GAIN-SCHEDULING CONTROL DESIGN

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Abstract

A High dynamic performance of Servomotor drives is required in various applications of to today's automatically controlled machines which provide high productivity and high-quality products in production lines. This technology is one of the most important bases of modern industry and economic development. Since the development of flux vector control is used in induction motor drives, ac servomotor control has attracted much attention, mainly due to its simplicity, raggedness and low cost. The robust and fast speed-control for an induction motor have been described (Dote, Suyitno, et al., 1993; K. et al., 2018; Rao & Kumar, 2019) *(Suyitno et al., 2024), which the zeroing control method and combine with feed forward controller is used. In the case of noise sensitive systems sometimes high gain controllers have caused problems. The Zeroing method has a high gain loop part inside it. In some cases, when the motor drive system is running, the operator must adjust the controller gain to suit the environment or certain conditions. So, if the controller gain can be changed when the operator operates the system, then the system will be perfect. As a result, the controller can be non-linear. This paper discusses the possibility of changing the parameter values using fuzzy theory to realize it.*

Keyword: Gain-scheduling Control, Zeroing Control, Robust and Fast Speed Control, Fuzzy Logic Control.

INTRODUCTION

The Fuzzy control is called an *intelligent control* since knowledge engineering is used in the controllers (Dote, Suyitno, et al., 1993). The Fuzzy control is useful only if human skill can be converted into control knowledge and only if it is simple and low cost. The algorithm is based on intuition and experience, can be considered as a set of heuristic decision rules or *rules of thumb*. Many papers have been published on the application of fuzzy control to build nonlinear controllers. However, the design procedure of fuzzy control has not been established perfectly.

If fuzzy control is used for the purpose of constructing nonlinear controllers, the controller design method should be based on available nonlinear control theories, such as Liapunov's method in reference (Suyitno et al., 1993a); neuroadaptive controller, or learning controllers, implementing fuzzy control schemes (Dote, Strefezza, et al., 1993) and (Jiang et al., 2016). Furthermore, results of Fuzzy controllers in applications have shown that fuzzy controllers perform better than, or at least as well as a PID controller.

1) Fuzzy Rules

The response of the Fuzzy control system generally depends on the Fuzzy rules which are described as *If~Then~* forms, provided that the membership functions and the Fuzzy inferences have been settled a priori. When the parameters and the structure of the plant are known, Fuzzy rules can be decided by trial and error. In most of the Fuzzy control designs for motor drive, assumptions are taken that the basic structure of the plant and rough values of the parameters are known. This assumption is never severe in realistic situations. Fuzzy rules for motor control design can be formulated as follows:

1. If the error is zero and the error-change is small and positive, then the control input is small and negative.
2. If the error is zero and the error-change is zero, then the control input is zero.
3. If the error is small and negative and the error-change is small and negative, then the control input is small and positive.
4. If the error is small and negative, and the error-change is zero, then the control input is large and positive.

These rules are then combined to form a decision table for the fuzzy controller. The table consists of values showing the different situations experienced by the system and the corresponding control input function (Abdelfattah et al., 2021).

2) Fuzzy Reasoning

There are in general two methods of fuzzy reasoning: (1) based on compositional rules of inference and (2) based on fuzzy logic (Li & Lau, 1989; Mohiuddin & Alam, n.d.). The second method is more understandable than the first. The second method is a simplified method based on fuzzy logic, where fuzzy variables with monotone membership functions are used.

An example (Mohiuddin & Alam, n.d.). Let consider two implications:

if x_1 is N, x_2 is P, then y is N;if x_1 is P, x_2 is N, then y is P,

Where x_1 and x_2 are input signals, P = positive and N = negative and y is an output-signal. The process of reasoning is illustrated in Figure 1.

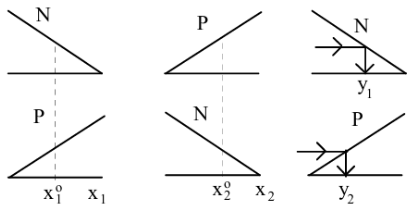


Figure 1. Fuzzy reasoning of the fuzzy logic method.

Letting the w_1 and w_2 be

$$w_1 = \mathrm{N}(y_1) \text{ and } w_2 = \mathrm{P}(y_2)$$

then for an input x_1^0, x_2^0, the following output y^0 is inferred by the equation below.

$$y^0 = \frac{w_1 y_1 + w_2 y_2}{w_1 + y_2} \tag{1}$$

where w_1 and w_2 are the weights of the first and the second implications. Those rules are possible to be interpreted linguistically.

