Design of Speed Controller for an Induction Motor with Inertia Variation

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ABSTRACT- In this paper, a novel design algorithm of speed controller for an Induction motor with the inertia variation is proposed. The main contribution of our work is a very robust, reliable and stable procedure for setting of the PI gains against the specified range of the inertia variation of an induction motor using Kharitonovs robust control theory. Therefore, the basic segment of controller design, the variation of induction motor inertia is estimated by the RLS (Recursive least square) method. PI based speed controller is widely used in industrial application for its simple structure and reliable performance. In addition the Kharitonov robust control theory is used for verification stability of closed-loop transfer function. The performance of this proposed design method is proved by digital simulation and experimentation with high performance DSP based induction motor driving system.

I. Introduction

It is generally accepted that Indirect field orientation, in one of its many forms, is the most promising control method for high dynamic performance AC drives. In particular, the Indirect Field Oriented Control (IFOC) for induction motors is a simple and highly reliable scheme which has become an industry standard. IFOC of an induction motor must guarantee that the high performance speed controller provides robust speed control as well as ideal current control over the full speed range.

Generally, PI controller that has a simple structure and superior performance than any other control scheme is accepted as speed control algorithms. But it makes an overshoot in transient region. Despite slow response, IP controller has the tendency to be chosen speed controller for its small vibration and stable control characteristics.

At this time the problem is tuning of the gains of Proportional Integral (PI) speed loop. Typical gain tuning method of PI controller is Ziegler-Nichols theory. Otherwise that gain may as well be selected by experience. If the variation of system parameter like inertia occurred in succession, the gain of PI or IP controller should be chosen each time. In this paper, we propose that the practically important problem of offline tuning of the gains of the PI speed loop with inertia variation. It is well known that the performance of FOC critically depends on the tuning of these gains. This paper gives here some simple, robust and powerful rules to carry out the PI tuning, ensuring robust stability with respect to these parameters. The main contribution of this work is to propose a simple & robust algorithm that, for each specific range of inertia variation which estimates RLS method, estimates the minimum -maximum range of values of the PI gains. In this way, we can estimate the stability margin of a PI controller, and the gain margin of the total closed-loop system for overall range. During the constant speed operation, the variation of inertia takes part in transferring closed-loop pole. Therefore overshoot, slow speed response and unwanted vibrations are generated in state-feedback loop system or two-mass system; the steel rolling mill drive system where the load is coupled to the driving motor by a long shaft having small elasticity. [1]-[3]

The purpose of this paper is improvement of speed controller for an induction motor drive system with inertia variation. The basic speed controller is general PI controller that is a widely used controller in real industrial field because of its simple and superior performance and it is widely applied as a speed controller for general motor control. In the mechanical parameter estimation, the off-line RLS algorithm and the information of the motor speed are used for the inertia estimation. Using the estimated mechanical parameters, the speed controller for PI control scheme is designed and its gains are determined using the Kharitonov robust control theory. The Kharitonov robust control theory can obtain the robust stability with the specified stability margin and the good performance for induction motor speed control if the parameters are varied within some specified limits. [1][2]

The effectiveness and usefulness of the proposed schemes are verified with the simulation and the experimental results on the fully-digitalized 2.2kW Induction motor drive system.

II. Speed control with inertia variation

The first consideration for high performance control of an induction motor is the vector control in condition that the mechanical parameter variation does not exist. The parameter variation plays an important role in the vector control as well as the flux estimation. There are two major recent trends, one is a method to design an estimator and a controller robustly with parameter variations, and the other is to apply to an estimator and a controller by estimating the parameters direct. The parameter estimation methods are general no-load test, locked-rotor test, and DC test. And there are methods using parameter calculation with model- and axis-transformations, adaptive theory, and neural network theory. However, because it is general to use the flux information as a basis in case of parameter estimation using adaptive theory and neural network theory practically. In this paper, a controller using the inertia of an induction motor by off-line estimation for the more accurate control design is proposed, and its controller gain is selected by applying the Kharitonov robust control method in order to compensate for the effects of the parameter variations during the operations. The purpose of this paper is to select the controller gain that is able to have the minimum response characteristic in spite of the mechanical parameter variations during the operations by applying the Kharitonov robust control.

