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Stator flux oriented control of three-phase induction motor with improved decoupling scheme (Conference Paper)

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Abstract

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This paper proposes an improved decoupling scheme of stator flux - oriented control for three-phase induction motor . The simulation software used in this paper is MATLAB Simulink®. The result of the simulation indicates that this stator flux - oriented control can control the speed of the rotor angle and stator magnetization current successfully. The angular velocity of 120 rad/s achieved by settling time 2 seconds in critically-damped response and steady-state error 0.083%. The controller can overcome the external disturbance in the form of load torque of 5 Nm which has been simulated in this paper. The proposed stator voltage decoupling scheme which is used in this simulation is correct and become one of success factor of this control method. © 2018 IEEE.

SciVal Topic Prominence ⓘ

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Decoupling model Induction motor SFOC Stator flux model

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Foreword from General Chair EECSI 2018

Foreword General Chair

In the name of Allah, the Most Beneficent, the Most Merciful.

Welcome to the 2018 5th International Conference on Electrical Engineering, Computer Science and Informatics (EECSI 2018) in Malang, Indonesia.

The 5th EECSI 2018 is themed “Toward the Next Generation of Technology“. This conference provides academicians, researchers, professionals, and students from various engineering fields and with cross-disciplinary working or interested in the field of Electrical Engineering, Computer Science, and Informatics to share and to present their works and findings to the world.

I would like to express my highly gratitude to all participants for attending, sharing and presenting your ideas and experiences in this interesting conference. Almost 300 papers had been submitted to EECSI 2018. However, the only high quality papers are selected and accepted to be presented in this event. We are also thankful to all the international committee, international reviewers, and steering committee for their valuable support. I would like to give a praise to all partners in publications and sponsorships for their valuable supports, especially for Ministry of Research and Higher Education (Kemenristekdikti) Indonesia.

Organizing a prestigious conference was incredibly challenging and would have been impossible to be held without outstanding committees. Such that, I would like to extend my sincere appreciation to all organizing committees and volunteers from Universitas Muhammadiyah Malang as a host and all colleagues from Universitas Diponegoro, Universitas Ahmad Dahlan, Universitas Sriwijaya, Universitas Islam Sultan Agung, Universitas Gadjah Mada, Universitas Budi Luhur, Universiti Teknologi Malaysia, and IAES Indonesia Section for providing me with much needed support, advice, and assistance on all aspects of the conference. A special thanks also for IEEE Indonesia Section for their contribution as technical co-sponsorship of the conference. We do hope that this event will encourage the collaboration among us now and in the future.

We wish you all find opportunity to get rewarding technical program, intellectual inspiration, renew friendships and forge innovation, and that everyone enjoys Malang.

Assoc. Prof. DR. Tole Sutikno
General Chair EECSI 2018



Foreword from IAES Indonesia Section

Bismillahirrohmannirrahim,

In the name of Allah Al Mighty, The Most Gracious, The Most Merciful

We are pleased to welcome our colleagues in the International Conference on Electrical Engineering, Computer Science and Informatics (EECSI 2018) in Malang, City of Heritage on October 16-18th, 2018.

It must be said proudly that the EECSI has been rolled out for five times since it was firstly initiated on year 2014 in Yogyakarta. Our colleagues all over the world supporting by many tops universities have successfully organized the conference to become the prestigious international annual event in Indonesia.

A highest appreciation is addressed to The Ministry of Research, Technology and Higher Education (Kemenristekdikti) Republic of Indonesia for a worthy technical and financial support during the conference and special thanks for IEEE Indonesia Section for the technical co-sponsorship for this prominent occasion. We do hope that this event will strengthen the collaboration among us now and in the future.

This year, the achievement in this conference is due to valuable contributions from our colleagues from Universitas Muhammadiyah Malang supporting by Universitas Diponegoro, Universitas Ahmad Dahlan, Universitas Sriwijaya, Universitas Islam Sultan Agung, Universitas Gadjah Mada, Universitas Budi Luhur and Universiti Teknologi Malaysia. I would like to express my sincere gratitude and appreciation for all partners, friends, Organizing committee, reviewers, keynote speakers, and participants who have made this event as great as today.

I would also like to extend my gratitude to Rector of Universitas Muhammadiyah Malang who friendly becomes a main host for this great conference. We optimist many following collaborative works will be carried out among us and all participants.

I hope you all had a nice time at the conference where all of you are able to learn something new, renewed and created new networks and at the same time have some fun in Malang City during the conference and Mount Bromo during the cultural tour.

Thank you.



Assoc. Prof. Mochammad Facta, Ph.D
IAES – Indonesia Chapter

Foreword from Rector of Universitas Muhammadiyah Malang

The advent of the next generation of technology, renown as Technology 4.0, is unavoidably incessant. This so-called technology has offered a new horizon in various aspects of man-beings' lives. To be particular in the fields of electrical engineering, electronics, computer science, computer engineering, and informatics, Technology 4.0 plays its potent role to underpin the future advancement of technology for the coming generations. Scientific forum titled as the 2018 5th International Conference on Electrical Engineering, Computer Science, and Informatics (EECSI 2018) hosted by University of Muhammadiyah Malang in collaboration with a number of universities is the manifestation of continuous effort to aim for the ever-changing technology.

Hereby, I would like to congratulate the Faculty of Engineering, University of Muhammadiyah Malang for their effort in organizing the 2018 5th International Conference on Electrical Engineering, Computer Science, and Informatics (EECSI 2018). I appreciate all co-organizers such as Universitas Diponegoro, Universitas Ahmad Dahlan, Universitas Sriwijaya, Universitas Islam Sultan Agung, Universitas Budi Luhur, and Universiti Teknologi Malaysia for their support in this mutual collaboration. Without the full and valuable supports from the international committee, international reviewers, and steering committee, this international conference remains a detached discourse without high commitment to conduct.

The expression of my high gratitude is devoted to the Ministry of Research, Technology, and Higher Education (Kemenristekdikti) Republic of Indonesia, IEEE Indonesia Section, and IAES Indonesia Section for their support to this event as the sponsors and technical co-sponsorship, respectively. Expectantly, this would be the initial and continual collaboration in the future.

To all speakers, presenters, and participants, thank you for participating and welcome to this conference. The success of this conference owes so much on your participation and contribution in promoting the knowledge, information, and robust creativity. To end with, this conference expectedly becomes an arena to build mutual ties among the academicians, researchers, industries, and society.

All the best to EECSI 2018

Dr. H. Fauzan, M.Pd.

Rector

Universitas Muhammadiyah Malang - Indonesia



Table of Contents

2018 5th International Conference on Electrical Engineering, Computer Science and Informatics (EECSI)

<i>Optimization of Modified Sliding Mode Control for an Electro-Hydraulic Actuator System with Mismatched Disturbance</i> Mohd Fua'ad Rahmat (Universiti Teknologi Malaysia, Malaysia), Siti Marhainis Othman (University Malaysia Perlis, Malaysia), Sahazati Md Rozali (Universiti Teknikal Malaysia Melaka, Malaysia), Zulfatman Has (University of Muhammadiyah Malang, Indonesia)	1
<i>Learning Motivation increased due to a Relaxed Assessment in a Competitive-Learning Environment</i> Muhammad Said Hasibuan (University Gadjah Mada & IBI Darmajaya, Indonesia), Onno W Purbo (IBI Darmajaya & XECUREIT, Indonesia)	7
<i>Factors Affecting Users' Purchase Intention and Attitudes towards Mobile Advertising</i> Clarita Nainqqolan (Faculty of Computer Science Universitas Indonesia, Indonesia), Putu Wuri Handayani (Universitas Indonesia, Indonesia), Fatimah Azzahro (Faculty of Computer Science Universitas Indonesia, Indonesia)	11
<i>Implementation Strategy of Knowledge Management System: A Case of Air Drilling Associates</i> Siti Hadjar (Universitas Indonesia, Indonesia), Putu Wuri Handayani (Universitas Indonesia, Indonesia), Riri Satria (Universitas Indonesia, Indonesia), Ave Adriana Pinem (Universitas Indonesia, Indonesia)	17
<i>Success Factors of HRIS: A Case of Ministry of State-owned Enterprise</i> Wita Puspitarini (Universitas Indonesia, Indonesia), Putu Wuri Handayani (Universitas Indonesia, Indonesia), Ave Adriana Pinem (Universitas Indonesia, Indonesia), Fatimah Azzahro (Faculty of Computer Science Universitas Indonesia, Indonesia)	23
<i>The Utilization of Ontology to Support The Results of Association Rule Apriori</i> Dewi Wardani (Universitas Sebelas Maret, Indonesia), Achmad Khususyaini (Universitas Sebelas Maret, Indonesia)	28
<i>Determination of Router Location for Optimizing Computer Network Using Dominating Set Methods</i> Nova El Maidah (University of Jember, Indonesia), Ivan Hardja (University of Jember, Indonesia), Slamun Slamun (University of Jember, Indonesia)	34
<i>Evaluating The Semantic Mapping</i> Dewi Wardani (Universitas Sebelas Maret, Indonesia)	40
<i>Web-based Campus Virtual Tour Application using ORB Image Stitching</i> Didik Dwi Prasetya (Universitas Negeri Malang, Indonesia), Triyanna Widiyaningtyas (Universitas Negeri Malang, Indonesia), Aji P Wibawa (Indonesia & Universitas Negeri Malang, Indonesia)	46
<i>User Experience Analysis of The Users Babacucu.Com</i> Ahmad Nurul Fajar (Bina Nusantara University, Indonesia), Ditdit Nugeraha Utama (Bina Nusantara University, Indonesia), Taruna Diyapradana (Bina Nusantara University, Indonesia), Gunawan Wang (Bina Nusantara University, Indonesia)	50
<i>A Measurement Framework for Analyze The Influence of Service Quality and Website Quality on User Sat</i> Beny Prasetyo (Jember University, Indonesia), Fahrobby Adnan (University of Jember, Indonesia), Shinta Wardhani (Jember University, Indonesia)	56
<i>Quantitative Strategic Planning Matrix Analysis On The Implementation Of Second Screen Technology</i> Jarot S Suroso (Bina Nusantara University, Indonesia)	62
<i>Investment Analysis of Smart Connected Motorbike in Machine to Machine Application in Indonesia</i> Jarot S Suroso (Bina Nusantara University, Indonesia)	67
<i>Efficiency and Reliability Performance's of the Bioinformatics Resource Portal</i> Edy Budiman (Universitas Mulawarman, Indonesia), Haeruddin Haeruddin (Universitas Mulawarman, Indonesia), Andi Tejawati (Universitas Mulawarman, Indonesia)	72
<i>ISO/IEC 9126 Quality Model for Evaluation of Student Academic Portal</i> Edy Budiman (Universitas Mulawarman, Indonesia), Joan Angelina Widiyans (Universitas Mulawarman, Indonesia), Masna Wati (Universitas Mulawarman, Indonesia), Novianti Puspitasari (Universitas Mulawarman, Indonesia), Muhammad Firdaus (Universitas Mulawarman, Indonesia), Faza Alameka (Universitas Mulawarman, Indonesia)	78
<i>Measurement of IS/IT Investment on the Implementation of ERP and the Effect on company productivity</i> Qilbaaini Effendi Muftikhali (University of Jember, Indonesia)	84
<i>The Role of Social User and Social Feature on Recommendation Acceptance in Instagram in Indonesia</i> Muhammad Aldi Yusron (Universitas Indonesia, Indonesia), Putu Wuri Handayani (Universitas Indonesia, Indonesia), Qorib Munajat (University of Indonesia, Indonesia)	90
<i>Modulation Strategies for Indirect Matrix Converter: Complexity, Quality and Performance</i> Hendril Satrian Purnama (Universitas Ahmad Dahlan & Institute of Advance Engineering and Science (IAES), Indonesia), Tole Sutikno (Universitas Ahmad Dahlan & Universiti Teknologi Malaysia, Indonesia), Mochammad Facta (Diponegoro University, Indonesia)	97
<i>Sentiment Analysis Based on Appraisal Theory for Assessing Incumbent Electability</i> Canrakerta Canrakerta (Universitas Indonesia, Indonesia), Pamuji Putro (University of Indonesia, Indonesia), Zikri Irfandi (Universitas Indonesia, Indonesia), Nur Fitriah Ayuning Budi (Universitas Indonesia, Indonesia), Achmad Hidayanto (University of Indonesia, Indonesia)	101
<i>Application for the diagnosis of pneumonia based on Pneumonia Severity Index (PSI) values</i> Elyza Wahyuni (University of Islam Indonesia, Indonesia), Ahmad Ramadhan (University of Islam Indonesia, Indonesia)	107
<i>Impact of Matrix Factorization and Regularization Hyperparameter on a Recommender System for Movies</i> Gess Fathan (Universitas Gadjah Mada, Indonesia)	113

