, $T_{load}$ .	102
5.14	Results of rotor speed, for generating condition dynamic response.	103
5.15	Results of generator torque, for generating condition dynamic response.	104
5.16	Results of stator current, for generating condition dynamic response.	105
5.17	The amount of power loss reduced by each control methods.	107
5.18	The graph of efficiency, $\eta$ against reference operating speeds, ( $ref$ ) for (a) results from this study and (b) efficiency improvement from the previous work [37].	109
5.19	The graph of power saved against reference operating speed, ( $ref$ ).	112

## LIST OF SYMBOLS

$V_s$	-	Supply voltage
$R_s$	-	Stator resistor
$R_r$	-	Rotor resistor
$L_s$	-	Stator inductor
$L_r$	-	Rotor inductor
$L_m$	-	Mutual inductor
$I_s$	-	Stator current
$I_r$	-	Rotor current
$X_s$	-	Stator impedance
$X_r$	-	Rotor impedance
$X_m$	-	Magnetizing impedance
$V/f$	-	Ratio of voltage over frequency
$s$	-	Slip
$\omega_e$	-	Synchronous frequency
$\omega_r$	-	Rotor frequency
$\omega_m$	-	Mechanical frequency
$\omega_{sl}$	-	Slip frequency
$P_{in}$	-	Input power
$\cos \emptyset$	-	Power factor
$P_{out}$	-	Output power
$T_e$	-	Electromagnetic torque
$P$	-	Number of poles
$v_{qs}$	-	q-axis stator voltage
$v_{ds}$	-	d-axis stator voltage
$v_{qr}$	-	q-axis rotor voltage



$v_{dr}$	-	d-axis rotor voltage
$\Psi_{qs}$	-	q-axis stator flux linkage
$\Psi_{ds}$	-	d-axis stator flux linkage
$\Psi_{qr}$	-	q-axis rotor flux linkage
$\Psi_{dr}$	-	d-axis rotor flux linkage
$\Psi_{mq}$	-	q-axis magnetizing flux linkage
$\Psi_{md}$	-	d-axis magnetizing flux linkage
$i_{qs}$	-	q-axis stator current
$i_{ds}$	-	d-axis stator current
$i_{qr}$	-	q-axis rotor current
$i_{dr}$	-	d-axis rotor current
$L_{ls}$	-	Stator leakage reactance
$L_{lr}$	-	Rotor leakage reactance
$T_{load}$	-	Load torque
$J$	-	Moment of inertia
$V_{as}$	-	Stator voltage of phase-a
$V_{bs}$	-	Stator voltage of phase-b
$V_{cs}$	-	Stator voltage of phase-c
$V_{ao}$	-	Stator voltage of line-a
$V_{bo}$	-	Stator voltage of line-b
$V_{co}$	-	Stator voltage of line-c
$\theta_e$	-	Supply phase angle
$v_{qs}^s$	-	q-axis of stator voltage in stationary frame
$v_{ds}^s$	-	d-axis of stator voltage in stationary frame
$i_{qs}^s$	-	q-axis of stator current in stationary frame
$i_{ds}^s$	-	d-axis of stator current in stationary frame
$i_{as}$	-	Stator current of phase-a
$i_{bs}$	-	Stator current of phase-b
$i_{cs}$	-	Stator current of phase-c
$f$	-	Frequency
$\Psi_s$	-	Magnetic flux in stator
$\xi$	-	Constant of coil

$T$	-	Torque
$P_m$	-	Mechanical power
$P_g$	-	Generated power
$i_s$	-	Dynamic stator current
$\omega_{r(ref)}$	-	Reference operating speed
$K_p$	-	Proportional gain
$K_i$	-	Integral gain
$P_{critical}$	-	Critical value of $K_p$
$\tau_{critical}$	-	Critical value of $K_i$
$P_{copper}$	-	Copper power
$ V $	-	Amplitude of terminal voltage
$R_c$	-	Line resistance
$Z_{in}$	-	Input impedance
$P_{air-gap}$	-	Air-gap power
$\omega_{r\_mot(rated)}$	-	Rated speed for motoring mode
$\omega_{r\_gen(rated)}$	-	Rated speed for generating mode
$\omega_{e(rated)}$	-	Rated synchronous speed
$T_{load}$	-	Load torque
$T_{e(rated)}$	-	Rated torque
$T_{g(rated)}$	-	Rated torque for generating mode
$ V $	-	Terminal voltage
$\eta$	-	Efficiency