1. Response for of machine parameter with variation.

Figure 2.1 shows the step response and the movement of system poles when the induction motor inertia J_M varies from -70% to +70%. In this figure, the inertia variation affects the speed response characteristic because it plays a role of moving the roots of the system characteristic equation. Furthermore, when an inertia disk or a DC motor is connected as a load, the total inertia is changed and the following response is changed.

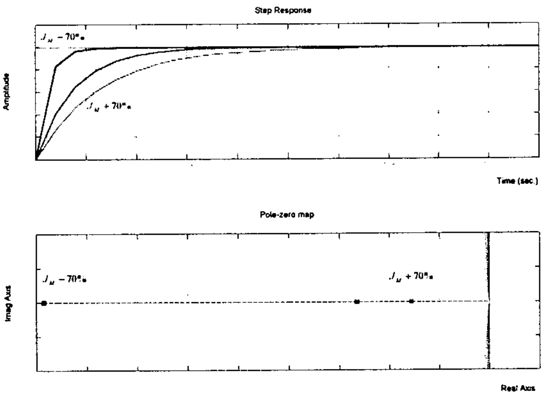


Fig. 2.1 Step Response and Movement of system pole according to motor inertia variation

2. Inertia estimation using RLS algorithm

The method using adaptive theory is easy to implement and its estimation characteristic is distinguished because of the convergence, therefore it is the most widely spread method among the inertia estimation methods. It is a parameter estimation method by choosing the gain of adaptive law for the difference between the output of a model and that of a real plant to converge to zero or by choosing the gain to minimize the difference by repetitive calculations. It has been generally applied in estimating the electric parameters and the mechanical inertia using RLS and MRAS (Model Reference Adaptive System), and it is widely used on-line due to its few calculations. In this paper, the RLS method which is known for its superiority of convergence and estimation capability is applied to estimate the inertia, and the result is applied to the controller. Figure 2.2 shows a block diagram of parameter estimation using adaptive theory.

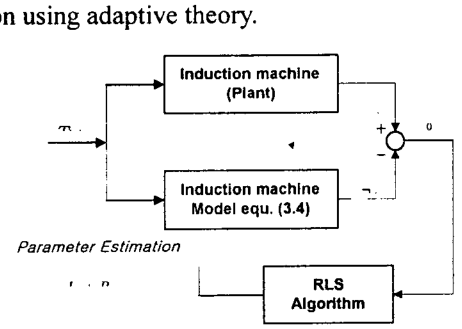


Fig. 2.2 Parameter estimation of induction machine system using RLS

3. PI controller[3]

PI controller is a widely used controller in real industrial field because of its simple and superior performance, and it is widely applied as the speed controller for general motor control. The block diagram of induction motor using PI speed controller, and the unit step response of the PI speed controller for one mass system in case that the ideal current control is assumed are shown in Figure 2.3 and Figure 2.4 respectively. As described previously, the total response of the system changes as the inertia of mechanical parameters changes, so the problem occurs to adjust the gain according to the conditions.

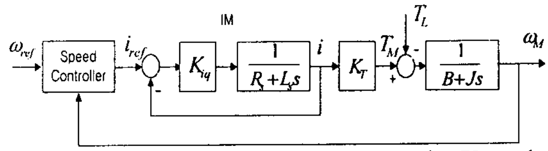


Fig. 2.3 Block diagram of induction motor using PI speed

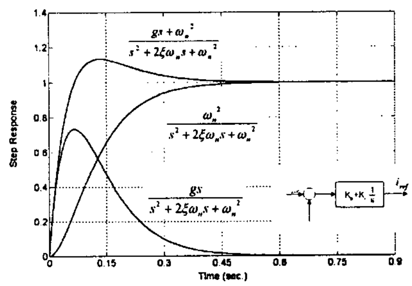


Fig. 2.4 PI speed controller and unit step response

III. Kharitonov robust control

1. Kharitonov Theory[4]

The Kharitonov robust control method represents a robust controller such that the total system stability is conserved in spite of the changes of parameters within the specified range. This theory presents to estimate the stability of a polynomial in case the arbitrary coefficients of the polynomial change within the specified range. So we can choose the controller gain ensuring the total system stability despite the changes of the system parameters, if we would apply the Kharitonov robust control method assuming that the total system characteristic polynomial which includes the controller and the coefficients of the characteristic polynomial change within the specified range. The set of real number polynomials alike the equation (3.1) is expressed as $p(s)$ to estimate the system stability. The interval polynomial is a polynomial of which the coefficients change within the specified range and has the same formation of the characteristic polynomial of the general systems of which the parameters change within the specified range. The individual coefficient change within the independent range and such the polynomial set is called the interval polynomial.

