Parameter Identification Scheme for Induction Motors Using Output Inter-Sampling Approach

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Abstract –This paper shows a parameter identification scheme for speed sensorless vector controlled induction motor using output inter-sampling approach and experimentally evaluates this method. It is well known that both the rotor speed and the rotor time-constant of induction motors cannot be identified under steady state operation. This is because vector control system of induction motors consists of a closed loop system, in which *d* axis current is always kept constant under steady state operation. In this paper, a novel signal processing method, output inter-sampling approach, is employed from the viewpoint of the amplitude of high frequency signal injection to realize accurate parameter identification. This paper describes an identification strategy based on output inter-sampling approach and robust estimation method of the *d* axis using adaptive observer with robust observer design, and finally accuracy of parameter identification is experimentally evaluated using 1.5kW test induction motor.

Keywords - Induction Motor, Parameter Identification, Output Inter-Sampling Approach

I. INTRODUCTION

Induction motors have widely been used for traffic machines, in industrial fields, and so on. Especially, speed sensorless vector controlled induction motor is superior to any other electrical motors in terms of cost, robustness, and its performance is still being improved.

Generally, the mathematical model of the induction motor necessitates in order to construct the control system, which means that all parameters should be identified in advance or in real-time. Especially, some of parameters need to be identified in on-line since the dynamics of the induction motor might change because of parameter perturbation, which is caused by temperature variation or load condition, and speed variation. This parameter identification problem of the vector controlled induction motor had been attractive for many researchers. Shinnaka has proved, however, that the simultaneous identification of both rotor speed and rotor time constant is impossible in continuous time domain [1]. This is because some current control loops are often constructed in vector control system of induction motors, in which d axis current is always kept constant in steady state operation.

In order to avoid this problem, many researches have already proposed some kinds of strategies such as high frequency signal injection to obtain the parameter knowledge from only stator quantities, which would cause the torque vibration and the degradation of efficiency unfortunately [2][3][4]. In addition, a method of utilizing the transitional d axis estimation error, which is appeared just when the rotor speed changes of the induction motor, have been proposed so far [5]. Consequently, simultaneous identification at steady state is impossible without high frequency signal injection, and is still remains as an open problem in continuous time domain.

For parameter identification, it is desirable to decrease the amplitude of the injected signal, but there exists few methods to minimize the amplitude of this unnecessary signal to control induction motors. In recent years, the closed-loop identification is becoming one of the most interesting problems among researchers in control theory field, which means that the identification of the input-output characteristics of the plant with feedback controllers. One of the difficulties on the closed-loop identification is known that all of the parameter knowledge cannot be obtained from input quantities (stator voltages) and the plant output (stator current) because some variables (e.g. d-axis current) are kept constant in steady state operation, which results in that some of parameters to be identified are not excited. In this problem (closed-loop identification), Sano et al. have proposed 'Output Inter-Sampling Approach' to realize closed-loop identification [6]. According to this literature, this approach makes it possible to relax necessary condition of the closed-loop identification. Even although this approach necessitates high frequency signal injection, this literature concludes that it is possible to reduce the amplitude of this unnecessary signal for plant control [7].

This paper proposes an appropriate strategy to apply 'Output Inter-Sampling Approach' for identification of speed sensorless vector controlled induction motor in steady state operation. Based on 'Output Inter-Sampling Approach' technique, this paper will firstly discuss simultaneous identification problem in discontinuous time domain, in which 'Output Inter-Sampling Approach' is utilized to identify the PWM inverter fed induction motor under speed sensorless vector control. Although an exogenous signal is also injected in this paper, reduction of the amplitude of this injected signal can be expected by using output inter-sampling approach.

This paper is organized as follows: Firstly, the identification model of the induction motor is defined in section II. Next, output inter-sampling approach is introduced for identification of vector controlled induction motor in section III, and a design of an adaptive observer is described, which can reduce phase estimation error of rotor flux in section IV. This becomes necessary condition for accurate d-axis model identification. Finally, some

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identification experiments are carried out, and the feasibility and the effectiveness of the proposed strategy are shown in Section V. Section VI describes the conclusions of this paper.

II. IDENTIFICATION MODEL OF INDUCTION MOTOR

This section defines the identification model of an induction motor. It should be noted that this model must not include rotor speed knowledge because this paper aims to identify parameters under speed sensorless vector control.

