Adaptive Fuzzy Logic Compensator for Permanent Magnet Synchronous Motor Torque Control System

Pewmaikam C., Srisertpol J., and Khajorntraidet C.

***Abstract*—A torque control system of Permanent Magnet Synchronous Motor (PMSM) is an important process in industries, especially in the hard disk drive assembly processes. For example, the automatic screw machine is one of important machines in the hard disk drive assembly processes. The PMSM is a fundamental component of the automatic screw machine. The feedback torque control system use estimated torque received from motor current. The disturbance torque caused by the screw process depends on the quality of the screw heads and screw holes. The automatic screw machine requires precise output torque because the error of output torque affects the automatic screw machine performance. The damage in the hard disk drive assembly process may result from an inaccurate output torque. For instance, the defect of product is broken threads of the screws and the out of length of the screw heads. When the control process requires precision output torque, the machines must be calibrated by operator with standard value consumed 20-30 minutes per machine. This paper presents a torque control system with an adaptive fuzzy logic compensator for torque control and torque estimation simultaneously. The method of the research can increase the efficiency of torque control system and decrease the calibration time of the automatic screw machines.**

***Index Terms*—Permanent magnet synchronous motor, control theory, observer and adaptive fuzzy logic compensator.**

I. Introduction

The PMSM has also been expolit in many fields. The screw driving process, one of the important machines in hard disk drive industry, can take part of hard disk drive to adjoin. By using a feedback control system of the automatic screw machine, torque of the machine converted from current and Linear Variable Differential Transformer (LVDT) is used to verify length of the screw heads. The torque screw driver must be controlled both speed and torque. In the original method speed control of PMSM use the procedure that ensure robust speed contrl against the variations of the moment of inertia and step change of load torque [1]. A screw driving process requires precise output torque. Many problems happen in the screw machine process, for example the screw and screw groove do not match and a quality of screw groove out of standard. The machines have to increase an output torque affected the physical system of the machine. Because of this reason, the physical system is changed. Each screw machine has different values of PID-controller parameters that improper for screw driving process. The screw driver of automatic screw must be calibrated by standard machine, which takes time in calibration process about 20 – 30 minutes per machine that affects the hard disk drive assembly processes performance.

The dynamic responses of the PMSM motor transformed to the estimated rotor frame are nonlinear, thus the observer and observer error dynamics are nonlinear. The stability of control system is analyzed as a linearized error model [2]. Nowadays, fuzzy logic is one of the well known methods, which is used to overcome the problem in many fields, and also in electrical machine control problems. The main idea to design the fuzzy logic is based on the exact behaviors of the machines. Therefore, fuzzy logic can perform very well with nonlinear system, e.g. AC machines [3]. A Fuzzy control has been employed to control temperature. The error-count is used to trigger the fuzzy inference process [4]. A novel self-tuning PI controller is real-time designed according to the identified parameters based on pole assignment theory; the least-square estimator and a torque observer are used in the system [5]. A fuzzy PI-Controller is described that take into account some of the unique characteristic of such a furnace. Entries in the rule base are used to prevent integrator windup, and a fuzzy gain scheduler allows the controller to be tuned and used over the whole operating temperature range of the system [6]. The structure hierarchy and computational complexity of the controller were simplified by reducing the number of fuzzy groups in the membership function without losing the system performance. The tuning of fuzzy logic controller is achieved by development of a knowledge/rule base with scaling factors [7]. Additionally, a fuzzy logic based direct torque control of PMSM can improve the performance of the drive in term of torque, flux, speed and current ripples [8].