$$p(s) = p_0 + p_1 s + p_2 s^2 + p_3 s^3 + \cdots + p_n s^n$$
$$p_0 \in [x_0, y_0],\ p_1 \in [x_1, y_1], \cdots\cdots,\ p_n \in [x_n, y_n],\ 0 \notin [x_n, y_n] \quad (3.1)$$

(3.2) which is called the Kharitonov polynomial represents the Kharitonov theory for interval polynomial which enables us to estimate the system stability with changes of parameters by estimating the stability of the polynomial. If this Kharitonov polynomial is Hurwitz stable, every polynomials in the set $p(s)$ of interval polynomials are Hurwitz stable. However, it is general that the individual coefficients change interactively in the ordinary closed-loop system, is suggested the generalized Kharitonov theory to solve such a problem.

$$\begin{aligned} K^1(s) &= x_0 + x_1 s + y_2 s^2 + y_3 s^3 + x_4 s^4 + x_5 s^5 + y_6 s^6 + \Lambda \\ K^2(s) &= x_0 + y_1 s + y_2 s^2 + x_3 s^3 + x_4 s^4 + y_5 s^5 + y_6 s^6 + \Lambda \\ K^3(s) &= y_0 + x_1 s + x_2 s^2 + y_3 s^3 + y_4 s^4 + x_5 s^5 + x_6 s^6 + \Lambda \\ K^4(s) &= y_0 + y_1 s + x_2 s^2 + x_3 s^3 + y_4 s^4 + y_5 s^5 + x_6 s^6 + \Lambda \end{aligned} \quad (3.2)$$

The Linear interval polynomial is defined in (3.3) such that the polynomial $F_i(s)$ is a fixed real number polynomial and the $P_i(s)$ is a real number polynomial of which the coefficients change within the specified range.

$$\Delta(s) = F_1(s)P_1(s) + F_2(s)P_2(s) + \Lambda + F_m(s)P_m(s) \quad (3.3)$$

If the Kharitonov polynomial for $p_i(s)$ in this defined polynomial is assumed to be same with the equation (3.4), the polynomial set is defined as $K_i(s)$. The equation (3.5) represents the variation ranges, and if these line segments are stable, every interval polynomials are stable.

$$\begin{aligned} K^1(s) &= x_0 + x_1 s + y_2 s^2 + y_3 s^3 + x_4 s^4 + x_5 s^5 + y_6 s^6 + \Lambda \\ K^2(s) &= x_0 + y_1 s + y_2 s^2 + x_3 s^3 + x_4 s^4 + y_5 s^5 + y_6 s^6 + \Lambda \\ K^3(s) &= y_0 + x_1 s + x_2 s^2 + y_3 s^3 + y_4 s^4 + x_5 s^5 + x_6 s^6 + \Lambda \quad (3.4) \\ K^4(s) &= y_0 + y_1 s + x_2 s^2 + x_3 s^3 + y_4 s^4 + y_5 s^5 + x_6 s^6 + \Lambda \\ \kappa_i(s) &:= \{K_i^1(s), K_i^2(s), K_i^3(s), K_i^4(s)\} \end{aligned}$$

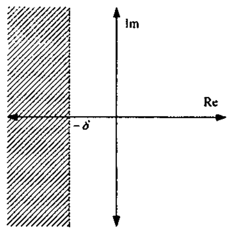
$$S_i(s) := \{ [K_i^1(s), K_i^2(s)], [K_i^1(s), K_i^3(s)], [K_i^2(s), K_i^4(s)], [K_i^3(s), K_i^4(s)] \} (3.5)$$

In order to apply the Kharitonov theory to the system is applied in this paper. We call Hurwitz polynomial such that the every roots of a polynomial of order n are in the left half of the complex plane, and the consistent system is stable.

2. Design of the robust controller of the gain margin.

The previously stated Kharitonov robust controller is using the method to place the system poles in the left half of the s-plane not considering the gain margin and the system damping only when the parameters change within the specified range can ensure the maximum speed control characteristic for the parameter changes so as for the total system to have the gain margin by extending this method.