<i>Object Detection of Omnidirectional Vision Using PSO-Neural Network for Soccer Robot</i>	
Novendra Setyawan (University of Muhammadiyah Malang, Indonesia), Nuralif Mardiyah (University of Muhammadiyah Malang, Indonesia), Zulfatman Has (University of Muhammadiyah Malang, Indonesia), Nurhadi I (University of Muhammadiyah Malang, Indonesia), Khusnul Hidayat (University of Muhammadiyah Malang, Indonesia)	117
<i>DSS Scheme Using Forward Chaining-Simple Multi Attribute Rating Technique For Cocoa Beans Selection</i>	
Januar Adi Putra (Universitas Jember, Indonesia), Agustinus Galwargan (Universitas Jember, Indonesia), Nelly Adiwijaya (Universitas Jember, Indonesia)	122
<i>CountNet: End to End Deep Learning for Crowd Counting</i>	
Bryan Wilie (Bandung Institute of Technology, Indonesia), Samuel Cahyawijaya (Institut Teknologi Bandung & Prosa, Indonesia), Widyawardana Adiprawita (Institut Teknologi Bandung, Indonesia)	128
<i>Robust Principal Component Analysis for Feature Extraction of Fire Detection System</i>	
Herminarto Nugroho (Universitas Pertamina, Indonesia), Muhammad Koyimatu (Pertamina University, Indonesia), Ade Irawan (Universitas Pertamina, Indonesia), Ariana Yunita (Universitas Pertamina, Indonesia)	133
<i>Sarcasm Detection on Indonesian Twitter Feeds</i>	
Dwi Rahayu (University of Muhammadiyah Malang, Indonesia), Soveatin Kuntur (University of Muhammadiyah Malang, Indonesia), Nur Hayatin (Universitas Muhammadiyah Malang, Indonesia)	137
<i>Aspect Based Sentiment Analysis approach with CNN</i>	
Budi Mukhamad Mulyo (Institut Teknologi Bandung & ITB, Indonesia), Dwi H Widyantoro (Institut Teknologi Bandung, Indonesia)	142
<i>Optimal ANFIS Model for Forecasting System Using Different FIS</i>	
Deasy Advanti (Universitas Islam Negeri Sunan Ampel Surabaya, Indonesia), Dian Candra Rini Novitasari (Universitas Islam Negeri Sunan Ampel, Indonesia), Ahmad Hanif Asyhar (Universitas Islam Negeri Sunan Ampel, Indonesia), Fajar Setiawan (Perak Maritime Meteorology Station II Surabaya, Indonesia)	148
<i>Automated Diagnosis System of Diabetic Retinopathy Using GLCM Method and SVM Classifier</i>	
Ahmad Zoebad Foady (UIN Sunan Ampel Surabaya, Indonesia), Dian Candra Rini Novitasari (Universitas Islam Negeri Sunan Ampel, Indonesia), Ahmad Hanif Asyhar (Universitas Islam Negeri Sunan Ampel, Indonesia), Muhammad Firmansjah (Airlangga University, Indonesia)	154
<i>Development of Discrete-Cockroach Algorithm (DCA) for Feature Selection Optimization</i>	
Yusuf Hendrawan (Universitas Brawijaya, Indonesia), Muchnuria Rachmawati (Universitas Brawijaya, Indonesia), Muchammad Fauzy (Institut Teknologi Sepuluh November, Indonesia)	161
<i>Narrow Window Feature Extraction for EEG-Motor Imagery Classification using k-NN and Voting Scheme</i>	
Adi Wijaya (Universitas Gadjah Mada, Indonesia, Indonesia), Teguh Bharata Adji (Universitas Gadjah Mada, Indonesia), Noor Akhmad Setiawan (Universitas Gadjah Mada, Indonesia)	167
<i>Emotion Recognition using Fisher Face-based Viola-Jones Algorithm</i>	
Kartika Candra Kirana (State University of Malang, Indonesia), Slamet Wibawanto (State University of Malang, Indonesia), Heru Wahyu Herwanto (State University of Malang, Indonesia)	173
<i>Indonesian Id Card Recognition using Convolutional Neural Networks</i>	
M. Octaviano Pratama (Premier Optima, Indonesia), Wira Satyawan (Premier Optima, Indonesia), Bagus Fajar (Premier Optima, Indonesia), Haris Hamzah (Premier Optima, Indonesia), Rusnandi Fikri (Premier Optima, Indonesia)	178
<i>Sizing Optimization And Operational Strategy Of HRES (PV-WT) Using Differential Evolution Algorithm</i>	
Ilham Pakaya (Universitas Muhammadiyah Malang, Indonesia), Zulfatman Has (University of Muhammadiyah Malang, Indonesia), Annas Alif Putra (Universitas Muhammadiyah Malang, Indonesia)	182
<i>A Survey on Topologies and Controls of Z-Source Matrix Converter</i>	
Tri Wahono (Ahmad Dahlan University, Indonesia), Tole Sutikno (Universitas Ahmad Dahlan & Universiti Teknologi Malaysia, Indonesia), Nuryono Widodo (Universitas Ahmad Dahlan, Indonesia), Mochammad Facta (Diponegoro University, Indonesia)	189
<i>A New Algorithm for Designing the Parameter of Damped-Type Double Tuned Filter</i>	
Haposan Yoga Pradika Napitupulu (Universitas Trisakti, Indonesia), Chairul Gagarin Irianto (Universitas Trisakti, Indonesia)	193
<i>Power Demand Forecasting Considering Actual Peak Load Periods Using Artificial Neural Network</i>	
Yuan Octavia DP (Universitas Negeri Malang, Indonesia), AN Afandi (Universitas Negeri Malang, Indonesia & Kumamoto University, Japan), Hari Putranto (Universitas Negeri Malang, Indonesia)	198
<i>Comparison of LFC Optimization on Micro-hydro using PID, CES, and SMES based Firefly Algorithm</i>	
Kadaryono Kadaryono (Universitas Darul Ulum, Jombang, Indonesia), Rukslin Rukslin (Universitas Darul Ulum & Universitas Islam Sultan Agung, Indonesia), Machrus Ali (Universitas Darul Ulum, Jombang & Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia), Asnun Parwanti (Universitas Darul Ulum, Jombang, Indonesia), Iwan Cahyono (Universitas Darul Ulum, Jombang, Indonesia)	204
<i>Optimal Power Flow using Fuzzy-Firefly Algorithm</i>	
Dwi Lastomo (Teknik Elektro Otomasi Institut Teknologi Sepuluh Nopember Surabaya & ITS Surabaya, Indonesia), Widodo Widodo (University of PGRI Adi Buana Surabaya, Indonesia), Herlambang Setiadi (The University of Queensland, Australia)	210
<i>Low-Frequency Oscillation Mitigation using an Optimal Coordination of CES and PSS based on BA</i>	
Dwi Lastomo (Teknik Elektro Otomasi Institut Teknologi Sepuluh Nopember Surabaya & ITS Surabaya, Indonesia), Herlambang Setiadi (The University of Queensland, Australia), Galih Banqqa (University of Stuttgart, Germany), Muhammad Faisal (PT. Schindler, Indonesia), Go Hutomo (Institut Teknologi Sepuluh Nopember, Indonesia), Imam Farid (Institut Teknologi Sepuluh Nopember Surabaya, Indonesia), Taurista Syawitri (Universitas Muhammadiyah Surakarta, Indonesia), Louis Putra (Politecnico di Milano, Italy), Yongki Hendranata (Texas A&M University College Station, USA), Kristiadi Stefanus (Imperial College London, Indonesia), Chairunnisa Chairunnisa (Politeknik Penerbangan Surabaya, Indonesia), Andri Ashfahani (Institut Teknologi Sepuluh Nopember, Indonesia), Ahmad Sabila (Universitas Brawijaya, Indonesia)	216