The state equation of the induction motor in a rotational reference frame (d-q axis) aligned with the rotor flux direction is expressed by

$$\frac{d}{dt}\begin{bmatrix} i_{ds} \\ i_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} = \begin{bmatrix} -\frac{R_s+M^2R_r/L_r^2}{\sigma L_s} & \omega & \frac{MR_r}{\sigma L_s L_r^2} & \frac{\omega_r M}{\sigma L_s L_r} \\ -\omega & -\frac{R_s+M^2R_r/L_r^2}{\sigma L_s} & -\frac{\omega_r M}{\sigma L_s L_r} & \frac{MR_r}{\sigma L_s L_r^2} \\ \frac{MR_r}{L_r} & 0 & -\frac{R_r}{L_r} & \omega-\omega_r \\ 0 & \frac{MR_r}{L_r} & -(\omega-\omega_r) & -\frac{R_r}{L_r} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} + \frac{1}{\sigma L_s}\begin{bmatrix} v_{ds} \\ v_{qs} \\ 0 \\ 0 \end{bmatrix} \qquad (1)$$

where

v_{ds}, v_{qs}: stator voltages on d-q axis

i_{ds}, i_{qs} : stator currents on d-q axis

λ_{dr}, λ_{qr} : rotor flux on d-q axis

R_s, R_r : stator and rotor resistances

L_s, L_r : stator and rotor inductances

M : mutual inductance

ω_r : angular speed of rotor in electrical angle

ω : angular frequency of rotational reference frame d-q axis

$\sigma = 1 - M^2 / L_s L_r$: total leakage coefficient

In this paper, the direction of the actual rotor flux can be assumed to be aligned with that of the estimated flux by using an adaptive observer with a robust gain design, rotor flux can be regarded as $\lambda_{dr} = |\lambda_r|,\ \lambda_{qr} = 0$, respectively. Therefore, (1) is rewritten by the following equation:

$$\frac{d}{dt}\begin{bmatrix} i_{ds} \\ i_{qs} \\ |\lambda_r| \end{bmatrix} = \begin{bmatrix} a & \omega & c \\ -\omega & a & -\frac{\omega_r M}{\sigma L_s L_r} \\ b & 0 & e \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ |\lambda_r| \end{bmatrix} + g\begin{bmatrix} v_{ds} \\ v_{qs} \\ 0 \end{bmatrix} \qquad (2)$$

in which

$$a = -\frac{R_s + M^2R_r/L_r^2}{\sigma L_s}, \quad b = \frac{MR_r}{L_r},$$
$$c = \frac{MR_r}{\sigma L_s L_r^2}, \quad e = -\frac{R_r}{L_r}, \quad g = \frac{1}{\sigma L_s}.$$

This induction motor model is then digitized with sampling time T from the first row in (2) and the third one as following:

$$\begin{aligned} i_{ds}[k+1] &= (1+aT)i_{ds}[k] + \frac{cbT^2z^{-1}}{1-(1+eT)z^{-1}}i_{ds}[k] \\ &\quad +\omega T i_{qs}[k] + gTv_{ds}[k]\ , \\ &= \frac{(1+aT)-(1+(a+e)T-(ae-bc)T^2)z^{-1}}{1+(-1-eT)z^{-1}}i_{ds}[k] \\ &\quad +\omega T i_{qs}[k] + gTv_{ds}[k]\ , \end{aligned} \qquad (3)$$

and $(ae - be)T^2$ is neglectable in this equation, the following equation can be obtained:

$$i_{ds}[k] = \frac{gTz^{-1} - gT(1+eT)z^{-2}}{1-(2+(a+e)T)z^{-1}+(1+(a+e)T)z^{-2}}v'[k]\ , \qquad (4)$$

in which $v'[k] = \omega\sigma L_s i_{ds}[k] + v_{ds}[k]$. It should be noted that ω_r is not included in (4) because back EMF(Electro-Magnetic Force) never appear in the direction of rotor flux (d axis). Consequently, this paper deals with this equation as identification model of the induction motor, whose parameters a, e and g should be identified.

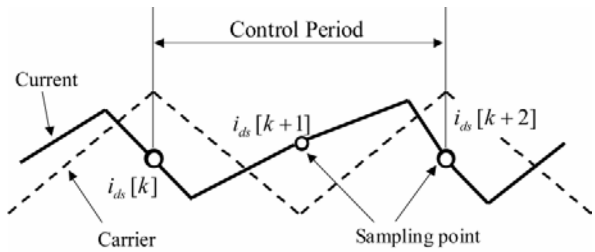

Fig. 1: Output inter-sampling approach in consideration of PWM carrier

III. PARAMETER IDENTIFICATION USING OUTPUT INTER-SAMPLING APPROACH

As previously mentioned, it is impossible to identify all parameter of sensorless vector controlled induction motor under steady state. Hence, some high frequency signals or 'Maximum-length linear shift register sequence signal' injection are required. It should be noted that these signals to identify some parameters would deteriorate performance of controlled motor and require larger capacity of PWM inverter. Hence, it can be concluded that smaller amplitude of injected signal would be desirable. Few approaches to reduce this injected signal amplitude, however, have not been proposed so far. This section describes a novel identification method using output inter-sampling approach [6].