A worldwide energy-saving emission has stimulated extensive application of permanent magnet synchronous motor in industry. This work is a contribution to velocity control of the permanent magnet synchronous motor. The model of the permanent magnet synchronous motor has multivariable, highly nonlinear, strong coupling character with external load; in order to control this complicated nonlinear model, the hierarchy model reference dynamic inversion control method has been developed [9]. The speed Sensorless Indirect Field Oriented Control (IFOC) of a Permanent Magnet Synchronous machine (PMSM) is studied. The closed loop scheme of the drive system utilizes fuzzy speed and current controllers [10]. A DSP-based nonlinear speed control of a permanent magnet synchronous motor (PMSM) is robustness for unknown parameter variations. The model reference adaptive system (MRAS) based adaptation mechanisms for the estimation of slowly varying parameters are derived using the Lyapunov's stability theory

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[11]. The current control schemes for a voltage source inverter-fed PMSM drive can be classified as the hysteresis control, ramp comparison control, synchronous frame proportional-integral (PI) control, and predictive control. Among them, the predictive control is known as a superior performance control scheme [12]. A technique for torque control of DC servo motor uses an adaptive load torque compensation method. The load torque can be compensated to the observer, the result show that the estimated current error from the observer is reduced [13].

This paper presents a torque control system with an adaptive fuzzy logic compensator for torque control and the torque estimator of the machine for torque measurement. The method in this research can increase efficiency and decrease the calibrated time of the automatic screw machines.

II. Mathematical Descriptions

The governing equation of an AC servo motor consists of two parts, electrical and mechanical systems.

A. Electrical Governing Equation

The mathematical model of the PMSM is composed of three phase's stator windings and permanent magnets mounted on the rotor surface (surface mounted PMSM). The electrical equations of the PM synchronous motor can be described in the rotor rotating reference frame, written in the (*d-q axis*) rotor flux reference frame are described as follows:

$$V_d = R_s i_d + \frac{d\lambda_d}{dt} - \omega_e \lambda_q \quad (1)$$

$$V_q = R_s i_q + \frac{d\lambda_q}{dt} + \omega_e \lambda_d \quad (2)$$

$$\lambda_d = L_d i_d + \lambda_m \quad (3)$$

$$\lambda_q = L_q i_q \quad (4)$$

B. Mechanical Governing Equation

The torque that is generated by the energy conversion process is used to drive mechanical loads. Its expression is related to mechanical parameters via the fundamental law of the dynamics as follows:

$$T_e = J\frac{d\omega_r}{dt} + B\omega_r + T_L \quad (5)$$

In the servo applications, the unknown load is a significant parameter. The propose scheme for permanent magnet synchronous motor torque control is shown in Fig. 1. This control system consists of PMSM and PI controller. In addition, the system will work with a full-state observer and an adaptive fuzzy logic load torque compensator. The feedback torque for this torque control system receives from estimated current of the observer.

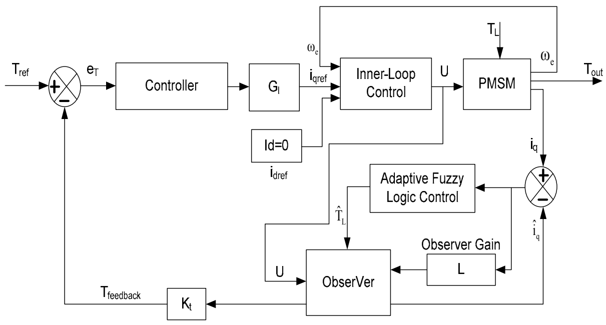

Fig. 1. PMSM torque control system

III. Observer Design

A cost and a complexity of the control system increase if the number of required sensor increases. A state observer can be designed to estimate the state variables of the PMSM via current measurement. Fortunately, if the system is completely observable, then it is possible to estimate the states that are not measured. The equations of observer are.

$$\frac{d\hat{i}_d}{dt} = \frac{V_d}{L_d} - \frac{R_s}{L_d}\hat{i}_d + \omega_e i_q \frac{L_q}{L_d} + eL_1 \quad (6)$$

$$\frac{d\hat{i}_q}{dt} = \frac{V_q}{L_q} - \frac{R_s}{L_q}\hat{i}_q - \omega_e i_d \frac{L_d}{L_q} - \omega_e \frac{\lambda_m}{L_q} + eL_2 \quad (7)$$

where L_1 and L_2 are the observer gains, (^) is the estimated state and an error is $e = i_q - \hat{i}_q$