<i>Computer Aided Model for an Off-grid Photovoltaic System using Batteries Only</i>	
Emil Lazarescu (Politehnica University Timisoara, Romania), Mihaela Friqura-Iliasa (Politehnica University Timisoara, Romania), Flaviu Friqura-Iliasa (Politehnica University Timisoara & National Institute for Research. and Development in Electrochemistry and Condensed Matter/LERF, Timisoara, Romania), Lia Dolqa (Politehnica University Timisoara, Romania), Marius Mirica (Nat. Institute for Res. and Dev. in Electrochemistry and Condensed Matter, Romania), Hannelore Filipescu (Politehnica University Timisoara, Romania)	222
<i>Computer Aided Model for a Low Voltage Varistor with Increased Thermal Stability</i>	
Mihaela Friqura-Iliasa (Politehnica University Timisoara, Romania), Flaviu Friqura-Iliasa (Politehnica University Timisoara & National Institute for Research. and Development in Electrochemistry and Condensed Matter/LERF, Timisoara, Romania), Lia Dolqa (Politehnica University Timisoara, Romania), Florin Balcu (Nat. Institute for Res. and Dev. in Electrochemistry and Condensed Matter, Romania), Hannelore Filipescu (Politehnica University Timisoara, Romania), Adrian Olariu (Politehnica University Timisoara, Romania)	226
<i>Economic Feasibility Study of Rooftop Grid Connected PV System for Peak Load Reduction</i>	
Syafii Syafii (University of Andalas, Indonesia), Novizon Novizon (Universitas Andalas, Indonesia), Wati Wati (STKIP PGRI Sumatera Barat, Indonesia), Dona Juliandri (Universitas Andalas, Indonesia)	231
<i>Automatic Switching Algorithm for Photovoltaic Power Generation System</i>	
Ivan Husain (Universitas Indonesia, Indonesia), Canny Dahlia (Universitas Indonesia, Indonesia), Feri Yusivar (Universitas Indonesia, Indonesia)	236
<i>Rotor Speed Control Maximum Power Point Tracking for Small Wind Turbine</i>	
Ni Luh Dharmaraditya (University of Indonesia, Indonesia), Lazarus Stefan (University of Indonesia, Indonesia), Feri Yusivar (Universitas Indonesia, Indonesia)	243
<i>Stator Flux Oriented Control of Three-Phase Induction Motor with Improved Decoupling Scheme</i>	
Irvan Arif (Universitas Indonesia, Indonesia), Bernadeta Harini (Universitas Indonesia, Indonesia), Feri Yusivar (Universitas Indonesia, Indonesia)	249
<i>Sensorless PMSM Control using Fifth Order EKF in Electric Vehicle Application</i>	
Nanda Avianto Wicaksono (Universitas Indonesia, Indonesia), Bernadeta Wuri Harini (Universitas Indonesia, Indonesia), Feri Yusivar (Universitas Indonesia, Indonesia)	254
<i>Smart Frequency Control using Coordinated RFB and TCPS based on Firefly Algorithm</i>	
Dwi Lastomo (Teknik Elektro Otomasi Institut Teknologi Sepuluh Nopember Surabaya & ITS Surabaya, Indonesia), Arif Musthofa (Institut Teknologi Sepuluh Nopember, Indonesia), Herlambang Setiadi (The University of Queensland, Australia), Eddy Setyo Koenhardono (Institut Teknologi Sepuluh Nopember, Indonesia), Muhammad Djalal (State Polytechnic of Ujung Pandang, Indonesia)	260
<i>Rain Attenuation Statistics over 5G Millimetre Wave Links in Malaysia</i>	
Mustafa Ghanim (Universiti Teknologi Malaysia, Malaysia), Manhal Alhilali (Universiti Teknologi Malaysia, Malaysia), Jafri Din (Universiti Teknologi Malaysia, Malaysia), Hong Yin Lam (Universiti Tun Hussein Onn Malaysia, Malaysia)	266
<i>UUID Beacon Advertisements For Lecture Schedule Information</i>	
Wiwin Kristiana (Universitas Narotama, Indonesia), Mochammad Mizanul Achlaq (Universitas Narotama, Indonesia), Benediktus Anindito (Universitas Narotama, Indonesia), Aryo Nugroho (Institut Teknologi Sepuluh Nopember & Universitas Narotama, Indonesia), Cahyo Darujati (Narotama University, Indonesia), Moh Noor Al-Azam (Universitas Narotama & Rahajasa Media Internet, PT., Indonesia)	270
<i>Comparative Performance Analysis of Linear Precoding in Downlink Multi-user MIMO</i>	
Subuh Pramono (Universitas Sebelas Maret, Indonesia)	277
<i>Application of LoRa WAN Sensor and IoT for Environmental Monitoring in Riau Province Indonesia</i>	
Evizal Abdul Kadir (Universitas Islam Riau, Indonesia), Akmar Efendi (University of Islam Riau, Indonesia), Sri Listia Rosa (Universitas Islam Riau, Indonesia)	281
<i>Co-channel Interference Monitoring based on Cognitive Radio Node Station</i>	
Arief Marwanto (Universiti Islam Sultan Agung (UNISSULA) Semarang, Indonesia), Ulin Nuha (Faculty of Industrial Engineering, Indonesia), Jenny Hapsari (Faculty of Industrial Engineering, Indonesia), Daniel Triswahyudi (PT. Hartono Istana Teknologi (Polytron), Indonesia)	286
<i>Simulation of Mobile LoRa Gateway for Smart Electricity Meter</i>	
Suqianto Suqianto (University of Indonesia, Indonesia), Azwar Anhar (University of Indonesia, Indonesia), Ruki Harwahyu (Universitas Indonesia & Universitas Indonesia, Indonesia), Riri Fitri Sari (University of Indonesia, Indonesia)	292
<i>Fuzzy Logic Controller Design for Leader-Follower Robot Navigation</i>	
Tresna Dewi (Politeknik Negeri Sriwijaya, Indonesia), Yudi Wijanarko (Politeknik Negeri Sriwijaya, Indonesia), Pola Risma (Sriwijaya Polytechnic, Indonesia), Yurni Oktarina (Polytechnic Sriwijaya Palembang-Indonesia, Indonesia)	298
<i>Arm Robot Manipulator Design and Control for Trajectory Tracking; a Review</i>	
Hendra Yudha (Universitas Tridinanti Palembang, Indonesia), Tresna Dewi (Politeknik Negeri Sriwijaya, Indonesia), Pola Risma (Sriwijaya Polytechnic, Indonesia), Yurni Oktarina (Polytechnic Sriwijaya Palembang-Indonesia, Indonesia)	304
<i>Magnetorheological Elastomer Stiffness Control for Tunable Vibration Isolator</i>	
Giqih Priyandoko (Universitas Widyagama, Malang, Indonesia), Tedi Kurniawan (FKM, UMP, Malaysia), Efistein Naga (FKM, UMP, Malaysia)	310
<i>Improving a Wall-Following Robot Performance with a PID-Genetic Algorithm Controller</i>	
Andi Adriansyah (Universitas Mercu Buana, Indonesia), Heru Suwoyo (Shanghai University, P.R. China), Yingzhong Tian (Shanghai University, P.R. China), Chenwei Deng (Beijing Institute of Technology, P.R. China)	314
<i>A Review of Solar Tracker Control Strategies</i>	
Ali Basrah Pulungan (Universitas Negeri Padang, Indonesia), Lovely Son (Universitas Andalas, Indonesia), Syafii Syafii (University of Andalas, Indonesia)	319
<i>Robust and Accurate Positioning Control of Solar Panel System Tracking based Sun Position Image</i>	
Zulfatman Has (University of Muhammadiyah Malang, Indonesia), Lailis Syafa'ah (University of Muhammadiyah Malang, Indonesia), Lailatul Fauziah (University of Muhammadiyah Malang, Indonesia)	324

<i>Robust Adaptive Sliding Mode Control Design with Genetic Algorithm for Brushless DC Motor</i>	
Zulfatman Has (University of Muhammadiyah Malang, Indonesia), Machmud Effendy, ME (University of Muhammadiyah Malang, Indonesia), Een Putra (University of Muhammadiyah Malang, Indonesia)	330
<i>Active Fault Tolerance Control for Sensor Fault Problem in Wind Turbine Using SMO with LMI Approach</i>	
Nuralif Mardiyah (University of Muhammadiyah Malang, Indonesia), Novendra Setyawan (University of Muhammadiyah Malang, Indonesia), Zulfatman Has (University of Muhammadiyah Malang, Indonesia), Bella Retno (University of Muhammadiyah Malang, Indonesia)	336
<i>Vibration Control of Magnetorheological Elastomer Beam Sandwich</i>	
Giqih Priyandoko (Universitas Widyagama, Malang, Indonesia), Tedi Kurniawan (FKM, UMP, Malaysia), Saffirna Mohd Soffie (FKM, UMP, Malaysia)	341
<i>Measurement of Thermal Expansion Coefficient on Electric Cable Using X-Ray Digital Microradiography</i>	
Yessi Affriyenni (State University of Malang, Indonesia), Gede Bayu Suparta (Gadjah Mada University, Indonesia), Galandaru Swalaganata (Institut Agama Islam Negeri Tulungagung, Indonesia)	345
<i>Review on Adjustable Speed Drive Techniques of Matrix Converter Fed Three-Phase Induction Machine</i>	
Arsyad Cahya Subrata (Universitas Ahmad Dahlan, Indonesia), Tole Sutikno (Universitas Ahmad Dahlan & Universiti Teknologi Malaysia, Indonesia), Aiman Zakwan Jidin (Universiti Teknikal Malaysia Melaka, Malaysia), Auzani Jidin (Universiti Teknikal Malaysia Melaka, Malaysia)	350
<i>Indoor Agriculture: Measurement of The Intensity of LED for Optimum Photosynthetic Recovery</i>	
Benediktus Anindito (Universitas Narotama, Indonesia), Adri Gabriel Sooai (Institut Teknologi Sepuluh Nopember & Universitas Katolik Widya Mandira, Indonesia), Mochammad Mizanul Achlaq (Universitas Narotama, Indonesia), Moh Noor Al-Azam (Universitas Narotama & Rahajasa Media Internet, PT., Indonesia), Aris Winaya (Universitas Muhammadiyah Malang, Indonesia), Maftuchah Maftuchah (Universitas Muhammadiyah Malang, Indonesia)	356
<i>Quasi Z-Source Inverter as MPPT on Renewable Energy using Grey Wolf Technique</i>	
Quota Alief Sias (Universitas Negeri Malang, Indonesia), Irham Fadlika (Universitas Negeri Malang, Indonesia), Irawan Dwi Wahyono (Universitas Negeri Malang, Indonesia), AN Afandi (Universitas Negeri Malang, Indonesia & Kumamoto University, Japan)	362
<i>Analysis of Waveform of Partial Discharge in Air Insulation Measured by RC Detector</i>	
Michael Stevano Sinurat (Insitut Teknologi Bandung, Indonesia), Umar Khayam (Institut Teknologi Bandung, Indonesia)	367
<i>Application of Ultra-Wideband Double Layer Printed Antenna for Partial Discharge Detection</i>	
Yuda Hamdani (Institut Teknologi Bandung, Indonesia), Umar Khayam (Institut Teknologi Bandung, Indonesia)	373
<i>Reliability Analysis of Randu Garut 3 Distribution System Using Section Technique Method</i>	
Jimmy Putra (Universitas Gadjah Mada, Indonesia), Raka Bagus (Universitas Gadjah Mada, Indonesia)	379
<i>Combined Computational Intelligence Approach for the Power System Optimization Problem</i>	
Arif Afandi (UM, Indonesia), Irham Fadlika (Universitas Negeri Malang, Indonesia), Lanqlang Gumilar (Universitas Negeri Malang, Indonesia), Yuni Rahmawati (Universitas Negeri Malang, Indonesia), Quota Alief Sias (Universitas Negeri Malang, Indonesia), Irawan Dwi Wahyono (Universitas Negeri Malang, Indonesia), Yunis Sulistyorini (IKIP Budi Utomo, Indonesia), Farrel Candra WA (Research Center of Smart Power and Energy Systems, Indonesia), Michiko Ryuu Sakura A (Research Center of Smart Power and Energy Systems, Indonesia)	385
<i>Partial Discharge and Breakdown Strength of Plasma Treated Nanosilica/LDPE Nanocomposites</i>	
Muhammad Abu Bakar Sidik (Faculty of Engineering, Universitas Sriwijaya Ogan Ilir, Indonesia), Mohd Hafizi Ahmad (Universiti Teknologi Malaysia, Malaysia), Zainuddin Nawawi (Universitas Sriwijaya, Indonesia), Muhammad Irfan Jambak (Faculty of Engineering, Universitas Sriwijaya Ogan Ilir, Malaysia), Aulia Aulia (Universitas Andalas, Indonesia), Eka Waldi (Andalas University, Indonesia), Zulkurnain Abdul-Malek (University Technology Malaysia, Malaysia), Noor 'Aliaa Awang (Universiti Teknologi Malaysia, Malaysia)	391
<i>Shortest Route at Dynamic Location with Node Combination-Dijkstra Algorithm</i>	
Achmad Fitro (Jl. Imam Bardjo SH No. 5 Semarang & Universitas Diponegoro, Indonesia), Suryono Suryono (Faculty of Science and Mathematics Diponegoro University, Indonesia), Retno Kusumaningrum (Diponegoro University, Indonesia)	395
<i>Analysis of Consumer Confidence on Mobile Commerce in Indonesia</i>	
Andhika Prabawati (Universitas Atma Jaya Yogyakarta, Indonesia), I Putu Widyana (Atma Jaya University Yogyakarta, Indonesia), Suyoto Suyoto (Universitas Atma Jaya Yogyakarta, Indonesia)	400
<i>Social Media and User Performance in Knowledge Sharing</i>	
Setiawan Assegaff (STIKOM Dinamika Bangsa & ISRG STIKOM DB, Indonesia), Akwan Sunoto (STIKOM Dinamika Bangsa, Indonesia)	405
<i>Analysis of Electronic Medical Record Reception using Expanded Technology Acceptance Model</i>	
Indra Kharisma Raharjana (Universitas Airlangga, Indonesia), Faisal Apriyana (Universitas Airlangga, Indonesia), Taufik Taufik (Universitas Airlangga, Indonesia)	411
<i>Development of Mobile Based Educational Game as Learning Media for Basic Programming in VHS</i>	
Hakkun Elmunsyah (Universitas Negeri Malang, Indonesia), Gradiyanto Radityo Kusumo (Universitas Negeri Malang, Indonesia), Utomo Pujianto (Universitas Negeri Malang, Indonesia), Didik Dwi Prasetya (Universitas Negeri Malang, Indonesia)	416
<i>Incident and Service Request Management for Academic Information System based on COBIT</i>	
Indra Kharisma Raharjana (Universitas Airlanqqa, Indonesia), Ibnu Ibadillah (Universitas Airlanqqa, Indonesia), Purbandini Purbandini (Universitas Airlangga, Indonesia), Eva Hariyanti (Institut Teknologi Sepuluh Nopember, Indonesia)	421
<i>Applying IT Services Business Relationship Management on Security Outsource Company</i>	
Indra Kharisma Raharjana (Universitas Airlangga, Indonesia), Susmiandri Susmiandri (Universitas Airlangga, Indonesia), Army Justitia (Universitas Airlangga, Indonesia)	426
<i>PSS Design Based on Fuzzy Controller with Particle Swarm Optimization Tuning</i>	
Ermanu Azizul Hakim (University of Muhammadiyah Malang, Indonesia), Nur Kasan (University of Muhammadiyah Malang, Indonesia), Nurhadi Nurhadi (University of Muhammadiyah Malang, Indonesia)	432