CONTROL METHOD

A. Gain-Scheduling Control Method.

This chapter proposes a Gain-Scheduling robust controller (Bett, 2005) whose structure is continuously changed by fuzzy logic. The Gain-Scheduling is introduced to the approximate Zeroing technique with an Equivalent Disturbance Observer and a Predictive Controller. Thus, the controller structure is changed continuously by fuzzy logic such that if the error is large or its rate is large, then the controller makes the system respond quickly and vice versa in order to obtain a robust controller which is insensitive to both the plant noise and the observation noise. Then, it is applied to the speed control for an induction servo motor (K. et al., 2018; Kumar Singh et al., 2017). In other words, the proposed controller is designed for the outer loop of the overall drive system. The control analysis is included the stability analysis of the overall system and the design procedure, by using Liapunov's method.

B. Robust and Fast Speed Control.

This control method used the same method as shown in the Zeroing method (Suyitno et al., 2024). Assuming that a flux vector control method is applied and the current control loop time constant is small enough to be negligible (1msec.) (Mustafa et al., 2013), then the equation (2) describes the machine transient.

$$J\dot{\omega} + B\omega + T_L = k_t i_a \tag{2}$$

Where J: moment of inertia; T_L : external load torque; B: viscous friction coefficient; ω : motor speed; K_t: torque constant; i_a: motor current

Letting $J = \hat{J} + \Delta J$, $K_t = \widehat{K_t} + \Delta K_t$ and $B = \hat{B} + \Delta B$; where ˆ denote the nominal value and Δ represents the variation or an unknown value, then the equivalent disturbance $T_e(s)$ is obtained as

$$T_e(s) = T_L(s) + \Delta J(s) + \Delta B\,\omega(s) + \Delta K_t i_a(s). \tag{3}$$

The first through the fourth term on the right-hand side of the equation (3) represent the external load torque, the torque due to the parameter variation of motor drive, the variation of viscous friction torque, and the torque variation due to the flux vectorcontrol failure and torque ripples, respectively. $T_e(s)$ is obtained in equation (4) from equations (2) and (3).

$$T_e(s) = \widehat{K}_t i_a(s) - s\hat{J}\omega(s) - \hat{B}\omega(s). \tag{4}$$

The estimation of $T_e(s)$, $\widehat{T_e}(s)$ is constructed by using a low-pass filter $\frac{1}{(T_0 s+1)}$, In fact this is an observer. Thus,

$$\widehat{T_e}(s) = \frac{\widehat{K_t} i_a(s) - s\hat{J}\omega(s) - \hat{B}\omega(s)}{T_0 s+1} \tag{5}$$

where T_0 is the observer time constant. The signal $T_e(s)$ shown in Figure 2. $T_e(s)$ is assumed to be slowly time-varying signal.

By some control block simplification, the equivalent block diagram is obtained and shown in Figure 3. It is noted that a PI controller is contained in this controller. The following transfer functions are calculated.

$$\frac{\omega(s)}{T_e(s)} = \frac{-1}{\left(1+\frac{1}{T_0+1}\right)+(\hat{J}s+\hat{B})} \tag{6}$$

Since T_0 is very small, ω(s)/$T_e(s)$ becomes zero quickly, (or it is called *approximate zeroing method* (Suyitno et al., 2024)). So, the equivalent disturbance has been cancelled. Therefore,

$$\frac{\omega(s)}{i_a^*(s)} = \frac{\widehat{K_t}}{\hat{J}s+\hat{B}} \tag{7}$$

This is shown in Figure 4.

In order to obtain a quick command response a proportional gain controller K_p is added. Then, a predict controller $\frac{\hat{J}s+\hat{B}}{\widehat{K_t}}$ is designed independently of the robust controller, since,

$$\frac{\omega(s)}{\omega^*(s)} = 1 \tag{8}$$

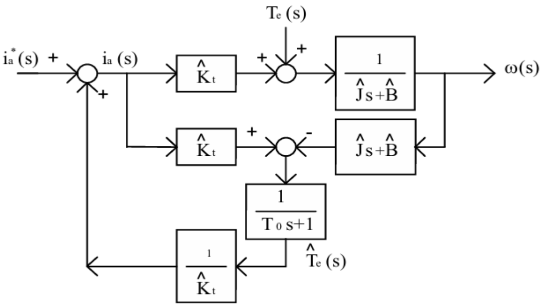


Figure 2. Block diagram of the motor and the equivalent disturbance observer.

