EFFICIENCY OPTIMIZATION OF AN INDUCTION MACHINE USING CONSTANT OPTIMAL FLUX CONTROL

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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 Maltlab/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 keupyaan 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.

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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
ω_e	-	Synchronous frequency
ω_r	-	Rotor frequency
ω_m	-	Mechanical frequency
ω_{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
Ψ_{qs}	-	q-axis stator flux linkage
Ψ_{ds}	-	d-axis stator flux linkage
Ψ_{qr}	-	q-axis rotor flux linkage
Ψ_{dr}	-	d-axis rotor flux linkage
Ψ_{mq}	-	q-axis magnetizing flux linkage
Ψ_{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
θ_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
Ψ_s	-	Magnetic flux in stator
$\boldsymbol{\xi}$	-	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
η	-	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

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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].

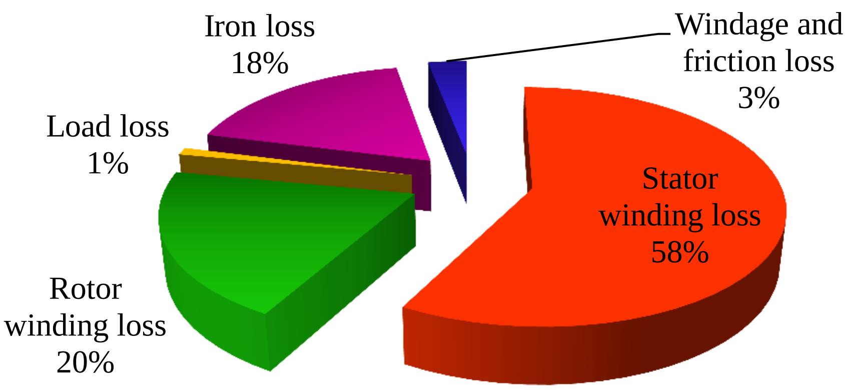

Figure 1.1 Loss distributions for 4-poles 0.75 kW IM [3].

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.

REFERENCES

[1] Bonnett, A.H., "An Update on AC Induction Motor Efficiency," *IEEE Transactions on Industry Applications*, vol. 30, no. 5, pp. 1362-1372, 1994.

[2] de Almeida, A.T., P. Bertoldi, and W. Leonhard, *Energy Efficiency Improvements In Electric Motors And Drives.* Springer Berlin, 1997.

[3] Manoharan, S., et al., "Review on efficiency improvement in squirrel cage induction motor by using DCR technology," *Journal of Electrical Engineering*, vol. 60, no. 4, pp. 227-236, 2009.

[4] Yoon, M., C. Jeon, and S.K. Kauh, "Efficiency increase of an induction motor by improving cooling performance," *IEEE Transactions on Energy Conversion*, vol. 17, no. 1, pp. 1-6, 2002.

[5] Parasiliti, F., "Design strategies, new materials and technologies to improve induction motors efficiency," *Proceedings of Electrotechnical Institute*, vol. 223, pp. 27, 2004.

[6] Wang, W.-J. and C.-C. Wang, "Speed and efficiency control of an induction motor with input-output linearization," *IEEE Transactions on Energy Conversion*, vol. 14, no. 3, pp. 373-378, 1999.

[7] Huget, E.W., "Squirrel cage induction motors-performance versus efficiency," *IEEE Transactions on Industry Applications*, no. 5, pp. 818-823, 1983

[8] Bandyopadhyay, M., *Electrical Machines: Theory and Practice*. PHI Learning Pvt. Ltd, 2007.

[9] Stephen, J., Chapman, *Electric Machinery Fundamentals.* McGraw-Hill, 1999.

[10] Vas, P., *Vector control of AC machines.* Clarendon press Oxford, 1990.

[11] Bose, B.K., *Modern power electronics and AC drives*. Prentice hall USA, vol. 712, 2002.

