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

Arif, I. ✉, Harini, B.W. ✉, Yusivar, F. ✉

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Department of Electrical Engineering Faculty of Engineering, Universitas Indonesia, Depok, Indonesia

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.

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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 lEEE 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

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

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

Irvan Arif, Bernadeta Wuri Harini, and Feri Yusivar
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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:

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

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

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

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

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

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.

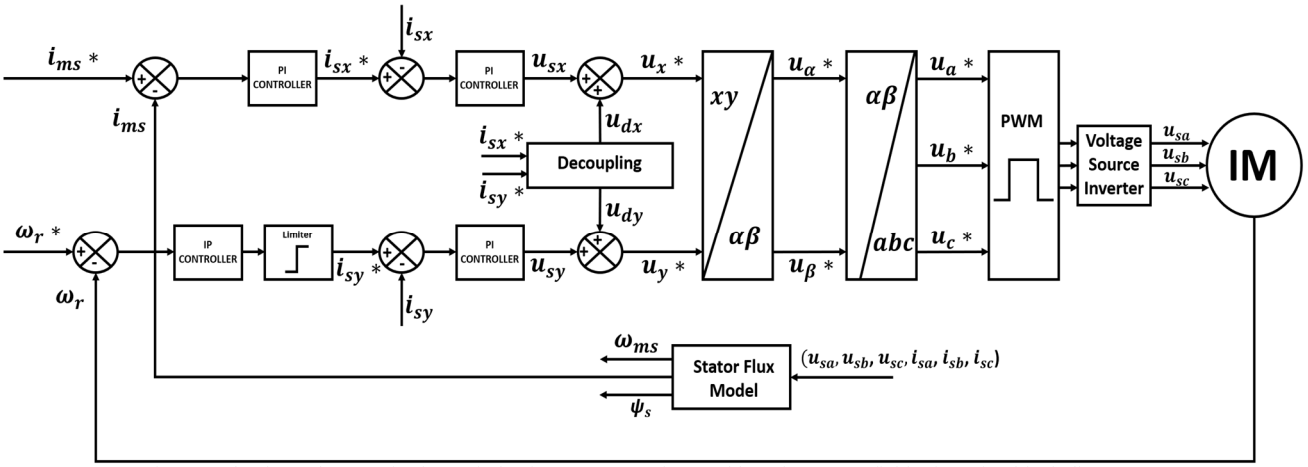

Figure 1 The three phase squirrel cage induction motor speed control based on stator field orientation block diagram

The algorithm inputs are reference rotor speed $\omega_r{}^*$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 $\hat{\imath}_{ms}$ 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)

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

In equation (6) there is still a rotor current component, where the component mus 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.

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

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

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

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

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)

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

The three phase squirrel cage induction motor stator voltage equation in the x and y axesarepresented 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.

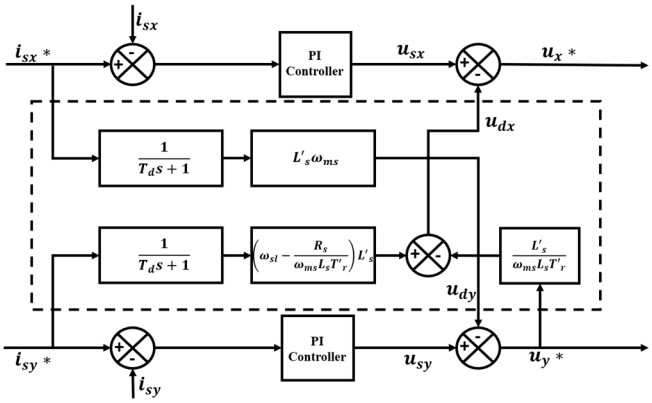

Figure 2 The improved decoupling scheme of three phase squirrel cage induction motor stator voltage

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 statof 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)

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

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)

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

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.

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

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.

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

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

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

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

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

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

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

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.