<i>OCT for non-destructive examination of the internal biological structures of mosquito specimen</i>	
Naresh Kumar Ravichandran (Kyungpook National University, Korea), Deokmin Jeon (Kyungpook National University, Korea), Junsoo Lee (Kyungpook National University, Korea), Jaeseok Park (Kyungpook National University, Korea), Byeonggyu Jeon (Kyungpook National University, Korea), Sangbonq Lee (Kyungpook National University, Korea), Pilun Kim (Kyungpook National University, Korea), Kwang Shik Choi (Kyungpook National University, Korea), Hee-Young Jung (Kyungpook National University, Korea), Byoung-Ju Yun (Kyungpook National University & IT College, Korea), Mansik Jeon (Kyungpook National University, Korea), Jeehyun Kim (Kyungpook National University, Korea)	436
<i>Analysis of EMG based Arm Movement Sequence using Mean and Median Frequency</i>	
Basri Cahyadi (University Malaysia Perlis, Malaysia), Wan Khairunizam Wan Ahmad (University Malaysia Perlis & Motion, Signal, Image Processing and Pattern Recognition Research Group, Malaysia), Zunaidi Ibrahim (University Malaysia Perlis, Malaysia), Shahrman Abu Bakar (Universiti Malaysia Perlis, Malaysia), Zuradzman Mohamad Razlan (Universiti Malaysia Perlis, Malaysia), Mohd Rudzuan Mohd Nor (Universiti Malaysia Perlis, Malaysia)	440
<i>Implementation of Myo Armband on Mobile Application for Post-stroke Patient Hand Rehabilitation</i>	
Tri Bintang Dewantoro (Politeknik Elektronika Negeri Surabaya, Indonesia), Riyanto Siqit (Politeknik Elektronika Negeri Surabaya, Indonesia), Heny Yuniarti (Politeknik Elektronika Negeri Surabaya, Indonesia), Yudith Dian Prawitri (Rumah Sakit Universitas Airlangga, Indonesia), Fridastya Andini Pamudyaningrum (Politeknik Elektronika Negeri Surabaya, Indonesia), Mahaputra Ilham Awal (Politeknik Elektronika Negeri Surabaya, Indonesia)	445
<i>Development of Embedded System for Centralized Insomnia System</i>	
Novi Azman (Universitas Nasional & Universiti Teknikal Malaysia Melaka, Indonesia), Mohd Khanapi Abd Ghani (Universiti Teknikal Malaysia Melaka, Malaysia), Haikal Satria (Universiti Teknologi Malaysia, Malaysia), Muhammad Zillullah Mukaram (Universiti Teknologi Malaysia, Malaysia)	451
<i>Performance Analysis of Color Cascading Framework on Two Different Classifiers in Malaria Detection</i>	
Cucun Very Anqkoso (University of Trunojoyo Madura, Indonesia), Yonathan Ferry Hendrawan (University of Trunojoyo Madura, Indonesia), Ari Kusumaningsih (University of Trunojoyo Madura, Indonesia), Rima Tri Wahyuningrum (University of Trunojoyo Madura, Indonesia)	456
<i>Monitoring Walking Devices For Calorie Balance In Patients With Medical Rehabilitation Needs</i>	
Wahyu Andhyka Kusuma, WAK (Universitas Muhammadiyah Malang, Indonesia), Zamah Sari (Universitas Muhammadiyah Malang, Indonesia), Diah Fitriani (Universitas Muhammadiyah Malang, Indonesia), Siti Norhabibah (Universitas Muhammadiyah Malang, Indonesia), Sabrina Ubay (Universitas Muhammadiyah Malang, Indonesia), Hardianto Wibowo (Universitas Muhammadiyah Malang, Indonesia)	460
<i>E-Government Maturity Model to Support System Dynamics in Public Policymaking</i>	
Feldiansyah Nasution (Universiti Teknologi Malaysia & PT. Bumi Siak Pusako, Indonesia)	464
<i>Comparative Analysis of Forensic Software on Android-based Blackberry Messenger using NIJ Framework</i>	
Imam Riadi (Universitas Ahmad Dahlan, Indonesia, Indonesia), Sunardi Sunardi (Universitas Ahmad Dahlan, Indonesia), Arizona Firdonsyah (Universitas Ahmad Dahlan, Indonesia)	472
<i>Semi-reactive Switch Based Proxy ARP in SDN</i>	
Fauzi Dwi Setiawan Sumadi (University of Muhammadiyah Malang, Indonesia), Diah Risqiwati (University of Muhammadiyah Malang, Indonesia), Syaifuddin Syaifuddin (University of Muhammadiyah Malang, Indonesia)	478
<i>Improvement of Cluster Importance Algorithm with Sentence Position for News Summarization</i>	
Nur Hayatin (Universitas Muhammadiyah Malang, Indonesia), Gita Marthasari (Universitas Muhammadiyah Malang, Indonesia)	483
<i>Comparison Between A* And Obstacle Tracing Pathfinding In Gridless Isometric Game</i>	
Lailatul Husniah (Universitas Muhammadiyah Malang, Indonesia), Rizky Ade Mahendra (Universitas Muhammadiyah Malang, Indonesia), Ali Sofyan Kholimi (Universitas Muhammadiyah Malang, Indonesia), Eko Budi Cahyono (Universitas Muhammadiyah Malang, Indonesia)	489
<i>Automatic Game World Generation for Platformer Games Using Genetic Algorithm</i>	
Ali Sofyan Kholimi (Universitas Muhammadiyah Malang, Indonesia), Ahmad Hamdani (Universitas Muhammadiyah Malang, Indonesia), Lailatul Husniah (Universitas Muhammadiyah Malang, Indonesia)	495
<i>Middleware for Network Interoperability in IoT</i>	
Eko Sakti Pramukantoro (Brawijaya University, Indonesia), Fariz Andri Bakhtiar (Brawijaya University, Indonesia), Binariyanto Aji (Brawijaya University, Indonesia), Rasidy Pratama (Brawijaya University, Indonesia)	499
<i>Face RGB-D Data Acquisition System Architecture for 3D Face Identification Technology</i>	
Aldi Bayu Kreshnanda Ismail (Politeknik Elektronika Negeri Surabaya, Indonesia), Ihsan Fikri Abdurahman Muharram (Politeknik Elektronika Negeri Surabaya, Indonesia), Dadet Pramadihanto (PENS, Indonesia), Adnan Rachmat Anom Besari (Politeknik Elektronika Negeri Surabaya (PENS) & Electronic Engineering Polytechnic Institute of Surabaya (EEPIS), Indonesia)	503
<i>Feature Expansion for Sentiment Analysis in Twitter</i>	
Erwin B. Setiawan (Telkom University, Indonesia), Dwi H Widyantoro (Institut Teknologi Bandung, Indonesia), Kridanto Surendro (Institu Teknologi Bandung, Indonesia)	509
<i>Individual Factors As Antecedents of Mobile Payment Usage</i>	
Radinal Setyadinsa (Faculty of Computer Science, Universitas Indonesia, Indonesia), Muhammad Rifki Shihab (Faculty of Computer Science, Universitas Indonesia, Indonesia), Yudho Sucahyo (University of Indonesia, Indonesia)	514
<i>Determine supporting features for mobile application of NUSANTARA</i>	
Dana Sensuse (Laboratory of E-Government, Indonesia), Ika Arthalia Wulandari (University of Indonesia, Indonesia), Erzi Hidayat (University of Indonesia, Indonesia), Elin Cahyaningsih (University of Indonesia & Badan Kepegawaian Negara, Indonesia), Pristi Sukmasetya (Universitas Indonesia, Indonesia), Wina Permana Sari (Bina Nusantara Institute of Creative Technology Malang, Indonesia)	519
<i>Knowledge Management Maturity Assessment in Air Drilling Associates using G-KMMM</i>	
Dana Sensuse (Laboratory of E-Government, Indonesia), Richard Vinc (Universitas Indonesia, Indonesia), Ricky Ruliputra (Universitas Indonesia, Indonesia), Siti Hadjar (Universitas Indonesia, Indonesia), Sofian Lusa (University of Indonesia, Indonesia), Pudy Prima (Universitas Indonesia, Indonesia)	525