Output inter-sampling [6] means to detect outputs of controlled object at smaller detection period T_d than the

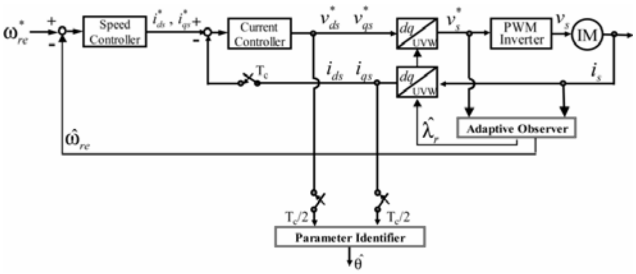

Fig. 2: Speed senssorless vector control system using adaptive observer with parameter identifier based on output inter-sampling approach

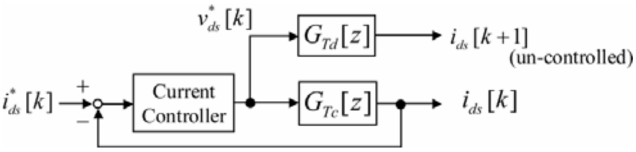

Fig. 3: Representation of single-input multi-out put model structure

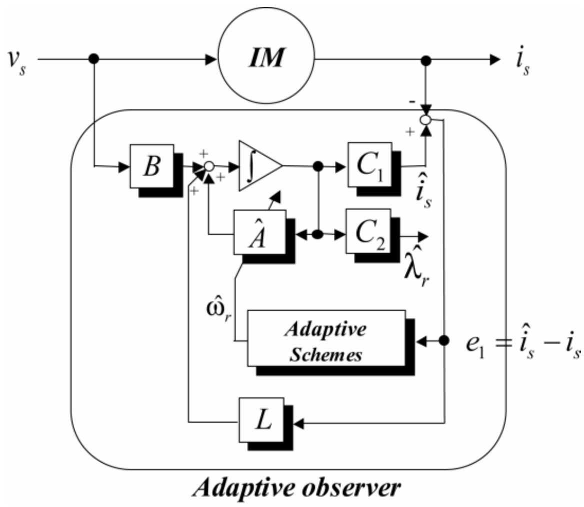

Fig. 4: configuration of adaptive observer

control-sampling period T_c $(T_d < T_c)$. The detail time chart in this paper is shown in Fig.1. In general, inter-sampling rate $p = T_c / T_d$ can be arbitrarily determined [6]. It should be noted that, in the case of AC drives, the control period and the detection one are usually synchronized with the PWM carrier in order to reduce the influence of the PWM carrier harmonics, which is often superimposed on detected stator current. Hence, the same consideration is required even when carrying out the output inter-sampling for the identification accuracy improvement. As a result, it is thought out that the current should be detected at the point as shown in Fig.1. Therefore, inter-sampling rate p is set to p=2. In this paper, the control period is set to 200 μs and the detection period is made into 100 μs since carrier frequency is 5kHz. All sampling operations are synchronized.

Fig. 2 shows speed sensorless vector control system using an adaptive observer with proposed identifier based on inter-sampling approach, in which the proposed parameter identifier is constructed on *d-q* axis because the identification model structure is also expressed in this coordinate as shown in (4).

Fig.3 represents the single-input multi-output model structure of inter-sampled system, in which $G_{Tc}[z]$ and $G_{Td}[z]$ mean the pulse transfer functions from the reference voltage $v_{ds}^{*}[k]$ to $i_{ds}[k]$ and $i_{ds}[k+1]$, respectively. It should be noted from this figure that $i_{ds}[k]$ is forced to be its reference $i_{ds}^{*}[k]$, but $i_{ds}[k+1]$ is not controlled. Hence, this inter-sampled system partly constructs the open-loop system, the design of vector controller is not affected by applying output inter-sampling approach. It should be noted that the inter-sampled data $i_{ds}[k+1]$ would perturb due to influence of parameter mismatches because this inter-sampled current is not regulated by the current controller. This implies that $i_{ds}[k+1]$ possesses more knowledge on induction motor parameters. Therefore, it can be expected that the amplitude of the injected signal is reduced for accurate parameter identification. In other words, identifiability condition can be extremely relaxed by using this inter-sampling approach [6], and identification accuracy will be improved if this input-output signal possesses enough degree in terms of PE property.

In this paper, three parameters, a, e and g are identified based on ARMAX (Auto-Regressive Moving Average eXogenous) model in Matlab/System Identification Toolbox.

IV. ROBUST ADAPTIVE OBSERVER DESIGN WITH LESS PHASE ERROR

The proposed identification requires that the direction of the actual rotor flux is assumed to be aligned with that of the estimated flux by using an adaptive observer. In adaptive observers with speed adaptation, the flux estimation error theoretically converge to zero in steady state despite there exists parameter mismatches in a, e and g, while the steady state error of the speed adaptation would be induced. In reality, however, rotor flux cannot be perfectly estimated at steady state as well as transient state due to detuned parameter used in the adaptive observer. Hence it is so necessary to the design the adaptive observer, which can estimate the direction of rotor flux (d axis) for precise parameter identification. This section describes the design strategy of observer gain to reduce phase estimation error of rotational reference frame (d-q axis) [9].