Assuming that the gain margin is δ, this range in the s-plane is which is called δ Hurwitz range and is shown in figure 3.1.



$$S_\delta := \{ s : s \in C, \mathrm{Re}[s] < -\delta, \ \delta > 0 \}$$

Fig. 3.1 δ Hurwitz stability area S_δ in s-planes

In this range, we can get the gain margin of δ by estimating the stability of polynomial $p(s)$ using the Kharitonov theory, and $p(s)$ is defined in (3.7). We can get (3.8) by substitution $s = -\delta + s_1$.

$$P(s) := \{ p_0 + p_1 s + p_2 s^2 + \Lambda + p_n s^n : x_i \le p_i \le y_i, i = 0,1,2,\Lambda, n : 0 \notin [x_n, y_n] \} (3.7)$$

$$g(s_1) = P(s_1 - \delta) = p_0 + p_1(s_1 - \delta) + p_2(s_1 - \delta)^2 + \Lambda + p_n(s_1 - \delta)^n \ (3.8)$$

The δ Hurwitz stability of $p(s)$ is equivalent to the stability of the following linear region polynomial $g(s_1)$, and we can estimate the stability with the polynomial which is applied to $g(s_1)$ with the generalized Kharitonov theory.

$$G(s_1) := \left\{ \begin{matrix} g(s_1) = p_0 + p_1(s_1 - \delta) + p_2(s_1 - \delta)^2 + \Lambda + p_n(s_1 - \delta)^n \\ p_i \in [x_i, y_i], \ i = 0,1,2,\Lambda, n \end{matrix} \right\} \quad (3.9)$$

$$\begin{aligned} F_i(s_1) &= (s_1 - \delta)^{i-1} \\ P_i(s) &= p_{i-1}, \ i = 1,2,\Lambda, n+1 \end{aligned} \quad (3.10)$$

So we can estimate the stability of $p(s_1)$ by estimating the Hurwitz stability for the Kharitonov polynomial set about S_1

3. Design of the robust controller within stable range.

The total system characteristic equation considering stability margin δ with (3.11) which are transfer functions of motor input torque, of angular velocity and of PI controller is (3.12).

$$\begin{aligned} G(s) &= \frac{\omega_M}{T_M} = \frac{N(s)}{D(s)} \\ N(s) &= b_0 = \frac{1}{J} \\ D(s) &= a_1 s + a_0 = s + \frac{B}{J} \\ G_c(s) &= K_p\left(1 + \frac{\omega_{pi}}{s}\right) \end{aligned} \quad (3.11)$$

$$\begin{aligned} \Delta(s - \alpha) &= g(s_1) \\ &= (s - \delta)D(s - \delta) + K_p(s - \delta + \omega_{pi})N(s - \delta) \\ &= c_2(s_1 - \delta)^2 + c_1(s_1 - \delta) + c_0 \\ &= c_2' s_1^2 + c_1' s_1^1 + c_0' \end{aligned} \quad (3.12)$$

The coefficients are

$$c_2 = a_1 = 1,\ c_1 = a_0 + K_p,\ c_0 = b_0 K_p \omega_{pi}$$
$$c_2' = a_1 = 1,\ c_1' = a_0 + b_0 K_p - 2\alpha,\ c_0' = \alpha^2 - a_0\alpha - b_0 K_p - 2\alpha$$

Only the coefficients of first and zero order terms are affected by the variation of inertia. We choose the controller gain satisfying (3.14) using the Hurwitz stability estimation after the estimation of the equations of (3.13) applying the general Kharitonov theory for stable margin assurance.

$$\begin{aligned} &F_0 c_{0\min} + F_1 c_{1\min} + F_2 c_2 \\ &F_0 c_{0\min} + F_1 c_{1\max} + F_2 c_2 \\ &F_0 c_{0\max} + F_1 c_{1\min} + F_2 c_2 \\ &F_0 c_{0\max} + F_1 c_{1\max} + F_2 c_2 \end{aligned} \quad (3.13) \qquad \begin{aligned} &1)\, c_2 \phi 0 \\ &2)\, c_1 \phi 0 \\ &3)\, c_0 \phi 0 \end{aligned} \quad (3.14)$$

We can get the value of 6 as the limit value of δ having the δ Hurwitz stability by simulation using the design method of speed controller that we have proposed above. Considering the characteristics of the device for experiment of induction motor drive system, stability margin is selected as the value of 5. Figure 3.2 is the speed controller gain region within the limits of the conditional region assuming that the total inertia of induction motor is varying between -70% and +70%. Therefore we can secure the selected stable margin after the range of motor inertia variation is selected. We would select the value of ω_{pi} and K_p as being between 0 and 10 in this paper and show the condition. The value of ω_{pi} and K_p is selected as 9.