<i>Measuring Knowledge Management Readiness of Indonesia Ministry of Trade</i>	
Dana Sensuse (Laboratory of E-Government, Indonesia), Jani Sireqar (Universitas Indonesia, Indonesia), Ronny Ansir (Universitas Indonesia, Indonesia), Sofian Lusa (University of Indonesia, Indonesia), Pudy Prima (Universitas Indonesia, Indonesia)	531
<i>Personal Extreme Programming with MoSCoW Prioritization for Developing Library Information System</i>	
Gita Marthasari (Universitas Muhammadiyah Malang, Indonesia), Wildan Suharso (Universitas Muhammadiyah Malang, Indonesia)	537
<i>Analysis on Customer Satisfaction Dimensions in P2P Accommodation using LDA: A Case Study of Airbnb</i>	
Kevin Situmorang (Universitas Indonesia, Indonesia), Achmad Hidayanto (University of Indonesia, Indonesia), Alfian Wicaksono (Universitas Indonesia, Indonesia), Arlisa Yuliaty (Universitas Indonesia, Indonesia)	542
<i>IDEnet: Inception-Based Deep Convolutional Neural Network for Crowd Counting Estimation</i>	
Samuel Cahyawijaya (Institut Teknologi Bandung & Prosa, Indonesia), Bryan Wilie (Bandung Institute of Technology, Indonesia), Widayawardana Adiprawita (Institut Teknologi Bandung, Indonesia)	548
<i>Multispectral Imaging and Convolutional Neural Network for Photosynthetic Pigments Prediction</i>	
Kestrilia Prilianti (Universitas Ma Chung, Indonesia)	554
<i>Substrate Integrated Waveguide Bandpass Filter with Complementary Split Ring Resonator at 2.45 GHz</i>	
Dian Widi Astuti (Universitas Mercu Buana, Indonesia), Mudrik Alaydrus (Universitas Mercu Buana, Indonesia)	560
<i>ML-Optimized Beam-based Radio Coverage Processing in IEEE 802.11 WLAN Networks</i>	
Mehdi Guessous (Mohammadia Engineering School, Morocco), Lahbib Zenkour (Mohammadia Engineering School, Morocco)	564
<i>Single-Tone Doppler Radar System for Human Respiratory Monitoring</i>	
Rizky Ambarini (Telkom University, Indonesia), Aloysius Adya Pramudita (Telkom University, Indonesia), Erfansyah Ali (Telkom University, Indonesia), Antonius Setiawan (Telkom University, Indonesia)	571
<i>Dual Frequency Continuous Wave Radar for Small Displacement Detection</i>	
Andarining Palupi (Telkom University, Indonesia), Aloysius Adya Pramudita (Telkom University, Indonesia), Dharu Arseno (Telkom University, Indonesia), Antonius Setiawan (Telkom University, Indonesia)	576
<i>A New Method for Minimizing the Unnecessary Handover in High-Speed Scenario</i>	
Hoe Tung Yew (Universiti Malaysia Sabah, Malaysia), Haikal Satria (Universiti Teknologi Malaysia, Malaysia), Rindu Nurma Illahi (Universiti Teknologi Malaysia, Malaysia)	580
<i>Automate Snort Rule For Xss Detection With Honeypot</i>	
Syaifuddin Syaifuddin (University of Muhammadiyah Malang, Indonesia), Hanuqra Sidharta (BINA NUSANTARA Institute of Creative Technology, Indonesia), Diah Risqiwati (University of Muhammadiyah Malang, Indonesia)	584
<i>Re-Ranking Image Retrieval on Multi Texton Co-Occurrence Descriptor Using K-Nearest Neighbor</i>	
Yufis Azhar (Universitas Muhammadiyah Malang, Indonesia), Agus Eko Minarno (Universitas Muhammadiyah Malang, Indonesia), Yuda Munarko (Universitas Muhammadiyah Malang, Indonesia)	589
<i>Monitoring The Usage of Marine Fuel Oil Aboard Ketapang Gilimanuk Ship</i>	
Arief Marwanto (Universiti Islam Sultan Agung (UNISSULA) Semarang, Indonesia), Sarman Sarman (Marine Merchant Academy of Surabaya, Indonesia), Suryani Alifah (Unissula University, Indonesia)	594
<i>Design of Low Noise Micro Liter Syringe Pump for Quartz Crystal Microbalance Sensor</i>	
Ridha Ikhsani (Brawijaya University, Indonesia), Dionysius J D H Santjojo (University of Brawijaya, Indonesia), Setyawan Sakti (Brawijaya University, Indonesia)	598
<i>Implementation of the Culinary Recommendation System Using Sentiment Analysis and SAW in Bengkulu</i>	
Yudi Setiawan (University of Bengkulu, Indonesia), Boko Susilo (University of Bengkulu, Indonesia), Aan Erlansari (Bengkulu University & Jl. Wr. Supratman Kandang Limun Bengkulu, Indonesia), Sumitra Firdaus (University of Bengkulu, Indonesia), Evi Maryanti (University of Bengkulu, Indonesia)	603
<i>Appropriate Sets of Criteria for Innovation Adoption of IS Security in Organizations</i>	
Sandy Kosasi (STMIK Pontianak, Indonesia), Vedyanto Vedyanto (Santu Petrus Junior High School, Indonesia), I Dewa Ayu Eka Yuliani (STMIK Pontianak, Indonesia)	608
<i>Self-Efficacy a Critical Factor of Information System: An Investigation using DeLone McLean</i>	
Tri Lathif Mardi Suryanto (Universitas Pembangunan Nasional Veteran JawaTimur, Indonesia), Djoko Budiyo Setyohadi (Universitas Atma Jaya Yogyakarta, Indonesia), Akhmad Fauzi (Universitas Pembangunan Nasional Veteran JawaTimur, Indonesia)	614
<i>Improvement of Information Technology Infrastructure in Higher Education using IT Balanced Scorecard</i>	
Clara Hetty Primasari (Universitas Atma Jaya Yogyakarta, Indonesia), Djoko Budiyo Setyohadi (Universitas Atma Jaya Yogyakarta, Indonesia)	619
<i>A Conceptual Framework of Cloud-Based Mobile-Retail Application for Textile Cyberpreneurs</i>	
Nik Zulkarnaen Khidzir (Global Entrepreneurship Research and Innovation Centre, Universiti Malaysia Kelantan & Faculty of Creative Technology and Heritage, Universiti Malaysia Kelantan, Malaysia), Wan Safra Diyana Wan Abdul Ghani (Universiti Malaysia Kelantan, Malaysia), Khairul Azhar Daud (Universiti Malaysia Kelantan, Malaysia)	625
<i>Implementation of Winnowing Algorithm for Document Plagiarism Detection</i>	
Nurissaidah Ulinuha (Universitas Islam Negeri Sunan Ampel, Indonesia), Muhammad Thohir (Universitas Islam Negeri Sunan Ampel, Indonesia), Dian Candra Rini Novitasari (Universitas Islam Negeri Sunan Ampel, Indonesia), Ahmad Hanif Asyhar (Universitas Islam Negeri Sunan Ampel, Indonesia), Ahmad Zaenal Arifin (Universitas PGRI Ronggolawe, Indonesia)	631
<i>A Design of Coreless Permanent Magnet Axial Flux Generator for Low Speed Wind Turbine</i>	
Abdul Aziz Yusuf (University of Muhammadiyah Malang, Indonesia), M. Irfan (University of Muhammadiyah Malang, Indonesia), M. Razzaq (University of Muhammadiyah Malang, Indonesia)	637
<i>Design of Hybrid System Power Management Based Operational Control System to Meet Load Demand</i>	
Zulfatman Has (University of Muhammadiyah Malang, Indonesia), Nurhadi Nurhadi (University of Muhammadiyah Malang, Indonesia), Fachmy Faizal (University of Muhammadiyah Malang, Indonesia)	642