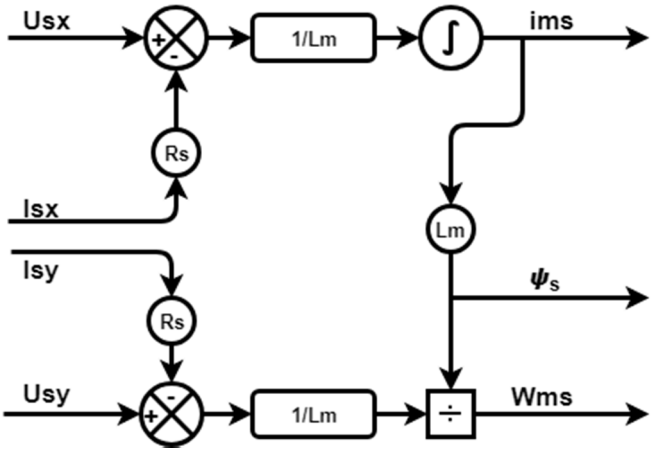

Figure 3 Stator flux model of three pase squirrel cage induction motor

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.

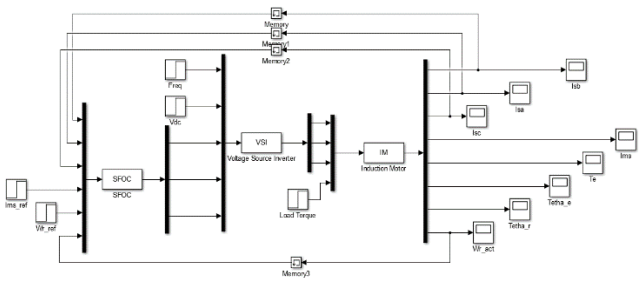

Figure 4 CMEX S-Function Simulation Diagram in MATLAB Simulink

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.