A. Configuration of adaptive observer

In this subsection, the adaptive observer with the speed identifier is briefly outlined.
The state equation of the induction motor in a rectangular coordinate fixed to the stator is expressed by

$$\frac{d}{dt}\boldsymbol{x} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{v}_s, \tag{5}$$

$$\boldsymbol{i}_s = [\boldsymbol{I} \quad \boldsymbol{o}_{2\times 2}]\,\boldsymbol{x} = \boldsymbol{C}_1\boldsymbol{x} \ , \tag{6}$$

in which

$$A = \begin{bmatrix} a\boldsymbol{I} & c\boldsymbol{I} - \frac{\omega_r M}{\sigma L_s L_r}\boldsymbol{J} \\ b\boldsymbol{I} & e\boldsymbol{I} + \omega_r \boldsymbol{J} \end{bmatrix}, \ B = \begin{bmatrix} g\boldsymbol{I} & 0_{2\times 2} \end{bmatrix}^T \ ,$$

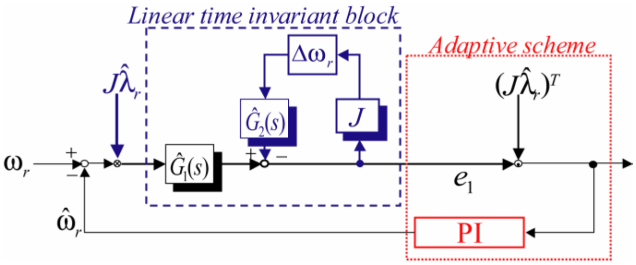

Fig. 5: Block diagram of speed identification system

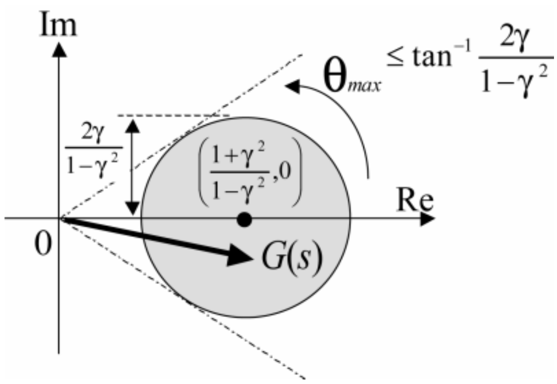

Fig. 6: γ -Positive realness

Where, I and J are the unit matrix and the skew symmetric matrix of 2x2, respectively.

For the rotor flux estimation and the speed identification, the adaptive full-order observer is constructed as follows:

$$\frac{d}{dt}\hat{\boldsymbol{x}} = \hat{\boldsymbol{A}}\hat{\boldsymbol{x}} + \boldsymbol{B}\boldsymbol{v}_s + \boldsymbol{L}\boldsymbol{e}_1, \tag{7}$$

$$\hat{\boldsymbol{i}}_s = \boldsymbol{C}_1\hat{\boldsymbol{x}} \ , \tag{8}$$

$$\hat{\boldsymbol{\lambda}}_r = [\boldsymbol{o}_{2\times 2} \quad \boldsymbol{I}]\,\hat{\boldsymbol{x}} \ = \boldsymbol{C}_2\hat{\boldsymbol{x}} \ , \tag{9}$$

$$\hat{\omega}_r = \left(K_p + \frac{K_I}{s}\right)\left((\boldsymbol{J}\hat{\boldsymbol{\lambda}}_r)^T\boldsymbol{e}_1\right) \ , \tag{10}$$

where $\boldsymbol{e}_1 = \hat{\boldsymbol{i}}_s - \boldsymbol{i}_s$ and L means an observer gain. Fig.4 shows the configuration of the adaptive observer, in which adaptive scheme stands for equation (10). In this paper, ω_r is regarded as a time invariant parameter due to the difference between the time constant of mechanical system and that of electrical system.

B. Error system of speed identification

Subtracting (5) and (6) from (7) and (8), the influence of current estimation error e_1 on speed identification error $\Delta\omega_r = \hat{\omega}_r - \omega_r$ can be described as follow:

$$\begin{aligned} \boldsymbol{e}_1 &= \boldsymbol{C}_1(s\boldsymbol{I} - \hat{\boldsymbol{A}} - \boldsymbol{L}\boldsymbol{C}_1)^{-1}\boldsymbol{B}_{\omega_r}(-\Delta\omega_r\boldsymbol{J}\boldsymbol{\lambda}_r) \\ &= \hat{\boldsymbol{G}}_1(s)\boldsymbol{J}\boldsymbol{\lambda}_r(\omega_r - \hat{\omega}_r) \ , \end{aligned} \tag{11}$$

in which

$$\hat{\boldsymbol{G}}_1(s) = \boldsymbol{C}_1(s\boldsymbol{I} - \hat{\boldsymbol{A}} - \boldsymbol{L}\boldsymbol{C}_1)^{-1}\boldsymbol{B}_{\omega_r} \ , \tag{12}$$

$$\boldsymbol{B}_{\omega_r} = [\boldsymbol{I}/\varepsilon \quad -\boldsymbol{I}]^T. \tag{13}$$

