On-Line Fuzzy Tuning of Indirect Field-Oriented Induction Machine Drives

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***Abstract*—This paper presents an on-line fuzzy tuning scheme for indirect field-orientation (IFO)-controlled induction machine drives. A fuzzy controller is used to regulate the speed, and another two fuzzy compensators are combined to correct detuning of field orientation. Since detuning effects of the IFO induction machine drive is minimized by the new fuzzy control scheme, the induction machine can achieve good performance in terms of overshoot, steady-state error, torque disturbance, and variable-speed tracking. Efficiency and torque/ampere capability are also enhanced. The results obtained by laboratory implementation are presented to verify the effectiveness of the proposed on-line fuzzy-tuning scheme.**

***Index Terms*—Field-orientation control, fuzzy logic, induction machine drive, on-line tuning.**

I. Introduction

INDIRECT field-oriented (IFO) induction machine drives are finding numerous industrial applications in recent years. In a typical IFO induction machine drive, either a synchronous-frame proportional and integral (PI) current regulator or a feedforward current regulator is often used to achieve ideal current regulation. In addition, a slip calculator is applied to accomplish feedforward field-oriented control. However, changes in the rotor time constant T_r often cause field-orientation detuning and degrade system performance, especially for large high-efficiency induction machine systems. When detuning occurs, the efficiency and torque capability of the drive are greatly reduced in steady state [1]. Furthermore, due to the inverter current limits, torque/ampere capability of the drive is significantly less, resulting in unsatisfactory drive performance, particularly for fast dynamic speed commands.

Many on-line rotor time-constant identification schemes and on-line tuning schemes have been studied in the last decade [2]–[4]. The various proposed methods have shown some improvement of the variable-speed drive. However, these methods usually need either more machine parameters or have hardware complications.

This paper introduces an on-line fuzzy-tuning scheme for IFO induction machine drives. A conventional synchronous PI current regulator and feedforward slip calculator are used to implement decoupled flux and torque control. To prevent detuning of field orientation, two fuzzy slip compensators are designed to handle machine parameter deviations. That is, one fuzzy compensator is used to on-line tune T_r in the slip calculator when the machine is working in the speed-tracking mode, and another is used to compensate T_r when the machine is working in the constant-speed mode. Compared to a conventional IFO drive, the new on-line tuning scheme does not need any machine parameter estimation and additional hardware. Since detuning effects of the IFO induction machine drive are corrected by the fuzzy compensators, good performance of the IFO drive is achieved in terms of overshoot, steady-state error, torque disturbance, and variable-speed tracking. The results obtained by laboratory implementation are presented to verify the effectiveness of the proposed on-line fuzzy-tuning scheme.

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II. Detuning of IFO Drive Systems

Assuming that the induction machine is supplied from a current-regulated voltage-source inverter with rotor flux orientation, the d-q equations of the machine in the synchronous reference frame are

$$r_r i_{qr}^e + \omega_s \lambda_{dr}^e = 0 \tag{1}$$

$$r_r i_{dr}^e + p\lambda_{dr}^e = 0 \tag{2}$$

$$L_m i_{qs}^e + L_r i_{qr}^e = 0 \tag{3}$$

$$\lambda_{dr}^e = L_m i_{ds}^e + L_r i_{dr}^e \tag{4}$$

$$T_e = \frac{3}{2}\frac{p}{2}\frac{L_m}{L_r}\lambda_{dr}^e i_{qs}^e. \tag{5}$$

From these equations, an important slip relation can be derived

$$s\omega_e = \frac{1}{T_r}\frac{i_{qs}^e}{i_{ds}^e}(1 + pT_r). \tag{6}$$

Equation (6) means that field-orientation control of an induction machine is equivalent to a correct slip control of the same machine. Note that in (6), T_r is the key parameter to determine field orientation. Unfortunately, T_r is a parameter, which is temperature and saturation dependent. Therefore, the desired independent control of flux and torque is often lost because of T_r variation.