<i>Circuit Simulation for Wind Power Maximum Power Point Tracking with Four Switch Buck Boost Converter</i>	
Machmud Effendy, ME (University of Muhammadiyah Malang, Indonesia), Khusnul Hidayat (University of Muhamadiyah Malang, Indonesia), Nuralif Mardiyah (University of Muhammadiyah Malang, Indonesia)	648
<i>Bioelectrical measurement for sugar recovery of sugarcane prediction using artificial neural network</i>	
Sucipto Sucipto (Agroindustrial Technology Departement, Faculty of Agricultural Technology, Universitas Brawijaya, Indonesia), Muhammad Arwani (Agricultural Technology, Universitas Brawijaya, Indonesia), Yusuf Hendrawan (Agricultural Technology, Universitas Brawijaya, Indonesia), Shinta Widaningtyas (Agricultural Technology, Universitas Brawijaya, Indonesia), Dimas F Al Riza (Universitas Brawijaya, Indonesia), Simping Yuliatun (Indonesian Sugar Research Institute, Indonesia), Supriyanto Supriyanto (Institut Pertanian Bogor, Indonesia), Agus Somantri (Indonesian Center Agricultural Post Harvest Research and Development, Indonesia)	652
<i>Implementation of MEMS Accelerometer for Velocity-based Seismic Sensor</i>	
Amalia Cemara Nur'aidha (Brawijaya University, Indonesia), Didik R. Santoso (Brawijaya University, Indonesia), Sukir Maryanto (University of Brawijaya Malang, Indonesia)	657
<i>Automatic User-Video Metrics Creations From Emotion Detection</i>	
Darari Nur Amali (Politeknik Elektronika Negeri Surabaya, Indonesia), Adnan Rachmat Anom Besari (Politeknik Elektronika Negeri Surabaya (PENS) & Electronic Engineering Polytechnic Institute of Surabaya (EEPIS), Indonesia), Ali Ridho Barakbah (Politeknik Elektronika Negeri Surabaya, Indonesia), Dias Agata (Poiliteknik Elektronika Negeri Surabaya, Indonesia)	663
<i>Real Time SIBI Sign Language Recognition Based on K-Nearest Neighbor</i>	
Fitrah Humaira (Politeknik Negeri Madura, Indonesia), Supria Supria (Politeknik Negeri Bengkalis, Indonesia), Darlis Herumurti (Institut Teknologi Sepuluh Nopember, Indonesia), Kukuh Widarsono (Politeknik Negeri Madura, Indonesia)	669
<i>Artificial Neural Network Parameter Tuning Framework For Heart Disease Classification</i>	
Mohamad Haider Abu Yazid (Universiti Teknologi Malaysia (UTM), Malaysia), Haikal Satria (Universiti Teknologi Malaysia, Malaysia), Shukor Talib (Unversiti Teknologi Malaysia, Malaysia), Novi Azman (Universitas Nasional & Universiti Teknikal Malaysia Melaka, Indonesia)	674
<i>Winter Exponential Smoothing: Sales Forecasting on Purnama Jati Souvenirs Center</i>	
Fahrobby Adnan (University of Jember, Indonesia), Putri Damayanti (University of Jember, Indonesia), Gama Fajarianto (University of Jember, Indonesia), Antonius Prihandoko (University of Jember, Indonesia)	680
<i>Analysis and Design of Decision Support System Dashboard for Predicting Student Graduation Time</i>	
Satrio Wibowo (Telkom University, Indonesia), Rachmadita Andreswari (Telkom University, Indonesia), Muhammad Hasibuan (Telkom University, Indonesia)	684
<i>Sentiment Analysis Using Support Vector Machine Algorithm</i>	
Fransiska Pinem (Telkom University, Indonesia), Rachmadita Andreswari (Telkom University, Indonesia), Muhammad Hasibuan (Telkom University, Indonesia)	690
<i>Group Formation Using Multi Objectives Ant Colony System for Collaborative Learning</i>	
Fitra Zul Fahmi (Telkom University, Indonesia), Dade Nurjanah (Telkom University, Indonesia)	696
<i>Smart Traffic Light based on IoT and mBaaS using High Priority Vehicles Method</i>	
Muhammad Izzuddin Mahali (Yoqyakarta State University, Indonesia), Bkti Wulandari (Yoqyakarta State University, Indonesia), Eko Marpanaji (Yoqyakarta State University, Indonesia), Umi Rochayati (Yoqyakarta State University, Indonesia), Satriyo Dewanto (Yogyakarta State University, Indonesia), Nur Hasanah (Yogyakarta State University, Indonesia)	703
<i>Correlation Between Bruto Domestic Products (Gdp) With Duty Schools</i>	
Hardianto Wibowo (Universitas Muhammadiyah Malang, Indonesia), Daroe Iswatiningsih (Universitas Muhammadiyah Malang, Indonesia), Wildan Suharso (Universitas Muhammadiyah Malang, Indonesia), Fachrunnisa Firdausi (Universitas Muhammadiyah Malang, Indonesia)	708
<i>Mobile Learning: Utilization of Media to Increase Student Learning Outcomes</i>	
Edy Budiman (Universitas Mulawarman, Indonesia), Sitti Nur Alam (STIMIK Sepuluh Nopember, Indonesia), Mohammad Aldrin Akbar (University of Yapis Papua, Indonesia)	712
<i>Study of the Android and ANN-based Upper-arm Mouse</i>	
Hartawan Suqihono (Ma Chung University, Indonesia), Romy Budhi Widodo (Universitas Ma Chung, Indonesia), Oesman Kelana (Universitas Ma Chung, Indonesia)	718
<i>FVEC feature and Machine Learning Approach for Indonesian Opinion Mining on YouTube Comments</i>	
Aina Musdholifah (Universitas Gadjah Mada, Indonesia), Ekki Rinaldi (Universitas Gadjah Mada, Indonesia)	724
<i>Clustering human perception of environment impact using Rough Set Theory</i>	
Ani Apriani (Sekolah Tinggi Teknologi Nasional Yoqyakarta, Indonesia), Iwan Riyadi Yanto (Universitas Ahmad Dahlan, Indonesia), Septiana Fathurrohmah (Sekolah Tinggi Teknologi Nasional Yogyakarta, Indonesia), Sri Haryatmi (Universitas Gajah Mada, Indonesia), D Danardono (Universitas Gajah Mada, Indonesia)	730
<i>E-Government Service Evaluation of Batu City Health Dept.using e-Govqual Approach and IPA Analysis</i>	
Evi Wahyuni, EDW (University of Muhammadiyah Malang, Indonesia), Dharma Pradana (University of Muhammadiyah Malang, Indonesia), Yasina Karina (University of Muhammadiyah Malang, Indonesia)	734
<i>Implementation of Obfuscation Technique on PHP Source Code</i>	
Maskur Maskur (Universitas Muhammadiyah Malang, Indonesia), Zamah Sari (Universitas Muhammadiyah Malang, Indonesia), Ahmad Miftakh (Universitas Muhammadiyah Malang, Indonesia)	738
<i>A Relative Rotation between Two Overlapping UAV's Images</i>	
Martinus Edwin Tjahjadi (National Institute of Technology (ITN) Malang, Indonesia), Fransisca Agustina (National Institute of Technology (ITN) Malang, Indonesia)	743
<i>Automatic Estimation of Human Weight From Body Silhouette Using Multiple Linear Regression</i>	
Hurriyatul Fitriyah (Universitas Brawijaya, Indonesia), Gembong Edhi Setyawan (Universitas Brawijaya, Indonesia)	749
<i>Variance and Symmetrical-based Approach for Optimal Alignment of 3D Model</i>	
Luh Putu Ayu Prapitasari (STMIK STIKOM Bali, Indonesia), Parth Rawal (Hamburg University of Technology, Germany), Rolf-Rainer Grigat (Hamburg University of Technology, Germany)	753

The Recognition Of Semaphore Letter Code Using Haar Wavelet And Euclidean Function
Leonardus Sandy Ade Putra (University of Diponegoro, Indonesia), Linggo Sumarno (Sanata Dharma University, Indonesia),
Vincentius Abdi Gunawan (University of Palangka Raya, Indonesia) 759

Game Show Themed Adventure, Audience Involvement, Destination Image, and Audience Behavior
Irwansyah Irwansyah (Universitas Indonesia, Indonesia), Dwininta Widyastuti (Universitas Indonesia, Indonesia) 764

Visual Emotion Recognition Using ResNet
Azmi Najid (Faculty of Computer Science, Universitas Indonesia, Indonesia), Dina Chahyati (Universitas Indonesia, Indonesia) 770

A Feature-Based Fragile Watermarking of Color Image for Secure E-Government Restoration
Lusia Rakhmawati (Universitas Negeri Surabaya, Indonesia), Wirawan Wirawan (Institut Teknologi Sepuluh Nopember, Indonesia), Suwadi Suwadi (ITS, Indonesia), Titiek Suryani (Institut Teknologi Sepuluh Nopember, Indonesia), E Endroyono (ITS & Institut Teknologi Sepuluh Nopember, Indonesia) 776

Stator Flux Oriented Control of Three-Phase Induction Motor with Improved Decoupling Scheme

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Abstract—This paper proposes an improved decoupling scheme of stator flux-oriented control for three-phase induction motor. The simulation software used in this paper is MATLAB Simulink®. The result of the simulation indicates that this stator flux-oriented control can control the speed of the rotor angle and stator magnetization current successfully. The angular velocity of 120 rad/s achieved by settling time 2 seconds in critically-damped response and steady-state error 0.083%. The controller can overcome the external disturbance in the form of load torque of 5 Nm which has been simulated in this paper. The proposed stator voltage decoupling scheme which is used in this simulation is correct and become one of success factor of this control method.

Keywords—Induction Motor; SFOC; Decoupling Model; Stator Flux Model

I. INTRODUCTION

Induction motor is a type of AC motor that is often used by industrial field because it has good self-starting ability, simple structure, low cost of production and maintenance, and reliable [1]. One of the problem of induction motor is that it is difficult to control. Further developments of power electronics and microelectronics open the issue of research and development of induction motor vector control. Some vector controlling techniques that have been proposed before are divided into two, direct vector control and indirect vector control based on field orientation vector. Direct vector control obtains the field orientation vector by using the quantity of stator terminal. In the other hand, indirect vector control obtains the field orientation vector by using slip frequency of machine.

Stator flux-oriented control of induction motor is a type of direct vector control because it uses the quantity of stator terminal. This method has several parts that can be developed, such as decoupling scheme and stator flux model.

This paper describes the simulation of three phase squirrel cage induction motor speed control based on stator flux orientation by using the proposed decoupling stator voltage scheme.

II. IM MODEL AND DRIVE OPERATING PRINCIPLE

To simulate the three-phase squirrel cage induction motor control, the dynamic model of induction motor is needed. The fundamental behavior of squirrel cage induction motor is usually based on a set of dynamical equations that can be

expressed in different reference frame. In this section, the induction machine model is defined by the stator currents and stator flux as state variables in the stationary α - β reference frame. The dynamic model that is used in this paper is same as in [4]. The following is the dynamic model of three phase squirrel cage induction motor:

$$\frac{di_{\alpha s}}{dt} = (R_s L_s i_{\alpha s} - N_p \omega_r L_m^2 i_{\beta s} - R_r L_m i_{\alpha r} - N_p \omega_r L_r L_m i_{\beta r} - L_r u_{\alpha s})K \quad (1)$$

$$\frac{di_{\beta s}}{dt} = (N_p \omega_r L_m^2 i_{\alpha s} - R_s L_r i_{\beta s} - N_p \omega_r L_r L_m i_{\alpha r} - R_r L_m i_{\beta r} - L_r u_{\beta s})K \quad (2)$$

$$\frac{di_{\alpha r}}{dt} = -(R_s L_m i_{\alpha s} - N_p \omega_r L_s L_m i_{\beta s} - R_r L_s i_{\alpha r} - N_p \omega_r L_s L_r i_{\beta r} - L_m u_{\alpha s})K \quad (3)$$

$$\frac{di_{\beta r}}{dt} = -(N_p \omega_r L_s L_m i_{\alpha s} - R_s L_m i_{\beta s} - N_p \omega_r L_r L_s i_{\alpha r} - R_r L_s i_{\beta r} - L_m u_{\beta s})K \quad (4)$$

$$K = \frac{1}{L_m^2 - L_s L_r} \quad (5)$$

Where:

- $u_{\alpha s}, u_{\beta s}$ = Stator voltages α - β in stationary reference frame (Volt)
- $i_{\alpha s}, i_{\beta s}$ = Stator currents α - β in stationary reference frame (Volt)
- R_s = Stator resistance (Ohm)
- R_r = Rotor resistance (Ohm)
- L_s = Stator inductance (Henry)
- L_r = Rotor inductance (Henry)
- L_m = Mutual inductance (Henry)
- ω_r = Rotor angle speed (rad/s)
- N_p = Number of pole pair

Figure 1 below shows the three-phase squirrel cage induction motor speed control based on stator field orientation block diagram with the proposed control algorithm.