IV. Controller and Compensator Design

A torque control system of the PMSM is an important process in industries, especially in the hard disk drive assembly processes. A PI controller is used in feedback control system. The current of the observer is the feedback signal to the torque control system before it is converted to torque of the motor. If the d-axis inductance is equal to the q-axis inductance (PMSMs with surface mounted magnets), the motor torque depends only on the q-axis, and motor current is show in equation.

$$T_e = \frac{3}{2} P\lambda_m i_q \quad (8)$$

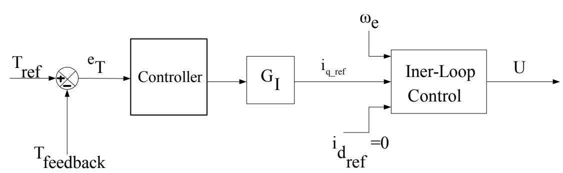

Fig. 2. Inner-loop control.

From Fig. 2, The G_I is the integral in the inner loop of control system and the inner loop control equations are show in equation (9) and (10) respectively.

$$PI\ Controller = K_p + \frac{K_i}{s} \quad (9)$$

$$G_I = \frac{1}{S} \tag{10}$$

The structure of fuzzy logic controller is shown in Fig. 3. There are four main parts for fuzzy logic approach. The first part is '*fuzzification unit*' to convert the input variable to the linguistic variable or fuzzy variable. The second part is '*knowledge base*' to keep the necessary data for setting the control method by the expert engineer. The '*decision making logic*' or the inference engine is the third part to imitate the human decision using rule bases and data bases from the second part. The final part is '*defuzzification unit*' to convert the fuzzy variable to easy understanding variable.

The compensating control using fuzzy logic controller in Fig. 3, i_q and $\hat{i}_q$ are the actual compensating current and the reference current, respectively. The inputs of the fuzzy logic controller are the error and the error rate that can be calculated by equation (11) and (12)

$$error = i_q - \hat{i}_q \tag{11}$$

$$error\ rate = \frac{d\left(i_q - \hat{i}_q\right)}{dt} \tag{12}$$

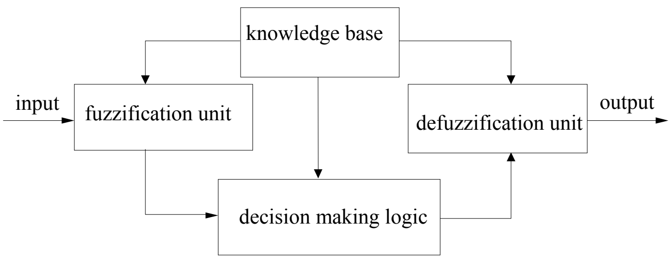

Fig. 3. The basic structure of fuzzy logic controller

The shape of the output signal from the fuzzy logic controller is the pulse waveform that can be adjusted. The linguistic variables of input and output for the fuzzy logic controller to control the compensating torques in the paper are shown in Table 1 and the parameter values of the input and output membership function are shown in Table II. The error input, the error rate and the disturbance torque output of the fuzzy logic controller are shown in Fig. 4, 5, and 6, respectively.

TABLE I. THE INPUT AND OUTPUT LINGUISTIC VARIABLES OF THE FUZZY LOGIC CONTROLLER

Variable name	Variable value	Meaning
Input of the fuzzy logic controller		
Error input	neg	The error is negative.
	zero	The error is zero.
	pos	The error is positive.
Error rate input	dec_rate	The error rate decreases.
	zero_rate	The error rate is zero.
	inc_rate	The error rate increases.
Output of the fuzzy logic controller		
Torque	zero	The zero.
	pos	The positive value.