Although a properly designed speed regulator can partially handle a slightly detuned case for speed control, for a fast dynamic speed command, the drive performance will degrade. Generally, for a large machine, detuning of the IFO-controlled induction machine results in a high-slip high-current low-flux condition if the actual value of T_r is large than the predicted value. Conversely, detuning results in a low-slip low-flux

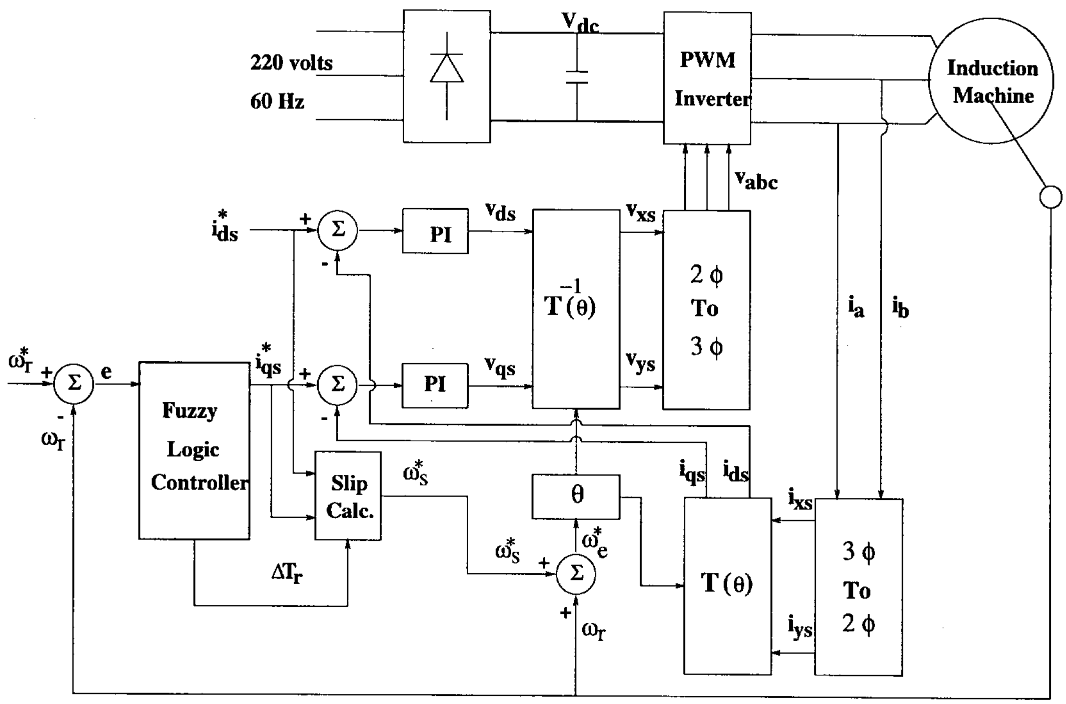

Fig. 1. Block diagram of the FLC induction machine IFO drive system.

condition if the actual value of T_r is less than the predicted value. For a small machine, the detuning effects are similar except that the current is always higher [1].

When the drive system is severely detuned, the machine is working in a low-efficiency region, and its torque capability is significantly reduced. In addition, the current limit of the inverter further lowers the machine's peak torque capability. This problem becomes very serious for large high-efficiency machines [1].

III. On-Line Fuzzy-Tuning Scheme

Fig. 1 shows the proposed controller with a fuzzy on-line tuning scheme for an IFO-controlled induction machine. The controller consists of two feedback loops. The inner one is a conventional synchronous-current regulation loop. Decoupled flux and torque control are accomplished by the tuned slip calculator. The torque command current i_{qs}^* is produced by the outer speed loop, implemented by a fuzzy logic controller (FLC_1) as shown in Fig. 2.

In this control scheme, T_r in the slip calculator is continuously tuned according to the machine-operating mode, transient or constant speed, by two fuzzy compensators—FLC_2 and FLC_3.

A. FLC_1: Speed-Control Loop

Closed-loop speed control is accomplished by the direct fuzzy controller FLC_1. The inputs to FLC_1 are e_1 and e_2, a scaled version of the speed error, and the change of the speed error as defined in

$$e_1(k) = G_1(\omega_r(k) - \omega_r^*(k)) = G_1 e(k) \tag{7}$$

$$e_2(k) = G_2 \frac{(e_1(k) - e_1(k-1))}{T} \tag{8}$$

where T is the sampling time. FLC_1 fuzzy controller has seven fuzzy sets with membership functions uniformly distributed on each normalized input by adjusting the gains G_1 and G_2. All of the membership functions used in the direct fuzzy controller are the standard triangle type. These input membership functions are used to transfer *crisp* inputs into fuzzy sets. The expert experience has been incorporated into a knowledge base with 7×7 rules. Then, the inference engine, based on the input fuzzy sets, uses appropriate IF–THEN rules in the knowledge base to imply the final output fuzzy sets. These output fuzzy sets are finally converted back to *crisp* values by a center of gravity (COG) defuzzification technique [5]. Note that the crisp output ΔI_{qs}^* is integrated in such a way that the command to the current regulator is

$$I_{qs}^*(k) = I_{qs}^*(k-1) + T \cdot \Delta I_{qs}^*(k) \tag{9}$$

where ΔI_{qs}^* is the incremental current command. It is apparent that FLC_1 is an integral-type fuzzy controller and forces the steady-state speed error to zero.