Ⅳ. Simulation

In this section, the previously described mechanical parameter estimation method, the speed controller gain best-fit method and the performance and characteristic by

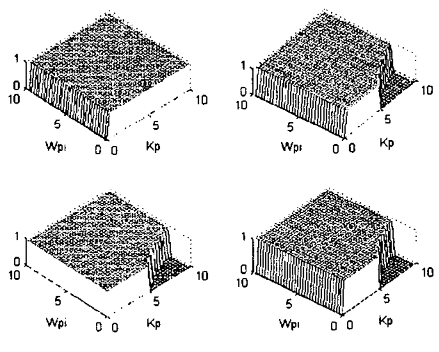


Fig. 3.2 Speed Controller gain select region according to gain margin

these methods are verified with computer simulations. Table 4.1 shows the mechanical parameters used in these simulations and the simulation is implemented on Matlab.

Table 4.1 Mechanical Parameters

Induction motor inertia J_M	$0.0088 [kg \cdot m^2]$
DC motor inertia J_R	$0.009\ [kg \cdot m^2]$
disk inertia J_D	$0.02\ [kg \cdot m^2]$

1. Mechanical Parameter Estimation

Figure 4.1 shows the estimation of total inertia assuming that an induction motor and a DC motor are connected each other, and as the result the real inertia of simulation is 0.0178 $kg \cdot m^2$ and the estimated value is 0.0179 $kg \cdot m^2$. Also, figure 4.2 shows the case two disks are added. The estimated inertia value is 0.0578 $kg \cdot m^2$ and the inertia value with these added disks can be obtained as 0.04 $kg \cdot m^2$. In this simulation of inertia estimation using RLS method, we can obtain the estimation performance of the accuracy of 100%.

2. Proposed PI speed controller

The motor speed is driven at 100 rpm, and both the forward and the backward direction loads of which the sizes are 9Nm are applied to verify the load characteristics. That is, the forward direction load of 9Nm is applied to motor at 5 second and the backward direction load of 9Nm is applied to motor at 8 second.

Figure 4.3 shows the speed and the load response characteristics of PI controller using the Kharitonov robust control theory for induction motor drive system, and the gains of this PI controller are selected as $\omega_{pi} = 9$, $K_p = 9$. (a) is the case without inertia variation , (c) and (d) are the speed and the load response characteristics when the inertia changes between $\pm 0.02\, kg \cdot m^2$. We can obtain the fast speed response in the case without inertia variation.

V. Experimental Result

1. Estimation of machine parameter

When we estimate the inertia and the friction coefficient of an induction motor drive system using RLS in real plant, the estimation reliability of friction coefficient is low because of delay time until the real torque and error that is difference of torque reference and real torque occur. However in inertia estimation, the effect of the friction coefficient is not large so we assume the estimation inertia and the inertia in. real system are the same. We can ignore the estimated friction coefficient. In this experiment, the system is made of an induction motor, a DC motor, and inertia disks. We apply RLS method to this experiment in order for the inertia estimation. The motor rotates at 150rpm(is 10% of a rated speed). Fig. 5.1 shows that the estimated inertia is 0.018 $kg \cdot m^2$ in the system made up of an induction motor and a DC motor. Fig. 5.2 shows an inertia estimation characteristic when the system is made up of an induction motor , a DC motor and two inertia disks. We can calculate the inertia of one inertia disk is 0.02 $kg \cdot m^2$ from Fig. 5.1 and Fig. 5.2. The estimated inertia is 0.018 $kg \cdot m^2$ and the designed inertia is 0.0178 $kg \cdot m^2$. We don't consider the inertia of the coupling shaft of the induction motor and the DC motor. When we calculate the disk inertia using the accurate value of quality, thickness and radius, the result is 0.02 $kg \cdot m^2$. The estimated inertia is very accuracy value 0.0207 $kg \cdot m^2$.