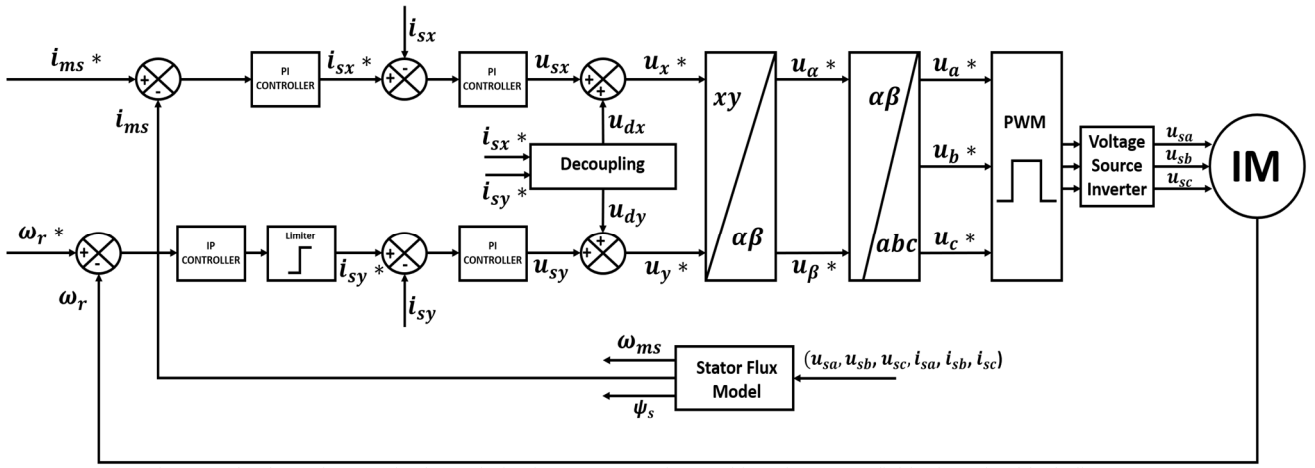


Figure 1 The three phase squirrel cage induction motor speed control based on stator field orientation block diagram

The algorithm inputs are reference rotor speed ω_r^* and stator magnetizing current i_{ms}^* . Main control loop consists of the speed IP regulator, the magnetizing current PI regulator, and the current controllers. The feedback signals of stator magnetizing current $\hat{i}_{ms}$ and rotor speed ω_r , needed for closed-loop control are provided by stator flux model and rotor speed sensor, respectively. The stator flux model utilizes the stator currents I_s and voltages U_s as the input variables. Decoupling scheme that is proposed in this paper is described later.

III. IMPROVED DECOUPLING SCHEME AND STATOR FLUX MODEL

A. Improved Decoupling Scheme

Decoupling scheme is a very important part of stator field oriented control. By using an appropriate decoupling scheme, the torque component and flux component can be separated and controlled respectively. In modelling the decoupling equation of induction motor stator voltage, it can be started from the equation of rotor voltage as in the following equation (6)

$$\bar{u}_{r\psi s} = R_r \bar{i}_{r\psi s} + L_r \frac{d\bar{i}_{r\psi s}}{dt} + L_m \frac{d\bar{i}_{s\psi s}}{dt} + j(\omega_{ms} - \omega_r)(L_r \bar{i}_{r\psi s} + L_m \bar{i}_{s\psi s}) \quad (6)$$

In equation (6) there is still a rotor current component, where the component must be eliminated by substituting equation (18) into equation (6), and by assuming the rotor coil of the squirrel cage type is a short circuit then $\bar{u}_{r\psi s} = 0$, then a new rotor voltage equation is obtain as follows.

$$0 = R_r \left[|\bar{i}_{ms}| - \frac{L_s \bar{i}_{s\psi s}}{L_m} \right] + L_r \frac{d|\bar{i}_{ms}|}{dt} - \left(\frac{L'_s L_r}{L_m} \right) \frac{d\bar{i}_{s\psi s}}{dt} + j\omega_{sl} \left[L_r |\bar{i}_{ms}| - \left(\frac{L'_s L_r}{L_m} \right) \bar{i}_{s\psi s} \right] \quad (7)$$

Then, it is necessary to separate the real and imaginary components from equation (7) to obtain the equation (8) and (9) as follows

$$\frac{L_m}{L'_s} \frac{d|\bar{i}_{ms}|}{dt} + \frac{L_m}{L_s T'_r} |\bar{i}_{ms}| = \frac{di_{sx}}{dt} + \frac{i_{sx}}{T'_r} - \omega_{sl} i_{sy} \quad (8)$$

$$\omega_{sl} \left(\frac{L_m |\bar{i}_{ms}|}{L'_s} - i_{sx} \right) = \frac{di_{sy}}{dt} + \frac{i_{sy}}{T'_r} \quad (9)$$

To obtain the stator voltage equation in the x and y axes it is necessary to substitute equations (22) and (10) into equations (8) and (9)

$$|\bar{i}_{ms}| = \frac{R_s}{\omega_{ms} L_m} \left(\frac{u_{sy}}{R_s} - i_{sy} \right) \quad (10)$$

The three phase squirrel cage induction motor stator voltage equation in the x and y axes are represented by the following equations (11) and (12)

$$u_{sx} = L'_s \frac{di_{sx}}{dt} + \left(\frac{L'_s}{T'_r} + R_s \right) i_{sx} - \left(\omega_{sl} - \frac{R_s}{\omega_{ms} L_s T'_r} \right) L'_s i_{sy} - \frac{L'_s}{\omega_{ms} L_s T'_r} u_{sy} \quad (11)$$

$$u_{sy} = \frac{L'_s \omega_{ms}}{\omega_{sl}} \frac{di_{sy}}{dt} + \left(R_s + \frac{L'_s \omega_{ms}}{\omega_{sl} T'_r} \right) i_{sy} + L'_s \omega_{ms} i_{sx} \quad (12)$$

In equations (11) and (12), it can be seen that there is coupling between the x and y components that can cause nonlinearity. Therefore, we can obtain the stator voltage decoupling equation as in the following equations (13) and (14)

$$u_{dx} = \frac{L'_s}{\omega_{ms} L_s T'_r} u_{sy} + \left(\omega_{sl} - \frac{R_s}{\omega_{ms} L_s T'_r} \right) L'_s i_{sy} \quad (13)$$

$$u_{dy} = -\omega_{ms} L'_s i_{sx} \quad (14)$$

The given stator voltage must satisfy the following equations (15) and (16)

$$u_x^* = u_{sx} + u_{dx} \quad (15)$$

$$u_y^* = u_{sy} + u_{dy} \quad (16)$$

Figure 2 below is the decoupling scheme proposed in this paper.

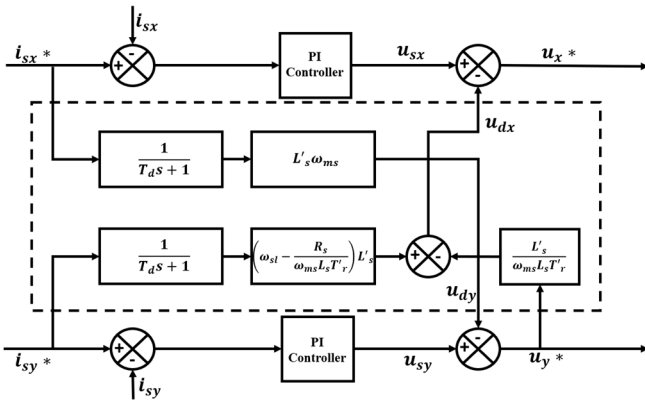


Figure 2 The improved decoupling scheme of three phase squirrel cage induction motor stator voltage

B. Stator Flux Model

Stator flux model is one of the important parts of stator field oriented control of induction motor. By using the appropriate stator flux model, the calculation results of the parameters required in the control objective will be more accurate and precise. In an attempt to model the stator flux model of three-phase squirrel cage induction motor, it can be started from the three phase squirrel cage induction motor stator voltage as in the following equation (17)

$$\bar{u}_{s\psi s} = R_s \bar{i}_{s\psi s} + L_s \frac{d\bar{i}_{s\psi s}}{dt} + L_m \frac{d\bar{i}_{r\psi s}}{dt} + j\omega_{ms} L_s \bar{i}_{s\psi s} + j\omega_{ms} L_m \bar{i}_{r\psi s} \quad (17)$$

In equation (17), there is still a rotor current component. As it is known that in the three phase squirrel cage induction motor, rotor current component is very difficult to obtain. Therefore, the rotor current component of the equation (17) must be eliminated by substituting the rotor current equation shown in equation (18)

$$\bar{i}_{r\psi s} = |\bar{i}_{ms}| - \frac{L_s \bar{i}_{s\psi s}}{L_m} \quad (18)$$

Substituting equation (18) into equation (17), equation (19) is obtained as the stator voltage equation of the three phase squirrel cage induction motor in which no rotor current component is present.

$$\bar{u}_{s\psi s} = R_s \bar{i}_{s\psi s} + L_m \frac{d|\bar{i}_{ms}|}{dt} + j\omega_{ms} L_m |\bar{i}_{ms}| \quad (19)$$

Then, simplify equation (19) to its real and imaginary component and make it in the x-y stator current equation as in the following (20) and (21) equations.

$$i_{sx} = \frac{u_{sx}}{R_s} - \frac{L_m}{R_s} \frac{d|i_{ms}|}{dt} \quad (20)$$

$$i_{sy} = \frac{u_{sy}}{R_s} - \omega_{ms} L_m \frac{|i_{ms}|}{R_s} \quad (21)$$

To obtain the equation of stator flux model, equation (20) and (21) must be processed to obtain the stator flux model as follows.

$$\frac{d|i_{ms}|}{dt} = \frac{u_{sx}}{L_m} - \frac{R_s}{L_m} i_{sx} \quad (22)$$

$$\omega_{ms} = \frac{1}{L_m |i_{ms}|} (u_{sy} - R_s i_{sy}) \quad (23)$$

$$\psi_s = L_m i_{ms} \quad (24)$$

$$\theta_e = \int \omega_{ms} dt \quad (25)$$

Equations (22) – (25) are the basic equations of stator flux model which are used to calculate the parameters of the three phase squirrel cage induction motor used for control. The representation of the stator flux model in a block diagram can be made from equations (22) – (25). Figure 3 below shows a diagram of the stator flux model of three phase squirrel cage induction motor that is used in this research.