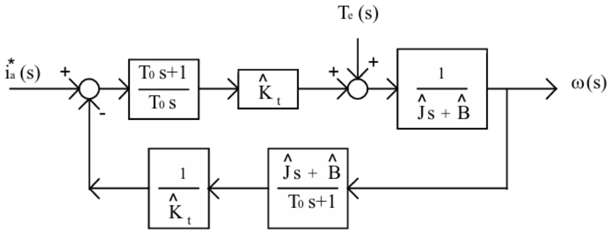


Figure 3. Equivalent block diagram of Fig. 2

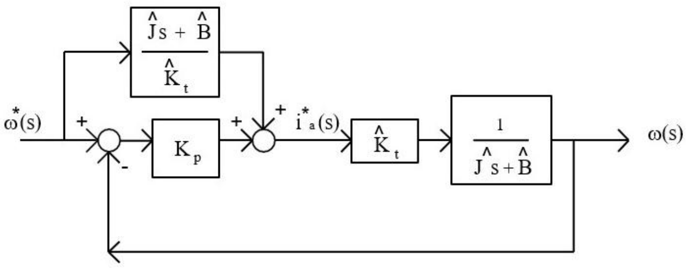


Figure 4. The predictive controller.

C. Gain-Scheduling Robust Control by Fuzzy Logic.

The derived controller is robust to the plant noises (external disturbances and system parameter variations), but sensitive to the observation noises which usually contain high frequency components. Thus, in this section a Gain-Scheduling robust controller, whose structure is continuously changed by fuzzy logic, such that if the error is large or its rate is large then the controller makes the system respond quickly and vice versa is designed (Suyitno et al., 1993a, 1993b; Veselý & Ilka, 2013). The design procedure is as follows:

1. Design an approximate fuzzy controller from a human being's knowledge (skill). (if the error is large or its rate is large, then the controller makes the system respond quickly and vice versa)
2. Apply Liapunov's method, in order to determine nonlinear controller parameters.

Alternatively, implement the approximate fuzzy controller with neural networks in order to construct a self-tuning controller. A novel real-time learning algorithm is devised (Dote, Strefezza, et al., 1993).

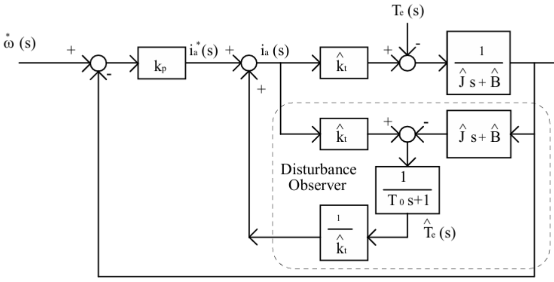


Figure 5.(a). Block diagram of the motor and equivalent disturbance observer with feed-back Loop.

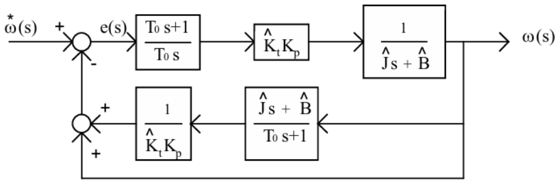


Figure 5(b). Equivalent block diagrams of Fig. 5.(a).

Figure 5(b) shows an equivalent control block diagram of Figure 5(a). Neither Figure 5a nor 5b include the feed forward controller.

The following Gain-Scheduling by fuzzy logic is introduced to the controller, in order to construct a nonlinear controller which is insensitive to both the plant noise (equivalent disturbance) and the observation noise. The fuzzy rules are as follows:

If e is large, then K_p is large; If e is large, then T_0 is small;

If e is small, then K_p is small; If e is small, then T_0 is large,

where e is the error which is defined by e = $\dot{\omega} - \omega$ (see Figure 5(a)).

In the proposed controller, approximated changes of nonlinear T_0 and K_p were made with respect to e; as shown in Figure 6. Therefore, when error e equals zero, the gain K_p is minimum and T_0 is maximum. Thus, the possibility of an offset appearing in the output response, will be suppressed, and the effect of the disturbances will be cancelled quickly.

The design of this curve can be completely changed, in order to match the special condition, or environment to the overall systems for other applications.