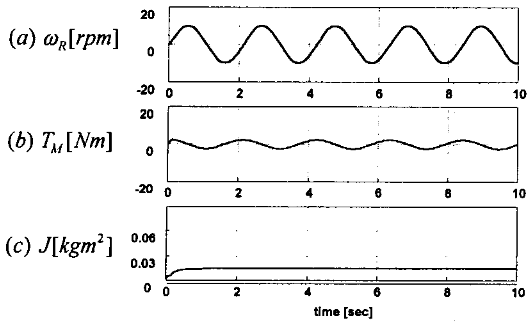


Fig. 4.1 Inertia estimation using RLS (IM+DC)

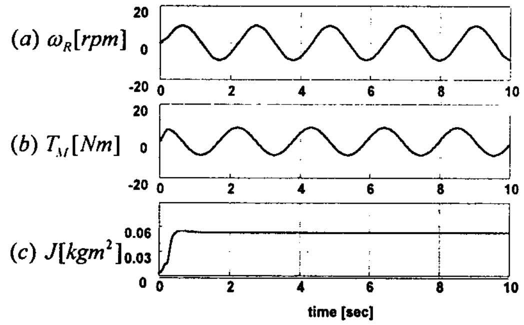
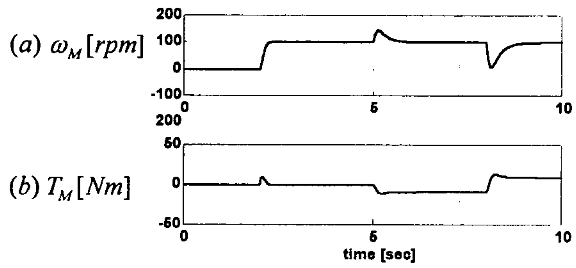
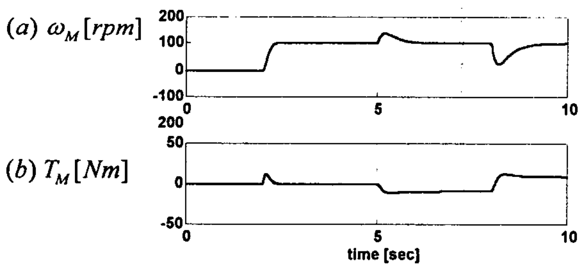


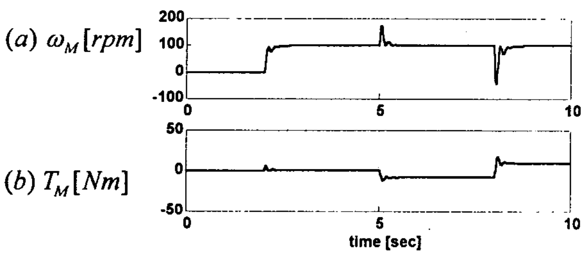
Fig. 4.2 Inertia estimation using RLS (IM+DCM+2 Round inertia)



(a) Without variation of IM inertia



(b) Variation of IM inertia : +0.02 $kg \cdot m^2$



(c) Variation of IM inertia : -0.02 $kg \cdot m^2$

Fig. 4.3 Speed and load response characteristic with Robust PI control

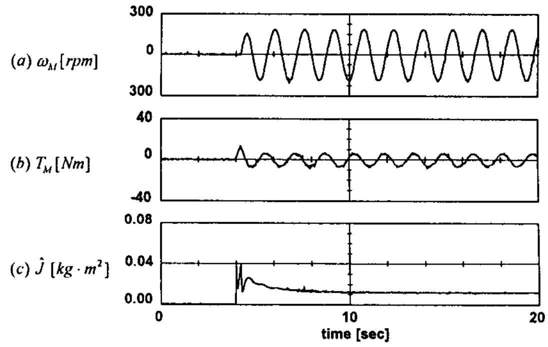


Fig. 5.1 Inertia estimation using RLS (IM+DCM)

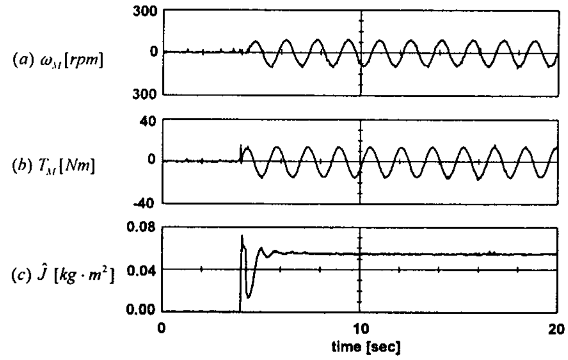
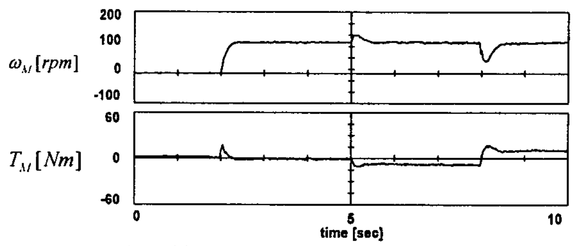