**LIST OF ABBREVIATIONS**

AC	-	Alternating Current
CLSC	-	Closed-Loop Scalar Control
DPF	-	Displacement Power factor
DTC	-	Direct-Torque Control
FOC	-	Field-Oriented Control
FW	-	Field Weakening
Hp	-	Horse Power
IEC	-	International Efficiency Classes
IG	-	Induction Generator
IM	-	Induction Machine
LMC	-	Loss Model based Control
ME	-	Maximum Efficiency
MPF	-	Maximum Power Factor
MTA	-	Maximum Torque per Ampere
MTV	-	Maximum Torque per Voltage
NEMA	-	National Electrical Manufacturers Association
OLSC	-	Open-Loop Scalar Control
PI	-	Proportional-Integral
RLOC	-	Reduced Losses Operating Condition
SC	-	Scalar Control
SCIM	-	Squirrel-Cage Induction Machine

SCIG	-	Squirrel-Cage Induction Generator
SVM-VSI	-	Space Vector Modulation- Voltage Source Inverter
VSD	-	Variable-Speed Drive
RFO	-	Rotor Flux-Oriented
SFO	-	Stator Flux-Oriented
COF	-	Constant Optimal Flux
SCA	-	Search Control Algorithm

**LIST OF APPENDICES**

<b>APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
A	Matlab/Script Codes for Constant $V/f$ Torque-speed Characteristic.	118
B	Matlab/Script Codes for Total Power Loss Curve.	120
C	Matlab/Script Codes the proposed 1.1kW SCIM Torque-speed Curve.	123

## **CHAPTER 1**

### **INTRODUCTION**

#### **1.1 Background of Study**

In early design of an induction machine (IM), the cost for the operational of an electric power plant is very expensive. For instance, in the late of 1880s, electric company needs to spend around 3 to 4 billion dollars to purchase IM to run the electric power plant. The company required approximately 12 to 15 years to get the payback cost [1]. Improvement in IM efficiency plays an important role in reducing the payback periods. In fact, 2% to 5% improvement of IM efficiency could provide a good return upon the investment [2]. Besides, small improvement in motor operating efficiency can produce significant cost saving and accelerates the payback time. By this reason, nowadays, the efficiency trend is mostly focused towards the efficiency and performance improvement in design and manufacturing, but with condition of a small extra cost. However, the design and manufacturing cost should be ensured must be less than the incurred cost to ensure that the improvement is still profitable [3].

To design and develop a high efficient IM with lower cost is one of the major challenges. Several strategies have been proposed and applied to produce IM with

higher efficiency, including improving steel properties, modifying slot design, increasing conductor's volume, thinner laminations, narrowing air gap and inventing more efficient controller design [4]. Using these strategies, higher efficient IM could be developed while provide significant profitable to the manufacturer and also users [5]. However, in terms of controller design, adaptive controller which is more modern, costly and complex in designs is usually involved. In such design, vector control (VC) is generally applied to increase the IM efficiency.

Efficiency of IM can be determined by calculating the ratio of output power to the amount of input power. The closer the output power to the input power, efficiency is better. Notably, loss of an IM can be determined by estimating the difference between the input and output powers. If power difference is smaller, power loss is smaller; hence efficiency of the system is better. Hence, it also can be said that the efficiency of an IM can be increased by reducing the IM losses.

In IM, losses can be classified into five categories. The five loss categories of a small size IM (0.75 kW) are shown in Figure 1.1[3]. From the figure, it is clearly shows that the primary loss which is caused by current losses in stator windings contributes a major percentage of IM losses. Current loss in rotor windings contributes 20% of the total losses meanwhile iron loss contributes just 2 % less than the rotor winding loss. The smallest loss was contributed by the load loss. From the same figure, it can be observed that stator and rotor winding losses contribute significant losses in an IM. There are two types of losses occur in stator and rotor windings; iron and copper losses. Eddy loss can be minimized by using lamination sheet. By laminating the core, area could be decreased and hence resistance of the core could be increased. Hence, this could result in decreasing the eddy currents. Hysteresis loss can be minimized by using high grade silicon steel in the core. Meanwhile, copper loss occurs due to the current flowing in the stator and rotor windings. As the load changes, the current flowing in the rotor and stator windings are also changes. Hence, copper losses also changes. It is therefore, study on reducing winding losses could be significant to be done in order to improve the overall system of IM efficiency, as one of the alternative. Reducing current losses in stator and rotor windings by implementing variable-speed drives is one of the good

options on how to improve the IM efficiency [6]. Variable-speed drive equipped with an excellent control algorithm is another choice. Operating IM in optimal flux condition also is another good option besides minimizing the IM power consumption [7].