In addition, the influence of flux estimation error $\boldsymbol{e}_2 = \hat{\boldsymbol{\lambda}}_r - \boldsymbol{\lambda}_r$ on $\Delta\omega_r$ is given by

$$\begin{aligned} \boldsymbol{e}_2 &= \boldsymbol{C}_2(s\boldsymbol{I} - \hat{\boldsymbol{A}} - \boldsymbol{L}\boldsymbol{C}_1)^{-1}\boldsymbol{B}_{\omega_r}(-\Delta\omega_r\boldsymbol{J}\boldsymbol{\lambda}_r) \\ &= \hat{\boldsymbol{G}}_2(s)(-\Delta\omega_r\boldsymbol{J}\boldsymbol{\lambda}_r) \end{aligned} \tag{14}$$

in which

$$\hat{\boldsymbol{G}}_2(s) = \boldsymbol{C}_2(s\boldsymbol{I} - \hat{\boldsymbol{A}} - \boldsymbol{L}\boldsymbol{C}_1)^{-1}\boldsymbol{B}_{\omega_r} \ . \tag{15}$$

Hence, the transfer function from the actual rotor flux to the estimated one in consideration of $\Delta\omega_r$ can be formulated as

$$\hat{\boldsymbol{\lambda}}_r = \boldsymbol{\lambda}_r + \boldsymbol{e}_2 = (\boldsymbol{I} + \boldsymbol{G}_2(s)\Delta\omega_r\boldsymbol{J})\,\boldsymbol{\lambda}_r \ , \tag{16}$$

and substituting (16) into (11),

$$\boldsymbol{e}_1 = \left(\boldsymbol{I} + \hat{\boldsymbol{G}}_2(s)\Delta\omega_r\boldsymbol{J}\right)^{-1}\left(\hat{\boldsymbol{G}}_1(s)\boldsymbol{J}\hat{\boldsymbol{\lambda}}_r(\omega_r - \hat{\omega}_r)\right) \tag{17}$$

can be obtained. From (10) and (17), the nonlinear feedback loop of the speed identification is constructed as shown in Fig.5.

To reduce the phase estimation error, the phase characteristics of the transfer function in (16) needs to be manipulated as small as possible. In the following, the design, which can reduce phase estimation error, is described.

C. γ –Positive realness for robust flux phase estimation

In this subsection, a notion of γ -positive realness [10] is introduced for the phase specification of a transfer function, since the notion of γ -positive realness enables us to solve the phase specification.

Given a transfer function $G(s)$ in general, $G(s)$ is γ -positive real [10] if and only if, in case of single-input single-output system $G(s)$, the Nyquist diagram of $G(s)$ exists in the circle (see Fig.6) of which center and radius are $\left(\frac{1+\gamma^2}{1-\gamma^2}, \ 0\right)$ and $\frac{2\gamma}{1-\gamma^2}$, respectively. It turns out from Fig.6 that the maximum of $|\angle G(s)|$ can be bounded by

$$\theta_{\max} = \tan^{-1}\frac{2\gamma}{1-\gamma^2} \ . \tag{18}$$

It can be seen from this equation that the smaller γ is found, the smaller $\theta_{\max}$ is achieved. Based on γ-positive realness, it is possible that the phase characteristics of

$G(s)$ are manipulated. The design strategy to find $G(s)$ γ-positive real is called as γ-positive real problem.

In this observer gain design, $I + \hat{G}_2(s)\Delta\omega_r J$ should be γ-positive real for small positive scalar γ. In this paper, this design strategy is introduced for the phase characteristics shaping of certain transfer function.

To solve directly the aforementioned design problem is difficult, but [10] has also shown that the problem can be solved as H_∞ control problem by using Cayley transformation:

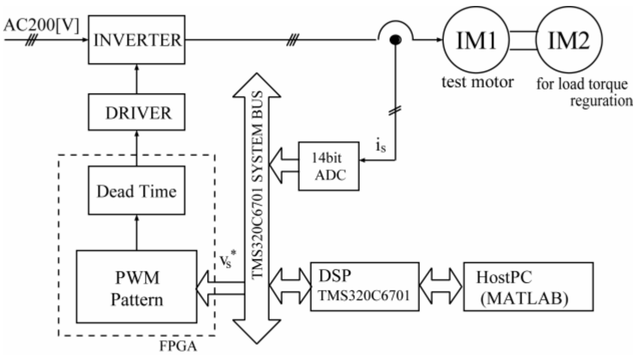

Fig. 7: Experimental setup

$$H(s) = (G(s) - I)(G(s) + I)^{-1}. \tag{19}$$

Then, $|\angle G(s)|$ can be reduced by applying H_∞ control problem for $H(s)$.