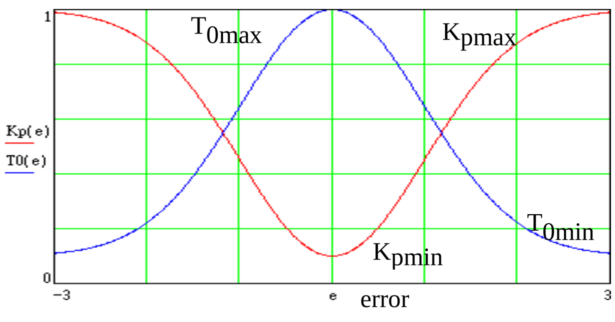


Figure 6. Nonlinear k_p and T_0.

STABILITY ANALYSIS OF THE OVERALL SYSTEM AND CONTROLLER MEASURE

When the command input $\dot{\omega}(s)$ is in the steady state condition, and by using the equivalent block diagram of the closed-loop system as shown in the Figure 5(b), where the predictive controller does not exist, the following nonlinear dynamics equation is calculated. Defining $e = e_1;\ \dot{e} = e_2$,

$$T_0\hat{J}\dot{e_2} + \left(\widehat{K_t}K_pT_0 + \hat{J}\right)e_2(s) + \widehat{K_t}K_pe_1(s) = 0 \tag{9}$$

Or in matrix form

$$\begin{bmatrix}\dot{e_1}\\ \dot{e_2}\end{bmatrix} = \begin{bmatrix}0 & 1\\ -\frac{K_p\widehat{K}_t}{\hat{J}T_0} & -\frac{\hat{J}+T_0K_pK_t}{\hat{J}T_0}\end{bmatrix}\begin{bmatrix}e_1\\ e_2\end{bmatrix} \tag{10}$$

$$\dot{e} = \mathbf{A}e\ ; \qquad e = [e_1 \quad e_2]^T$$

As mentioned above according to the experiments, the proposed variables in the-controller are approximately changed using non-linear functions as follows:

$$K_p = K_{pmax} - K_{p1}e^{-K_{p2}|e_1|^2}$$

$$T_0 = T_{0min} + T_{01}e^{-T_{p2}|e_1|^2}, \tag{11}$$

Where K_{pmax} and T_{0min} are the maximum values of K_p and minimum value of T_0 and $k_{p1}=K_{pmax} - K_{pmin}$ and $T_{01}=T_{0max} - T_{0min}$. A matter of fact the functions are Gaussian functions with K_{p2} and T_{02} as positive constants which represent the wide swings of the error. Thus, K_p and T_0 are monotone decreasing and increasing functions of e_1, respectively, so that equation (9) becomes a non-linear function.

1) Stability Analysis of the Linear System

Referring to the equation (10) T_0 and K_p are constants, then the eigenvalues of **A** are obtained as follows:

$$\lambda_1 = -\frac{K_p\widehat{K_t}}{\hat{J}} < 0 \qquad \text{and} \qquad \lambda_2 = -\frac{1}{T_0} < 0 \tag{12}$$

It can be seen that the eigenvalues are negative therefore the linear system is stable.

2) Stability Analysis of the Nonlinear System

By using Liapunov's stability theorem, in which it is known that if the elements of $\mathbf{A}(e)$ are slowly time-varying parameters and all the eigenvalues of $\mathbf{A}(e)$ have negative real parts, then the nonlinear system $\mathbf{A}(e)$ is asymptotically stable [1]. It is applicable to this system, since e is slowly time-varying. Consequently, the elements of $\mathbf{A}(e)$ in (10) are slowly time-varying and contain K_p and T_0. Therefore, the non-linear system in (9) is asymptotically stable. The values of K_{pmax} , K_{pmin} , T_{0max} *and* T_{0min} can be obtained from the desired output response of the system without affecting stabilities.

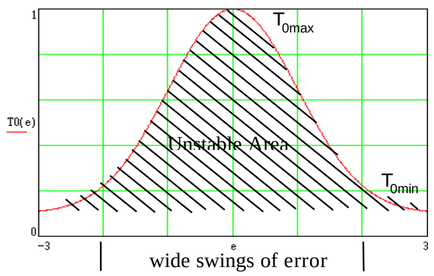
3) Instability of the Systems

When $\dot{T}_0$ is $\left({dT_0}/{de}\right)\dot{e}$, and ${dT_0}/{de}$ is large, $\dot{e}$ causes instability. In other words, if slope of T_0 versus error e exists in the shaded area in Figure 7, instability occurs (Strefezza et al., n.d.).