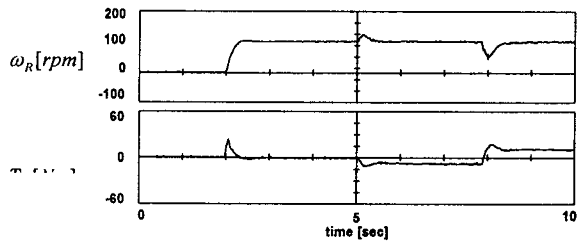
Fig. 5.2 Inertia estimation using RLS (IM+DCM+2 Round inertia)

2. Kharitonov Robust PI speed controller

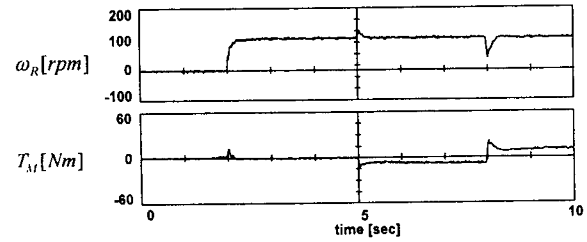
In this paper, we experimented on the speed-torque characteristic using the proposed PI controller. We carried out this experiment in 100rpm the first stage initial condition and 1500rpm a rated speed. Furthermore to observe the load response characteristic the load is applied forward and inverse direction. The amplitude of the applied load is 9Nm. Fig. 5.4 show the speed and the load response characteristic using PI speed controller applying Kharitonov robust control in 1500rpm. Especially (b) and (c) are shown that the latter is more outstanding than the former when the inertia is varied $\pm 0.02\, kg \cdot m^2$



(a) Without variation of IM inertia

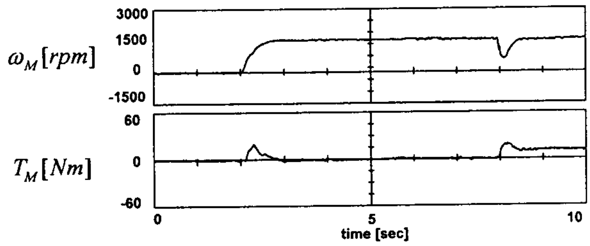


(b) Variation of IM inertia : +0.02 $kg \cdot m^2$

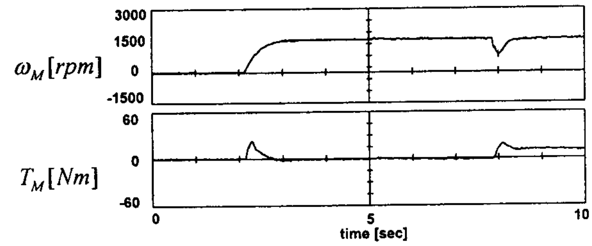


(c) Variation of IM inertia : -0.02 $kg \cdot m^2$

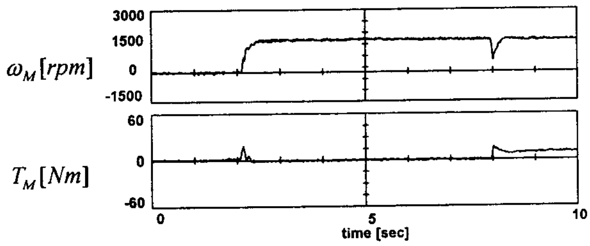
Fig. 5.3 Speed and load response characteristic with Robust PI control



(a) Without variation of IM inertia



(b) Variation of IM inertia : +0.02 $kg \cdot m^2$



(c) Variation of IM inertia : -0.02 $kg \cdot m^2$

Fig. 5.4 Speed and load response characteristic with Robust PI control

VI. Conclusion

This paper proposed new speed controller that can become speed control that solid to change of inertia of induction motor driving. Especially, Chose speed controller gain that robust method because estimate machine parameter by off-line and consider variation of machine parameter that can happen during the operation. Through simulation and experiment, showed superior repeatability of way that propose. Also, maximized speed response that robust as that choose gain of PI controller so that can secure fast convergence and controller gain margin applying Kharitonov's robust control theory.

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