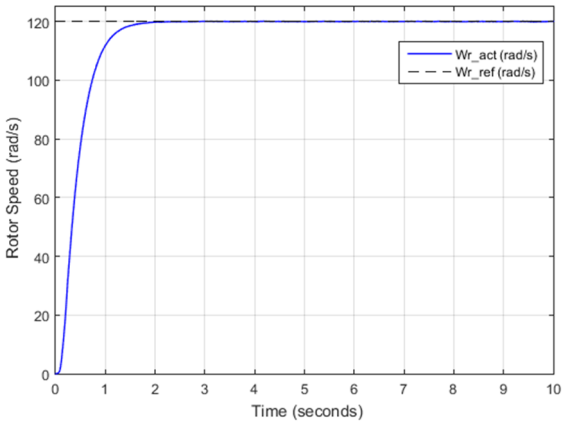

Figure 5Rotor speed response in no load testing

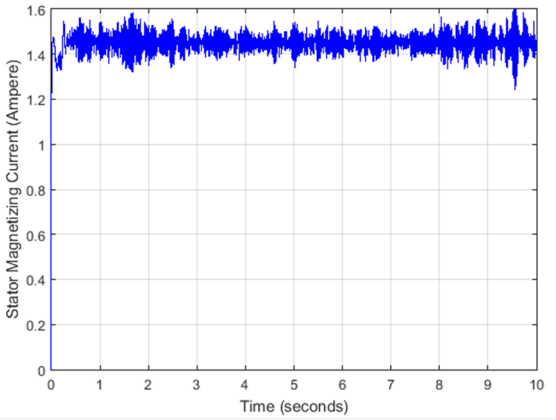

Figure 6 Stator magnetizing current response in no load testing

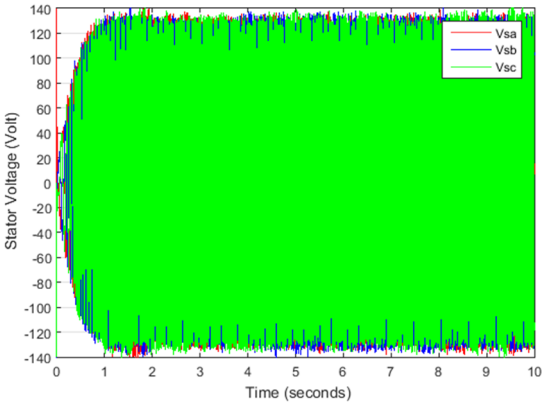

Figure 7 Stator voltage (control signal) response in no load testing

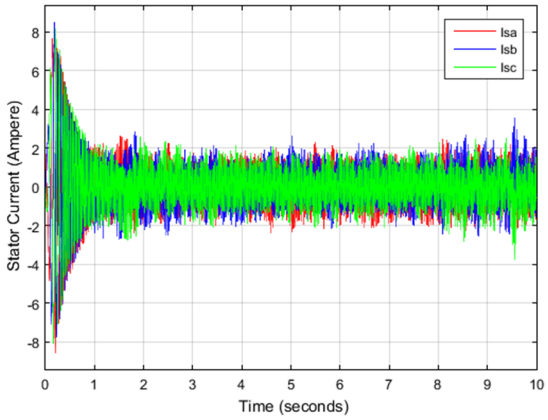

Figure 8 Stator current response in no load testing

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 amplitudo 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 amplitudo of stator current increased from 2 A to 4 A after the load torque was applied to the system.

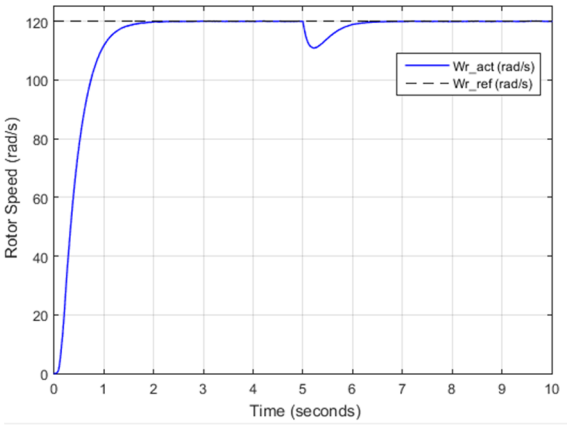

Figure 9 Rotor speed response in load testing

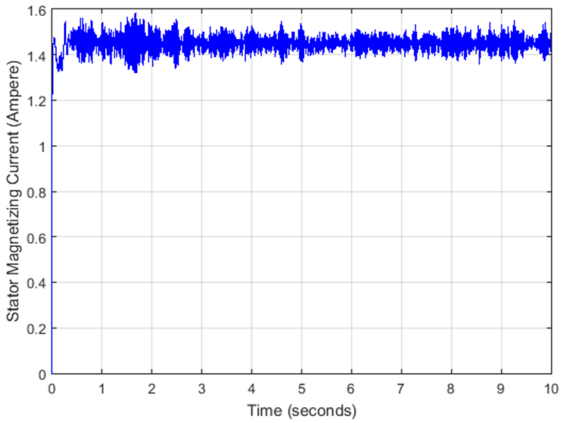

Figure 10 Stator magnetizing current response in load testing

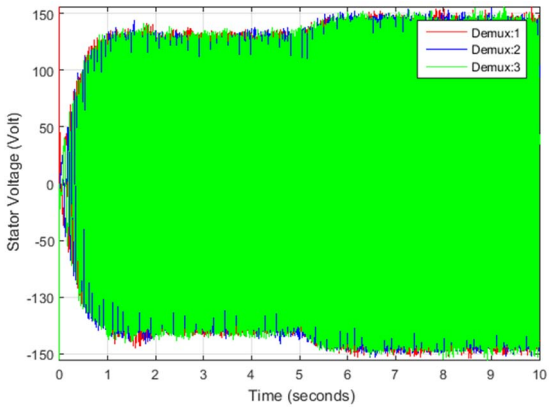

Figure 11 Stator voltage (control signal) response in load testing

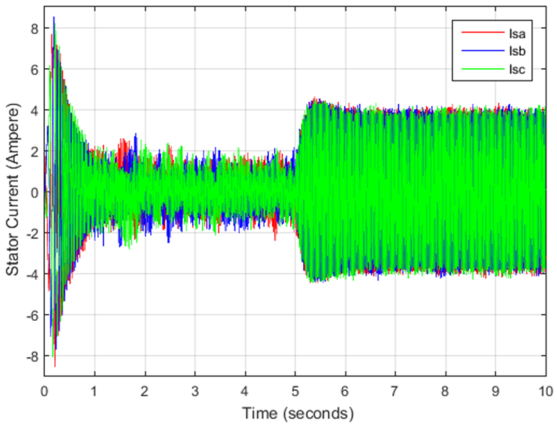

Figure 12 Stator current response in load testing

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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