[12] Consoli, A., et al, "New scalar control for full speed operating range IM drives," *in IEEE International Electric Machines & Drives Conference*, pp. 170-175, 2011.

[13] Larabee, J., B. Pellegrino, and B. Flick. "Induction motor starting methods and issues," in *IEEE Petroleum and Chemical Industry Conference*, pp. 217-222, 2005.

[14] Ozpineci, B. and L.M. Tolbert. *Simulink implementation of induction machine model-a modular approach*. in *IEEE International Electric Machines and Drives Conference,* vol. 2, pp. 728-734, 2003.

[15] Andersson, L.-G. *Induction Machine Speed Control.* Master Thesis in Electronics, Mälardalen University, 2007.

[16] Kwon, C.-K., "Study on an Adaptive Maximum Torque Per Amp Control Strategy for Induction Motor Drives," *Journal of Electrical Engineering & Technology*, vol. 8, no. 1, pp. 110-117, 2013.

[17] Song, S.-H., J.-W. Choi, and S.-K. Sul. "Transient torque maximizing strategy of induction machine in field weakening region," in *IEEE Power Electronics Specialists Conference*, vol. 2, pp. 1569-1574, 1998.

[18] Wasynczuk, O., et al., "A maximum torque per ampere control strategy for induction motor drives," *IEEE Transactions on Energy Conversion*, vol. 13, no. 2, pp. 163-169, 1998.

[19] Wasynczuk, O., et al., "A maximum torque per ampere control strategy for induction motor drives," *IEEE Transactions on Energy Conversion*, vol. 13, no. 2, pp. 163-169, 1998.

[20] Metwally, H., et al., "Proposed torque optimized behavior for digital speed control of induction motors," *Energy conversion and management,* vol. 43, no. 13, pp. 1675-1688, 2002.

[21] Markadeh, G.A., et al., "Maximum torque per ampere control of sensorless induction motor drives with dc offset and parameter compensation," *Energy conversion and management*, vol. 51, no. 7, pp. 1354-1362, 2010.

[22] Consoli, A., et al., "Induction motor sensorless control based on a maximum torque per ampere approach," *in IEEE Industry Applications Conference*, vol. 3, pp. 2005-2011, 2003.

[23] Kwon, C. and S.D. Sudhoff, "An adaptive maximum torque per amp control strategy," in *IEEE International Conference of Electric Machines and Drives*, 2005, pp. 783-788.

[24] Kwon, C. and S.D. Sudhoff, "An improved maximum torque per amp control strategy for induction machine drives," *in IEEE Applied Power Electronics Conference and Exposition*, vol. 2, pp. 740-745, 2005.

[25] Consoli, A., et al., "Energy efficient sensorless scalar control for full speed operating range IM drives," in *Proceedings of Power Electronics and Applications Conference*, pp. 1-10, 2011.

[26] Kim, S.-H. and S.-K. Sul, "Maximum torque control of an induction machine in the field weakening region," *IEEE Transactions on Industry Applications*, vol. 31, no. 4, pp. 787-794, 1995.

[27] Seibel, B.J., T.M. Rowan, and R.J. Kerkman, "Field-oriented control of an induction machine in the field-weakening region with DC-link and load disturbance rejection," *IEEE Transactions on Industry Applications*, vol. 33, no. 6, pp. 1578-1584, 1997.

[28] Harnefors, L., K. Pietilainen, and L. Gertmar, "Torque-maximizing field-weakening control: design, analysis, and parameter selection," *IEEE Transactions on Industrial Electronics*, vol. 48, no. 1, pp. 161-168, 2001.

[29] Abrahamsen, F., et al., "On the energy optimized control of standard and high-efficiency induction motors in CT and HVAC applications," *IEEE Transactions on Industry Applications*, vol. 34, no. 4, pp. 822-831, 1998.

[30] Abrahamsen, F., et al., "Efficiency-optimized control of medium-size induction motor drives," *IEEE Transactions on Industry Applications*, vol. 37, no. 6, pp. 1761-1767, 2001.