D. Observer gain design based on γ-positive real problem

The transfer function from actual rotor flux to estimated one is given by (16), and this phase characteristics should be reduced. Using γ-positive realness, necessary condition for stable speed identification is that $I + \hat{G}_2(s)\Delta\omega_r J$ is γ-positive real for small positive scalar γ under given $\Delta\omega_r$, because to achieve positive real $\hat{G}_1(s)$ is almost equivalent to the reduction of flux phase estimation error as previously described [9].

According to our design strategy [9], $I + \hat{G}_2(s)\Delta\omega_r J$ is γ-positive real for small positive scalar γ if and only if there exists $X = X^T > 0$, and K such that

$$\begin{bmatrix} X\Gamma + KC_1 + \Gamma^T X + C_1^T K^T & XB_{\omega_r}\Delta\omega_r J/\sqrt{2} & C_2^T/\sqrt{2} \\ (B_{\omega_r}\Delta\omega_r J)^T X/\sqrt{2} & -\gamma I & o_{2\times 2} \\ C_2/\sqrt{2} & o_{2\times 2} & -\gamma I \end{bmatrix} < 0, \tag{20}$$

in which

$$\Gamma = \hat{A} - \frac{B_{\omega_r}\Delta\omega_r J C_2}{2}.$$

Next, in consideration of implementation, the pole of the observer is restricted by the following LMIs [11]:

$$\begin{bmatrix} -rX & X\hat{A} + KC_1 \\ C_1^T K^T + \hat{A}^T X & -rX \end{bmatrix} < 0, \tag{21}$$

and

$$X\hat{A} + KC_1 + \hat{A}^T X + C_1^T K^T + 2hX < 0, \tag{22}$$

for some r>0 and h>0. By minimizing γ under constraints (20) - (22) with Matlab/LMI Toolbox, X and K can be obtained. As a result, the robust observer gain is determined as

$$L = X^{-1}K. \tag{23}$$

V. Experiments

A. Experimental setup

Some experiments were carried out to confirm feasibility and effectiveness of the proposed system shown in Fig.2. The experimental setup shown in Fig. 7 consists of a tested induction motor (1.5kW) fed by a voltage source PWM inverter, regulated by speed control mode, and another induction motor (2.2kW) for the load torque regulation. In addition, the stator current was detected by 14bit ADC. On the other hand, the stator voltage on *d-q* axis, which is utilized for parameter identification, were substituted for voltage reference v_{ds}^*, v_{qs}^*, which can be obtained from output of current controller shown in Fig.2.

The tested induction motor parameters are shown in Table 1. Theses parameters of the tested motor were measured by the no-load test and the locked test using sinusoidal power source.

The adaptive observer (which was constructed on $\alpha-\beta$ coordinate), the speed controller, the current controller, and the coordinate transformer were executed by DSP(TI:TMS320C6701), and the pulse width modulation of the stator voltage reference was made by FPGA(Altera:EPF10K20TC144-4), where the DC link voltage and the carrier frequency of the PWM inverter were set to 200V and 5kHz, respectively.

TABLE 1 PARAMETER OF TESTED MOTOR

Rated power	1.5kW
Rated speed	1710min^{-1}
Rated stator voltage	200V
Rated stator current	6.2 A
Stator resistance	0.9Ω
Rotor resistance	0.784Ω
Stator inductance	110 mH
Rotor inductance	98.0 mH
Mutual inductance	98.0 mH

B. Identification results at standstill

First, the tested induction motor was kept at standstill for simplification. In this parameter identification experiments, M sequence signal was injected into the d-axis current reference as the exogenous signal, in which the amplitude of M sequence signal changed from 0.1A to 0.5A, and voltage reference data and measured current ones were detected for 5 seconds, respectively. Based on (4), parameter identification was performed in off-line by ARMAX model [8] in MATLAB/System Identification Toolbox, and Fig.8 shows average for 5 times data of same identification experiments. For evaluation of parameter identification results $\hat{\theta}=[\hat{a}\ \ \hat{e}\ \ \hat{g}]^T$,this paper utilizes the following equation as 2-norm of each parameter identification error:

$$\textit{Identification Error} = \sqrt{\left(\frac{a-\hat{a}}{a}\right)^2+\left(\frac{e-\hat{e}}{e}\right)^2+\left(\frac{l-\hat{l}}{l}\right)^2}, \qquad (24)$$

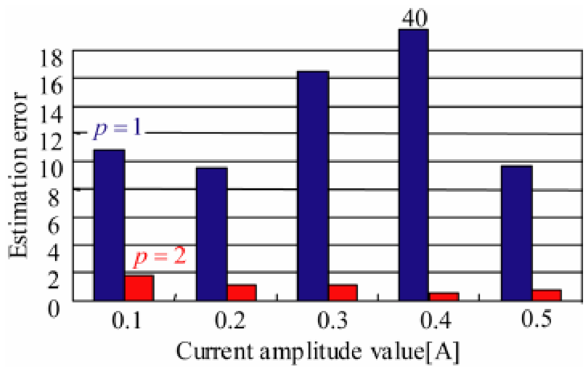

Fig. 8: Identification estimation error of standstill

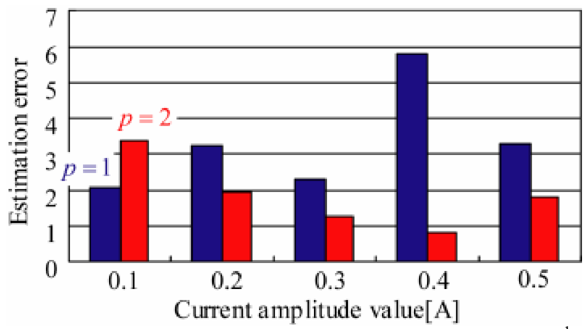

Fig. 9: Identification estimation error of no-load (180min^{-1})