The input/output mapping of the FLC_1 fuzzy controller is shown in Fig. 3, which is a continuous and highly nonlinear function. Detailed discussion about FLC_1 construction is referred to in [6].

B. FLC_2: Slip Compensator for Transient Speed-Tracking Mode

As mentioned before, detuning of IFO degrades performance of the drive system, especially for a fast dynamic speed command. When the drive system is operating in dynamic speed-tracking mode, detuning causes a detectable speed error. Fig. 4 shows speed-tracking performance under a typical detuning condition (ω_r^* and ω_r are the command and actual speed, respectively, and I_a is the Phase-A current).

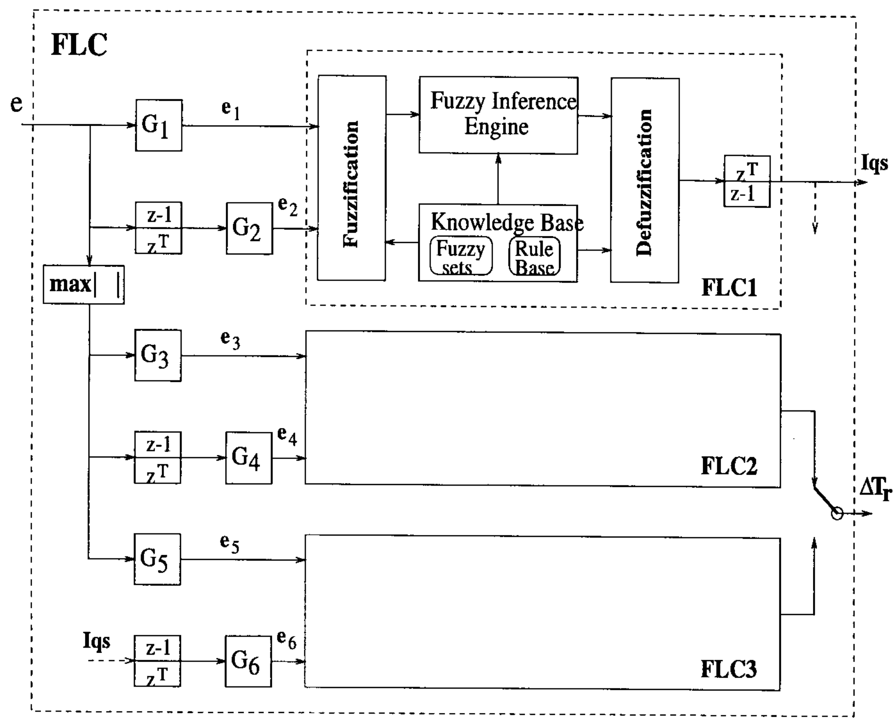

Fig. 2. Fuzzy controller block diagram.

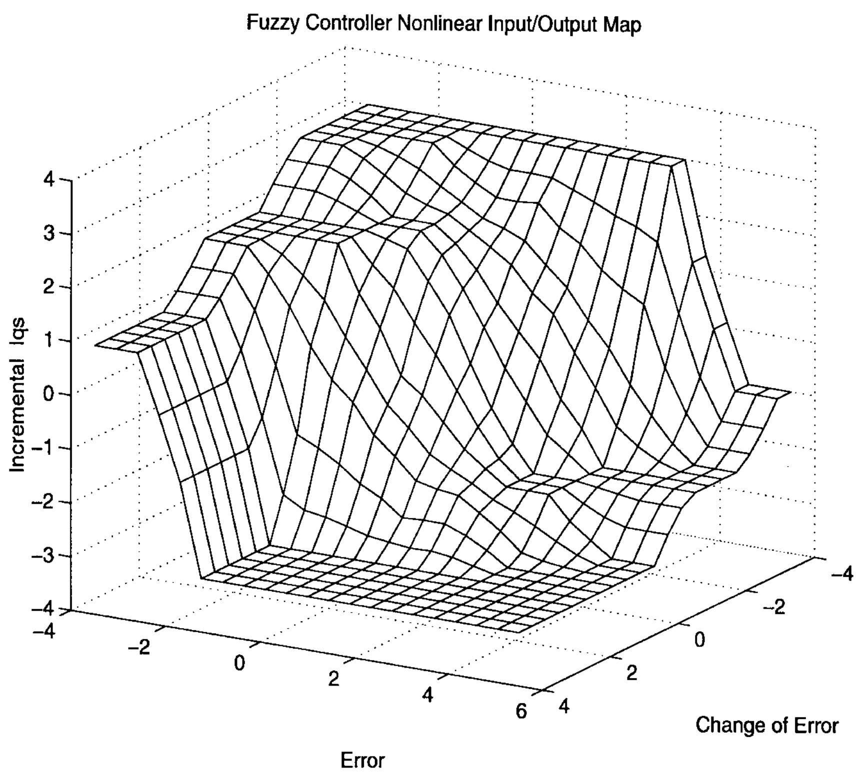

Fig. 3. *Crisp* input/output map.