[31] Kioskeridis, I. and N. Margaris, "Loss minimization in scalar-controlled induction motor drives with search controllers," *IEEE Transactions on Power Electronics*, vol. 11, no. 2, pp. 213-220, 1996.

[32] Ghozzi, S., K. Jelassi, and X. Roboam, "Energy optimization of induction motor drives," in *IEEE International Conference on Industrial Technology*, 2004, vol. 2, pp. 602-610.

[33] Shin, M.-H., "A Study on Fast Maximum Efficiency Control of Stator-Flux-oriented Induction Motor Drives," *Journal of Electrical Engineering & Technology*, vol. 6, no. 5, pp. 626-633, 2011.

[34] Kioskeridis, I. and N. Margaris, "Loss minimization in induction motor adjustable-speed drives," *IEEE Transactions on Industrial Electronics*, vol. 43, no. 1, pp. 226-231, 1996.

[35] Leidhold, R., G. Garcia, and M.I. Valla, "Field-oriented controlled induction generator with loss minimization," *IEEE Transactions on Industrial Electronics*, vol. 49, no. 1, pp. 147-156, 2002.

[36] Ibrahim, D.I., "Starting Method for Induction Motors" [Online]. Available http://uotechnology.edu.iq/depeee/lectures/3rd/Communication/machine/PAR.pdf.

[37] Cacciato, M., et al., "Efficiency optimization techniques via constant optimal slip control of induction motor drives," in *International Symposium on Power Electronics and Electrical Drives, Automation and Motion*, pp. 33-38, 2006

[38] Bonnett, A.H., "An update on AC induction motor efficiency," in *Industry Applications of Petroleum and Chemical Industry Conference, The Institute of Electrical and Electronics Engineers Incorporated. Society 40th Annual*, pp. 221-231, 1993.

[39] Chapman, S., *Electric machinery fundamentals*. Tata McGraw-Hill Education, 2005.

[40] Das, J., "Effects of momentary voltage dips on the operation of induction and synchronous motors," *IEEE Transactions on Industry Applications*, vol. 26, no. 4, pp. 711-718, 1990.

[41] Krause, P.C., et al., *Analysis of electric machinery and drive systems*. John Wiley & Sons, vol. 75. 2013.

[42] Kohlrusz, G. and D. Fodor, "Comparison of Scalar and Vector Control Strategies of Induction Motors," *Hunggarian Journal of Industrial Chemistry*, vol. 39, no. 2, pp. 265-270, 2011.

[43] Upasan, A. and Y. Kumsuwan, "Closed Loop Speed Control of Induction Generator with Scalar-control Inverters," *Energy Procedia*, vol. 34, pp. 371-381, 2013.

[44] J. Zhong, “PID Controller Tuning : A Short Tutorial,” *Mechanical Engineering, Purdue University*. [Online]. Available: http://wwwdsa.uqac.ca/~rbeguena/Systemes_Asservis/PID.pdf.

[45] Famouri, P. and J.J. Cathey., "Loss minimization control of an induction motor drive," in *IEEE Industry Applications Society Annual Meeting Conference Record*, vol. 1, pp. 226-231, 1989.

[46] Mantilla, S.C.E.R.L., "How the efficiency of induction motor is measured? " *Energy* [Online]. Available : http://www.icrepq.com/icrepq-08/352-mantilla.pdf

[47] Bazzi, A.M. and P.T. Krein, "Review of methods for real-time loss minimization in induction machines," *IEEE Transactions on Industry Applications*, vol. 46, no. 6, pp. 2319-2328, 2010.

[48] Uddin, M.N. and S.W. Nam, "New online loss-minimization-based control of an induction motor drive," *IEEE Transactions on Power Electronics*, vol. 23, no. 2, pp. 926-933, 2008.

[49] Munteanu, I., *Optimal control of wind energy systems: towards a global approach.* Springer, 2008.