4) Control Design Measure

The eigenvalues λ_1 and λ_2 in (12) are the function of parameters T_0 and K_p

which are continuously changing. Thus, the controller design can be performed by examining both of the eigenvalues λ_1 and λ_2 in (12) where the stability which has slope T_0 versus e curves existing outside the shaded area in Figure 7.



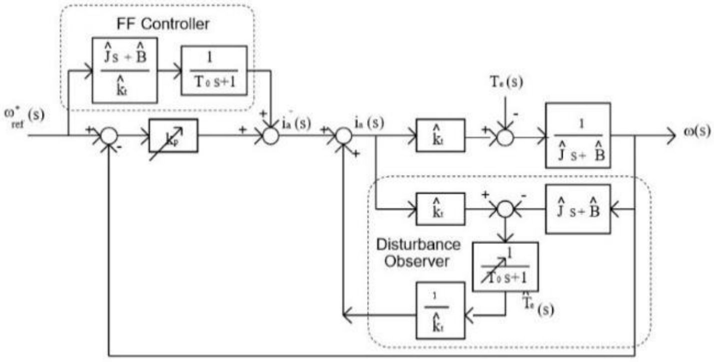


Figure 7. Unstable border of T_0.

Figure 8. Overall control block diagram.

SIMULATION RESULTS

The overall control block diagram is shown in Figure 8. Guard filters whose time constants are 1.6 msec. The control object is an induction motor of 7.5Kw, 200V, 600Hz, 4p and 1800rpm. The load is a 11Kw dc machine. The constants value of J, K_t and K_p are J:0.2 Kgm², K_t:1.0, K_p:10.0, and the Pulse Generator (PG): 600 pulses per revolution. The simulations were done using the above parameters. Figure 9, Figure 10 show the comparison between the conventional PI controller, and the proposed controller. Their results are as follows:

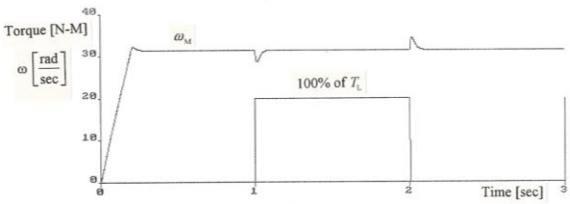


Figure 9. Output time responses for the conventional PI controller.

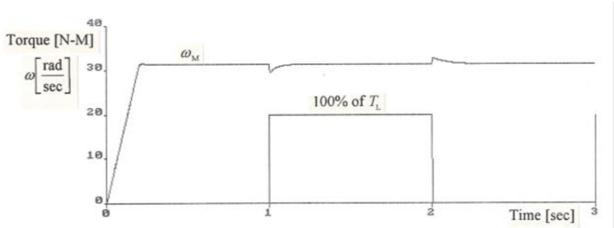


Figure 10. Output time responses for the proposed controller.

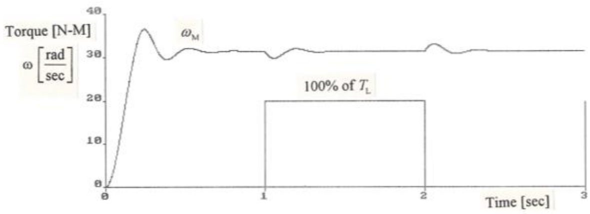


Figure 11. The conventional PI controller, when J_M is increased by 10.

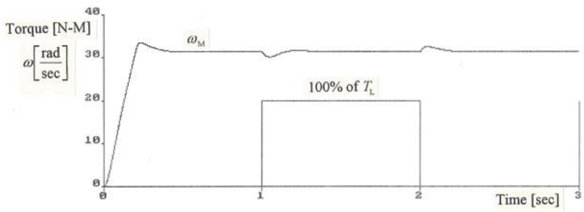


Figure 12. The proposed controllers J_M is increased by 10.

DISCUSSION AND CONCLUSION

Gain-scheduling Robust controller which is insensitive to the external disturbances, the system parameter variations and the observation noises has been proposed. The proposed controller is simple and is easily designed. It is a general controller to different drive systems.

It's shown the difference between result of PI controller, Zeroing and proposed controller. The results of proposed controller is improvement in the robustness effect due to disturbances acting in the system. The simulation has been done also for different parameters of the system, and can be found in Figure 11 and Figure 12.

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