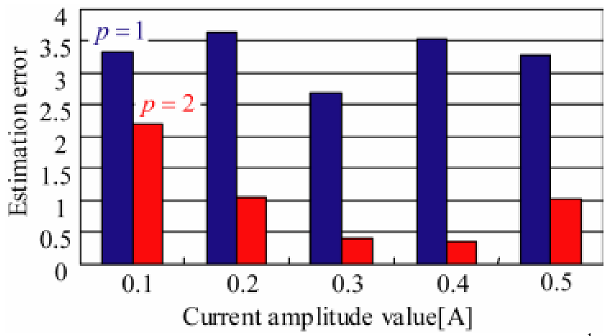

Fig. 10: Identification estimation error of half-load (180min^{-1})

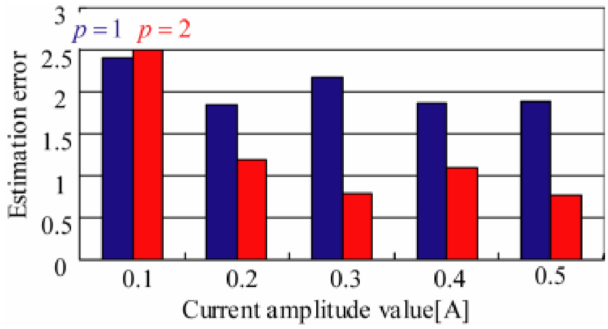

Fig. 11: Identification estimation error of full-load (180min^{-1})

where $l=g^{-1}$ is the leakage inductance. $\theta=[a\ \ e\ \ g]^T$ is a nominal value vector, which is obtained from motor parameter by no-load test and the locked-test in advance.

It can be seen from Fig.8 that the parameter identification accuracy using output inter-sampling approach (p=2) is dramatically superior to conventional method (p=1) as previously expected. In addition, it is revealed from this figure that parameter identification was becoming more precise as M sequence signal enlarged. In other words, the output inter-sampling approach makes it possible to realize a certain accuracy of parameter identification with less amplitude of injected signal for parameter identifiability.

C. Identification results at 180 min^{-1} *under various load conditions*

Next, identification experiments were carried out when the tested induction motor was operated at 180 min^{-1}. Figs. 9,10 and 11 show the identification error when induction motor was operated at 180 min^{-1}\$ under no-load, 50%, and 100% load, respectively. The results of parameter identification were also evaluated by (24). It can be seen from these figures that the parameter identification error decreased by about 50% in average, which concludes that identification based on output inter-sampling approach is effective.

According to the literature [7], this is because the identifiability condition of the parameter can be relaxed so much, and the amount of input data and output ones increase twice in comparison with p=1. In addition, since PE condition for identification is satisfied by M sequence signal in input and output, it is thought that the accuracy of parameter identification can be improved.

As described above, to apply of output inter-sampling approach to parameter identification would be effective for identification accuracy at 180min-1 as well as at standstill. However, identification results of output inter-sampling approach at 180min-1 were inferior to that at standstill. This is because the phase estimation error of rotor flux, which is estimated by the adaptive observer, would slightly affect to parameter identification despite the proposed identification model (4) requires the assumption that the phase estimation error does not exist.

Although many literatures have already been described rotor flux estimation of induction motors [2] and a few parameter identification (only speed, stator resistance and rotor one) using high frequency signal injection [3][4], few literature deals with to decrease amplitude of the injected signal by parameter identification strategy, where the injected signal would cause losses and acoustic noise. Hence, general comparison of the proposed method with these methods would be difficult, but the proposed method is said to be superior in terms that this paper tackles simultaneous identification of all parameter of induction motors, and deals with amplitude minimization of the injected signal injection, which is necessary for parameter identification, but is not necessary for control the motor.

D. Influences of thermal variation on parameter identification characteristics

In this subsection, influences of thermal variation on parameter identification characteristics were surveyed, whose results are shown in Fig.12. In these experiments, amplitude of M sequence signal was 0.4A, and parameter identification was carried out every 10 minutes after half load was applied. Temperature of the tested motor surface was measured by a thermal sensor (IT-550 by HORIBA) at the same time.