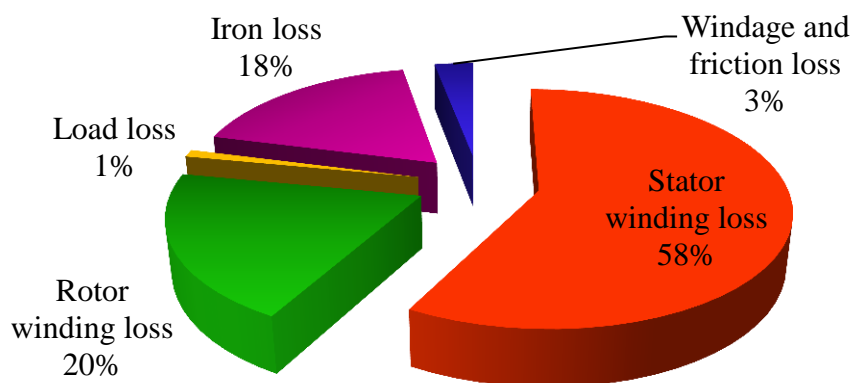


Figure 1.1 Loss distributions for 4-poles 0.75 kW IM [3].

## 1.2 Problem Statement

The constant  $V/f$  control is the most common conventional scalar based control method used in VSIM system.  $V/f$  control is also known as scalar control (SC). This is because the constant  $V/f$  control method is very reliable for maximizing the torque capability during the VSIM operation. However, by controlling the VSIM using SC approach, the losses of IM could not be reduced. Thus, the efficiency or performance of the VSIM system could not be improved. Applications of loss minimization and efficiency optimization approaches are anticipated could improve the performance of a VSIM system. Efforts on how to improve the VSIM performance using loss minimization strategies have been proposed in many works. Meanwhile, in terms of efficiency optimization, no attempt has been made when VSIM is controlled using SC approach. Presently, the efficiency optimization works were only proposed for Vector Control (VC) control approach, in which brought the control drives to a complex design.



### **1.3 Objectives of Study**

The objectives of this study are:

1. To study and develop a model of SCIM based on dynamic equations using Matlab/Simulink software.
2. To develop the Constant Optimal Flux (COF) controller to optimize the efficiency of the developed SCIM by minimizing the power losses of the machine winding.
3. To perform comparative study between the proposed COF control strategy and the conventional constant  $V/f$  control methods; in Open-Loop Scalar Control (OLSC) and Closed-Loop Scalar Control (CLSC) systems.

### **1.4 Scopes of Study**

In this research, a small size of 1.1 kW Squirrel-Cage Induction Machine (SCIM) is considered throughout this study. The scopes of the proposed works are:

1. Reducing power losses at the winding of IM only.
2. The operation of IM involves in two operation modes; motoring and generating mode.
3. The performance assessment of the comparative study includes the power loss reduction, efficiency and potential of power saving.

### **1.5 Major Contribution of Study**

The major contribution of this study is the implementation of a COF control strategy which is based on SC approach to a small size SCIM. The COF control

strategy provides flux optimization to the proposed 1.1kW SCIM whereby the optimal flux controls the stator current losses, thus reducing the copper losses at the machine windings. The overall performance of the proposed COF on the variable-speed SCIM has been proven improved. The efficiency also proven has been increased and power consumed by the SCIM to operate has been notably saved.

## **1.6 Thesis Outline**

This thesis is organized into six chapters. The organizations of the chapters are as follows:

Chapter 1 describes the background of the study which includes the problem statements, objectives, scopes and major contributions of this study. Meanwhile, Chapter 2 investigates the existing efficiency optimization techniques. It involves the efficiency improvement technique by adapting the vector control (VC) method and the procedure for loss minimization of IM. In this chapter, a compare-contrast study among the previous works is carried out.

Chapter 3 presents the methodology and process that have been undertaken during the development of a SCIM model whereby the developed model will be controlled in OLSC and CLSC systems. The first section of this chapter covers the detailed modelling of SCIM in Simulink model while the second section involves the development of the conventional OLSC and CLSC models.

In Chapter 4, an additional element to the developed SCIM dynamic model with the purpose to reduce the inrush response during the starting condition of IM is discussed. Then, the development of the proposed COF control strategy is briefly explained. The implementation of loss minimization technique and adaptation of conventional approach in increasing the efficiency of IM are also discussed in detail in this chapter.

Chapter 5 presents the performance of the proposed COF, the conventional OLSC and the conventional CLS control. Performance comparison including the performance of dynamic response for both motoring and generating conditions, power loss reduction, efficiency and potential of power saving are given in this chapter.

Lastly, in Chapter 6, conclusions of the study and several recommendations for future work are stated.

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