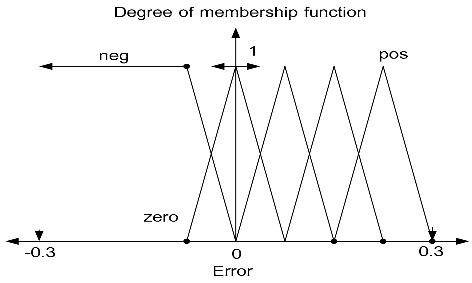

Fig. 4. The error input

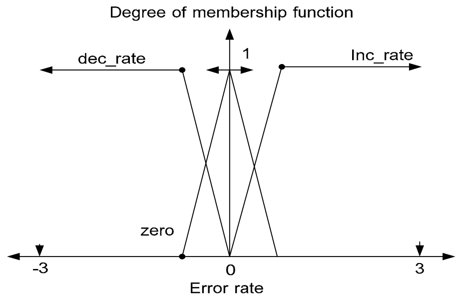

Fig. 5. The error rate input

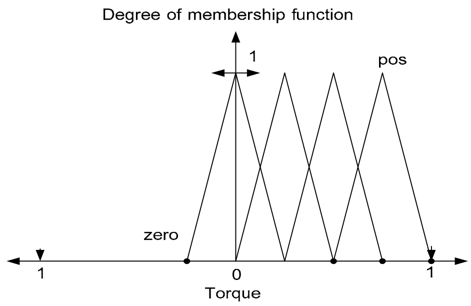

Fig. 6. The disturbance torque output

TABLE II. THE PARAMETER VALUES OF THE INPUT AND OUTPUT MEMBERSHIP FUNCTION

Error Input (A)	Error Rate Input (A/s)	Output Torque (Nm)
0.0247	[0,3]	0.1
0.0505	[0,3]	0.2
0.0772	[0,3]	0.3
0.1048	[0,3]	0.4
0.1334	[0,3]	0.5
0.1629	[0,3]	0.6
0.1933	[0,3]	0.7
0.2245	[0,3]	0.8
0.2565	[0,3]	0.9
0.2893	[0,3]	1.0

V. SIMULATION RESULTS

This section demonstrated the simulation results of permanent magnet synchronous motor torque control system when the system and controller parameters are as follow:

$$J = 1.854\times10^{-4} kg\cdot m^2 / rad, K_t = 2.2224 N\cdot m / A$$

$$P = 8, B = 1.0\times10^{-6} N\cdot m\cdot s / rad, \lambda_m = 0.1852 Wb$$

$$R_s = 1.6\Omega, L_d = L_q = 6.365\times10^{-3} H$$

$$K_p = 2500 A / N\cdot m, K_i = 25 A / N\cdot m$$

$$V_{rms} = 220 V_{rms}, f = 50 Hz$$

The simulation of the torque control system was be applied the disturbance torque as the step function, as shown in Fig.7. In the simulation, there were three patterns of desired inputs. The first pattern of desired input was the step function. Then, the desired input was the ramp function. Finally, the step and ramp functions were combined as the process of torque screw driver. If no load torque interacted with the system, the torque control system which used estimated current from the observer had high efficiency to control the output torque. On the other hand, an error between the desired torque and the output torque was occurred when the system received the disturbance torque because of the incorrect estimated current from the observer. Therefore, the adaptive fuzzy logic load torque compensator was be used to compensate load torque to the observer. The results of torque compensation to the torque control system were shown in Figure 8, 9, 10 and 11.

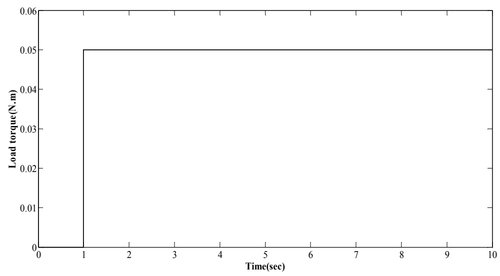

Fig. 7. Disturbance torque

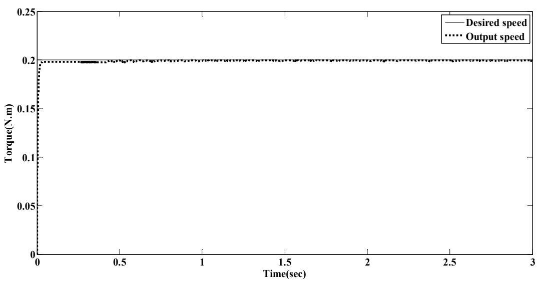

Fig. 8. Dynamic response of torque control in the case of the step function input with load torque compensation