It turns out from this figure that error of parameter identification using conventional method (p=1) was fluctuated regardless of temperature variation. On the other hand, it can be seen that identification error of proposed method (p=2) enlarged in relation with increase of motor surface temperature. This implies that the proposed method would catch up resistive parameter variation of the test motor, which is caused by temperature variation, because identification error was calculated with constant nominal parameters. From these results, it can be concluded that the proposed method becomes effective of parameter identification strategy.

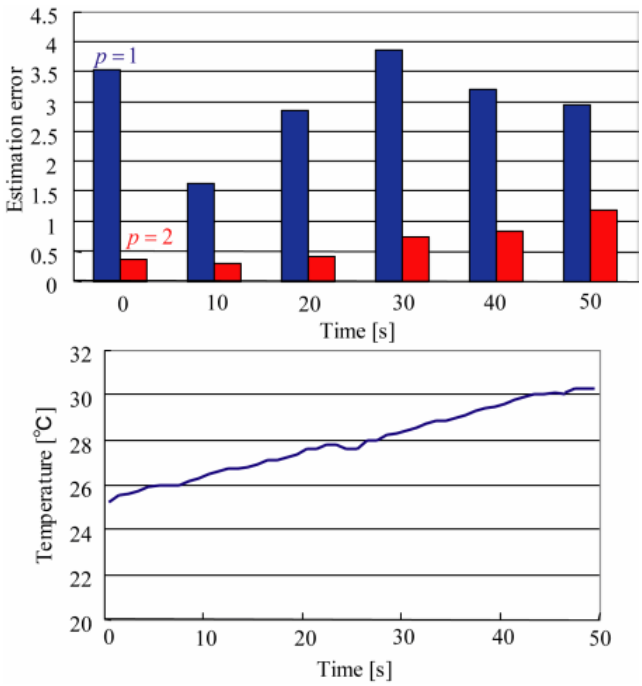

Fig. 12: Influences of thermal variation on parameter identification characters

E. Discussions using singular values of data matrix

Finally, this subsection quantitatively evaluates effectiveness of the proposed method. Identification model (4) can be formulated without any generality by

$$i_{ds}[k] = \frac{b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}} v'[k] \tag{25}$$

and, this is manipulated by the following:

$$\begin{bmatrix} i_{ds}[2] \\ \vdots \\ i_{ds}[n] \end{bmatrix} = \begin{bmatrix} -i_{ds}[1] & -i_{ds}[0] & * \\ \vdots & \vdots & \\ -i_{ds}[n-1] & -i_{ds}[n-2] & \end{bmatrix}$$

$$* \begin{bmatrix} v'[1] & v'[0] \\ \vdots & \vdots \\ v'[n-1] & v'[n-2] \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ b_1 \\ b_2 \end{bmatrix}.$$

For simple notation,

$$Y = \Omega\Theta \; . \tag{26}$$

This equation describes that output data Y will be sensitive to identified parameter Θ when a norm of data matrix Ω enlarges. In this case, singular value is well known as evaluation of this norm of Ω. Pseudo-inverse matrix of Ω tends to be numerically stable if the products of all singular values of Ω, which makes it possible to realize accurate parameter identification.

Fig.13 shows the products of all singular values characteristics with respect to amplitude of injected M sequence signal. This figure demonstrates that the products of all singular values of Ω with respect to amplitude of M sequence signal under half load condition. These plots mention that the norm of Ω in the proposed method becomes considerable larger than the other, one can conclude from these singular values that this is why the proposed method becomes effective for parameter identification.

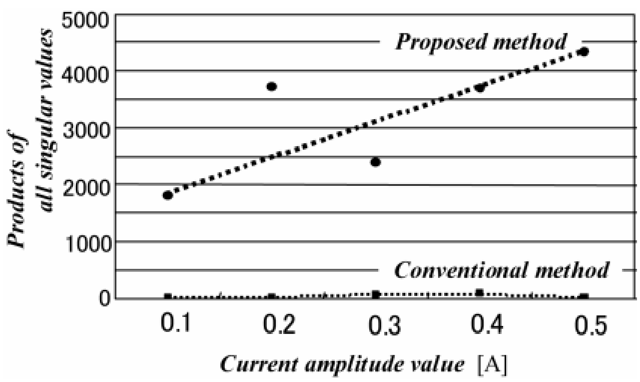

Fig. 13: Singular values of data matrix (half load condition)

IV. Conclusion

This paper has shown how to apply parameter identification based on output inter-sampling approach to speed sensorless vector controlled induction motor. Both identification results at standstill and that at 180min^{-1} under three-load conditions with output inter-sampling approach show that the accuracy of the parameter identification can be improved. In addition, this paper has revealed why the proposed identification method becomes effective using singular matrix of data matrix. As a result, the proposed approach is concluded to be effective for vector controlled induction motor.

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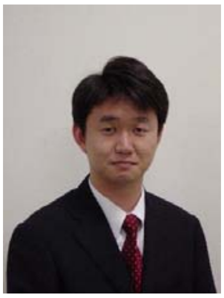
BIOGRAPHIES



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