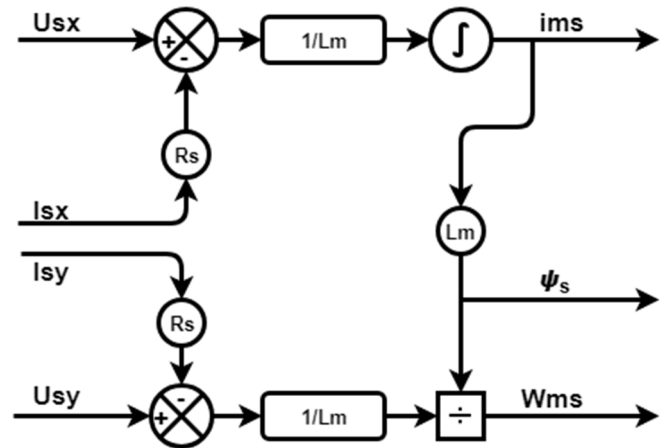


Figure 3 Stator flux model of three phase squirrel cage induction motor

IV. SIMULATION RESULT

The proposed simulation of three phase squirrel cage induction motor in this paper is simulated by C-MEX S-Function block diagram in MATLAB Simulink. The simulation was run for 10 seconds. Figure 4 below is the simulation block diagram in MATLAB Simulink.

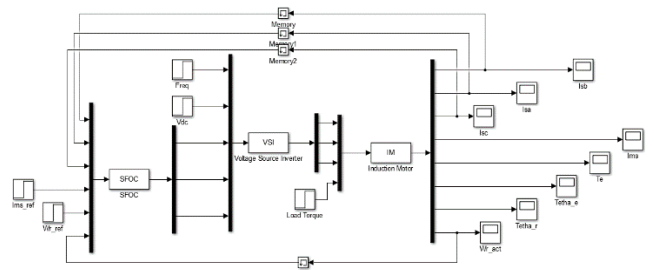


Figure 4 CMEX S-Function Simulation Diagram in MATLAB Simulink

The test was done within two condition testing. For the first segment, system was tested by stating the load torque as 0 Nm, the stator magnetizing current as 1.45 A and the rotor speed as 120 rad/s. This is shown as a no load testing. The second segment was tested by stating the load torque as 5 Nm after 5 seconds of the simulation, the stator magnetizing current as 1.45 A and the rotor speed as 120 rad/s. This is shown as load testing.

The parameter and rating of a three-phase induction motor that is used in this simulation shown in the table below

Table 1 Induction Motor Parameters and Ratings

V_{rated}	220 V	R_r	1.7979 Ω
I_{rated}	5.1 A	L_s	0.4633 H
N_{rated}	1433 rpm	L_r	0.4633 H
R_s	2.4057 Ω	L_m	0.4531 H

A. No Load Testing

Figure 5, 6, 7, and 8 showed the rotor speed, stator magnetizing current, stator voltage of three phase induction motor during the no load testing. Based on figure 5, the response of the rotor speed is critically-damped by settling time of 2 seconds and the steady-state error is 0.083%. Figure 6 showed the response of stator magnetizing current that is successfully controlled by the controller. The response is fluctuated in the range of 1.45 A. Figure 7 showed the response of stator voltage (control signal) during the no load test. The amplitudo of control signal is 130 Volt. Figure 8 showed the response of stator current during the no load testing. The amplitudo of stator current in steady-state condition is 2 A, still below the maximum current allowed.

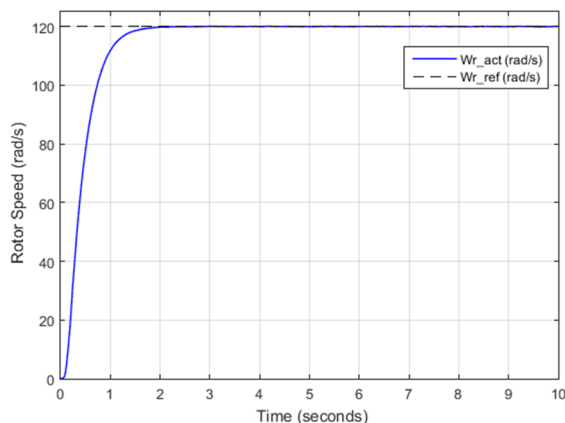


Figure 5 Rotor speed response in no load testing

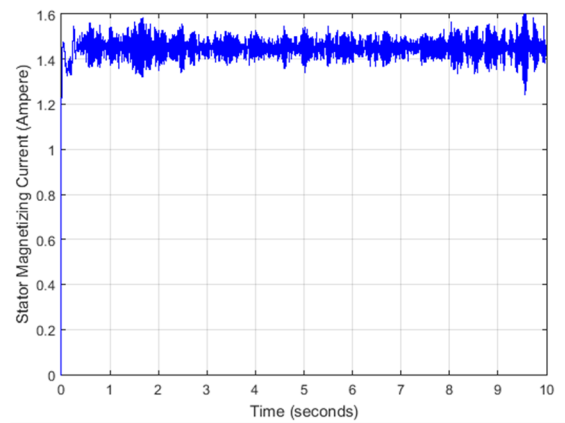


Figure 6 Stator magnetizing current response in no load testing

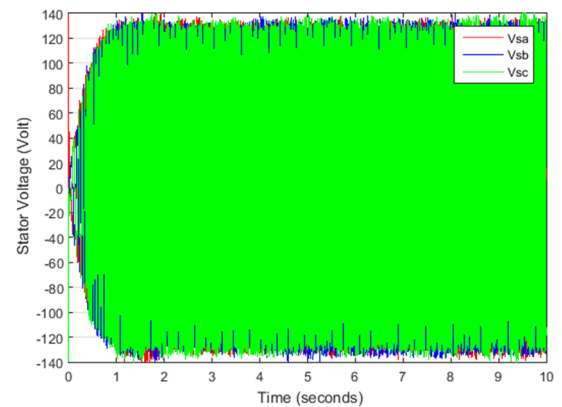


Figure 7 Stator voltage (control signal) response in no load testing

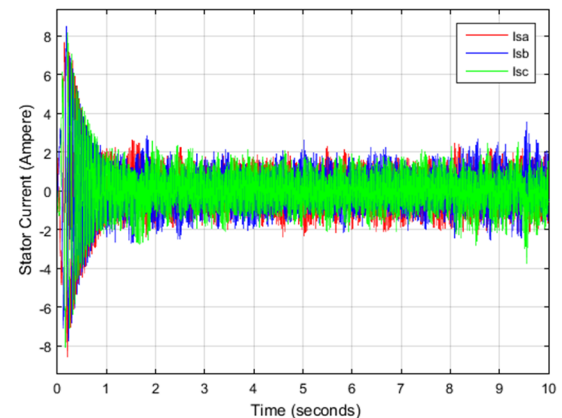


Figure 8 Stator current response in no load testing

B. Load Testing

Figure 9, 10, 11, and 12 showed the rotor speed, stator magnetizing current, and stator voltage of three phase induction motor during load testing. Based on figure 9, the response of the rotor speed is critically-damped by settling time of 2 seconds, and when the load torque was changed from 0 to 5 Nm after 5 seconds of simulation, the rotor speed decreased but the controller can handle the load torque and the rotor speed

increased back to 120 rad/s. Figure 10 showed that the response of stator magnetizing current in the load testing is same as in the no load testing. Figure 11 showed the response of control signal (stator voltage) during the load testing. The amplitude of control signal increased from 130 Volt to 150 Volt after the load torque was applied to the system. Figure 12 showed the response of stator current during load testing. The amplitude of stator current increased from 2 A to 4 A after the load torque was applied to the system.

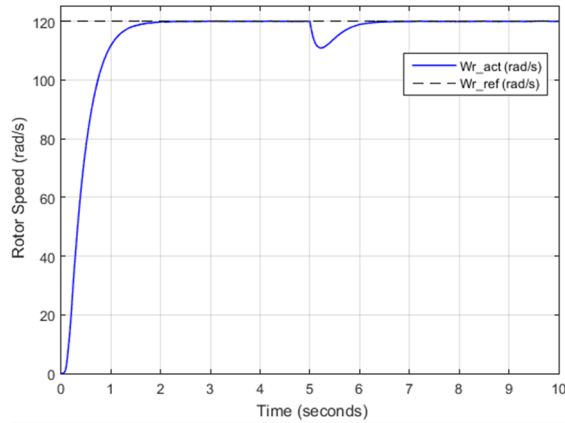


Figure 9 Rotor speed response in load testing

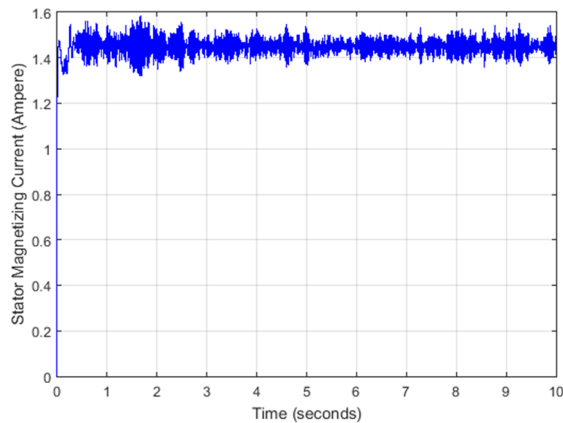


Figure 10 Stator magnetizing current response in load testing

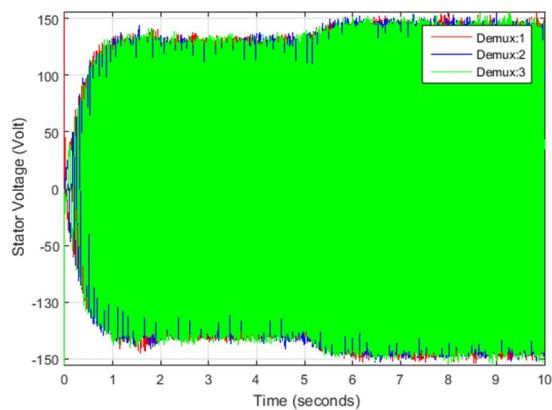


Figure 11 Stator voltage (control signal) response in load testing

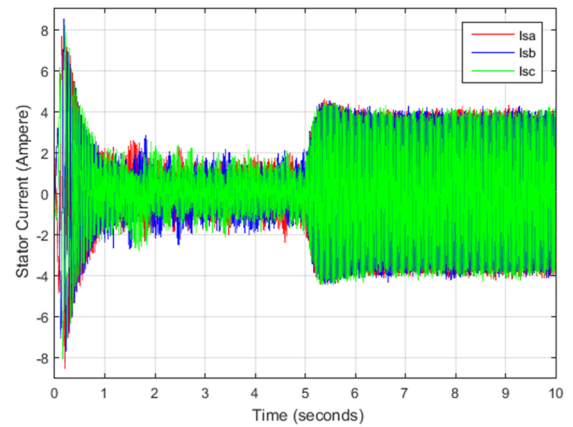


Figure 12 Stator current response in load testing

V. CONCLUSION

The result of the simulation indicates that this stator flux oriented control with improved stator voltage decoupling scheme is capable to control both speed of the rotor angle and stator magnetization current successfully. The angle velocity of 120 rad/s achieved by settling time 2 seconds in critically-damped response and steady-state error 0.083%. The controller can overcome the external disturbance in the form of load torque of 5 Nm which has been simulated in this paper. The proposed stator voltage decoupling scheme which are used in this simulation is correct and also become one of success factor of this control method.

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