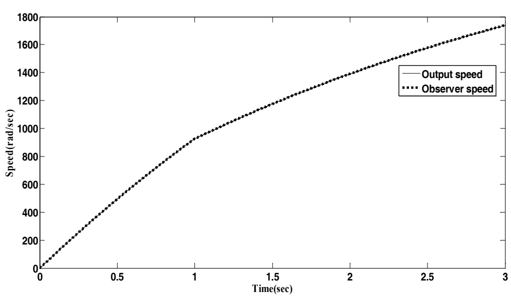

Fig. 9. Dynamic response of speed in the case of the step function input with load torque compensation

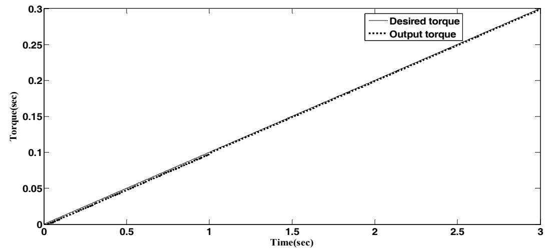

Fig. 10. Dynamic response of torque control in the case of the ramp function input with load torque compensation

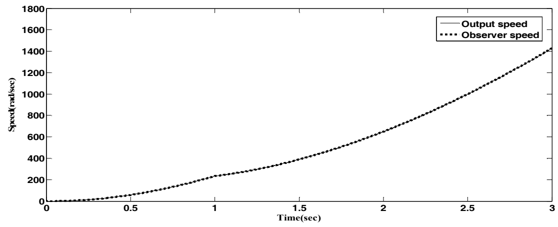

Fig. 11. Dynamic response of speed in the case of the ramp function input with load torque compensation

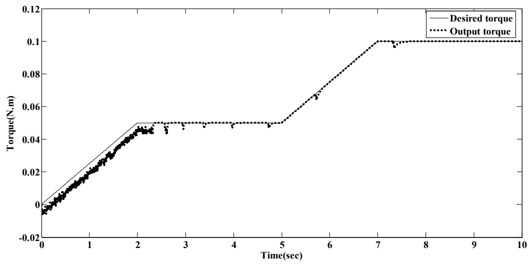

Fig. 12. Dynamic response of torque control in the case of no-load operation

For the control process of the torque screw driver in the case of no-load operation, PI controller can control the output torque of permanent magnet synchronous motor by using current feedback from the observer as shown in Fig. 12 and in Fig. 13 shown the speed response of the torque screw driver. The response of torque and speed depict good results because of without system disturbance.

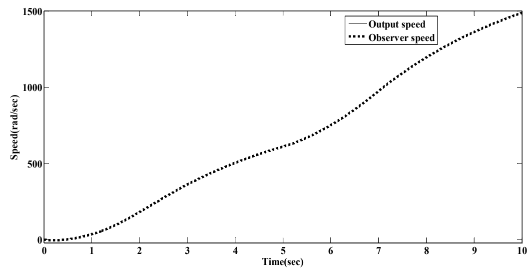

Fig. 13. Dynamic response of speed in the case of no-load operation

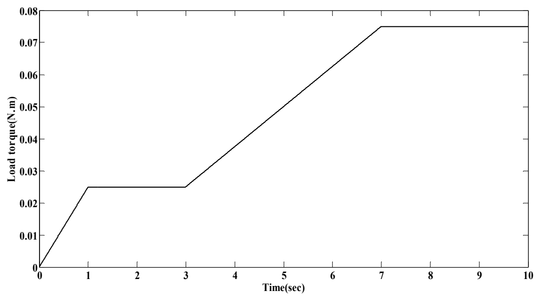

Fig. 14. The disturbance torque of torque screw process

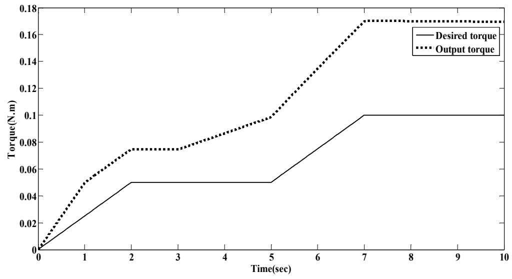

Fig. 15. Dynamic response of torque control in the case of load operation without load torque compensation

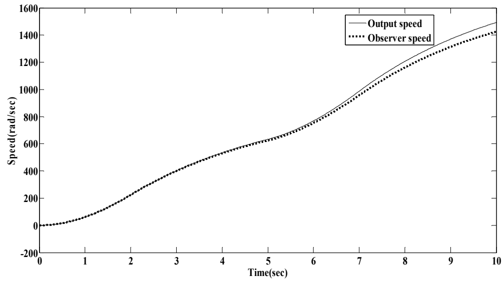

Fig. 16. Dynamic response of speed in the case of load operation without load torque compensation

When the permanent magnet synchronous motor system, an actuator of screw driver, receives disturbance torque during the operation as shown Fig.14, the state variable which is estimated form the observer was incorrect. If the incorrect estimated current is used to control torque of the system, the inaccurate output torque will occur. The result is shown in Fig. 15 and 16.

After compensate the estimated load torque form the adaptive fuzzy logic compensator to the observer, the error of estimated current was reduced. The responses of torque control system are shown in Fig. 17 and 18.

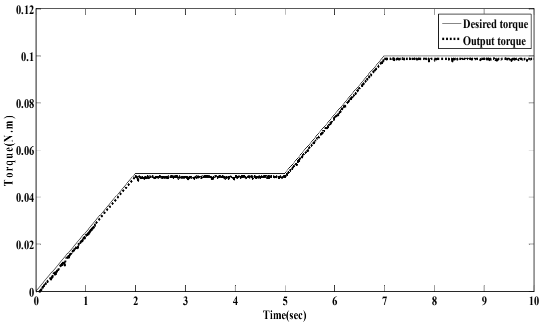

Fig. 17. Dynamic response of torque control in the case of load operation with load torque compensation

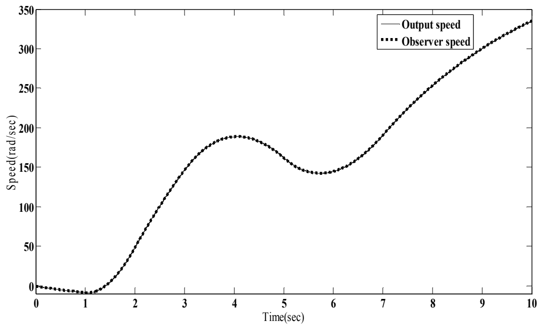

Fig. 18. Dynamic response of speed in the case of load operation with load torque compensation

Additionally, the responds of load torque from the adaptive fuzzy logic compensator can indicate that the torque screw in assembly process work well or has some problems during the process. For example, if the value of load torque increases rapidly, the misalignment of screw may occur or some parts of the product are not match with each other.

VI. CONCLUSIONS

The feedback of the torque control system of this method hinges on the estimated current from the observer. The load torque not only disturbed the system but also affected the quality of estimated current. This paper demonstrated advantages of the adaptive fuzzy logic compensation technique that can be developed to the PMSM torque estimation. The results of the research shown that, this method can improve the efficiency of the torque control system. Additionally, this method leads to the process that can apply to decrease the calibration time of the automatic screw machines, reduce the cost of sensors, and develop the diagnostic system.

NOMENCLATURES:

R_S – Motor phase resistance (Ω)
L_d – d-axis inductance (H)
L_q – q-axis inductance (H)
p – Number of magnetic poles
T_e – Electromagnetic torque (Nm)
T_L – Load torque (Nm)
B – Viscous damping coefficient (Nm.s)
J – Moment of inertia of the motor (kg/m^2)
i_d – d-axis current in synchronous frame (A),
i_q – q-axis current in synchronous frame (A)
V_d – d-axis voltage in synchronous frame (V)
V_q – q-axis voltage in synchronous frame (V)
ω_r – Motor electrical angular velocity (rad/s)
ω_e – The machine angle velocity of rotor (rad/s)
λ_d – d-axis flux linkage in synchronous frame (Wb)
λ_q – q-axis flux linkage in synchronous frame (Wb)
λ_m – PM flux linkage in synchronous frame (Wb).

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