FLC_2 is constructed to emulate an experienced operator to tune up the IFO controller. Assume that speed error resulting from detuning is detected. As an experienced operator, he/she would immediately take control actions. Initially, he/she would slightly change the rotor time constant used in the slip calculator until the speed error disappears. Suppose that after increasing T_r, the error decreases, he/she would continue to increase T_r until the error is removed. Otherwise, if the error increases, he/she would make a quick decrease of T_r. Obviously, the magnitude of the adjustment depends upon the operator's experience, size of the error, and rate of change of the error.

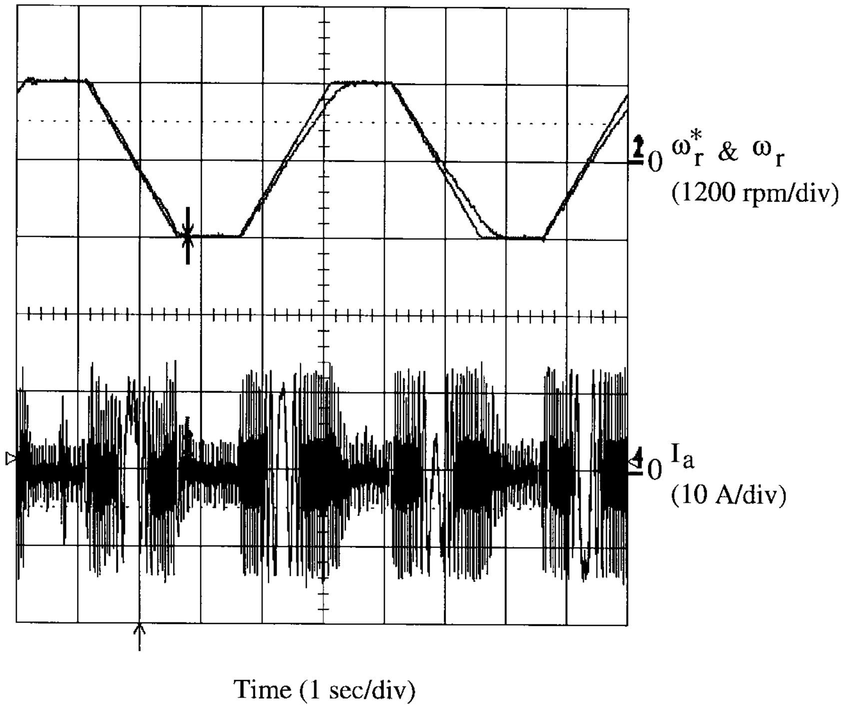

Fig. 4. Detuning effects on speed tracking.

Rule Base		E_4^j		
	U_2	**-1**	0	1
E_3^j	0	1	0	**-1**
	1	1	1	**-1**
	2	2	1	**-2**

Fig. 5. Knowledge base of FLC_2.

The expert experience is built into FLC_2. The inputs to FLC_2 are e_3 and e_4 as defined in (10) and (11), where G_5 and G_6 are adjustable input gains. The same type of membership functions used in FLC_1 are applied in fuzzy sets for FLC_2. Since the input e_3 is always positive, the associated membership functions E_3^j have only positive parts

$$e_3(k) = G_3 \max\left|\omega_r(k) - \omega_r^*(k)\right| \tag{10}$$

$$e_4(k) = G_4 \frac{(e_3(k) - e_3(k-1))}{T}. \tag{11}$$

A knowledge base of 3×3 rules, as shown in Fig. 5, is applied to tune T_r to reduce the speed error to zero.

In the figure, "2, 1, 0, -1, and -2" correspond to *Positive Large, Positive Small, Zero, Negative Small, and Negative Large*. The linguistic rules can be expressed by the following example:

IF "e_3" is "1" and "e_4" is "-1", THEN δT_{r1} is "1".

This rule means that if the absolute value of the maximum speed error is *Positive Small* and the change of it is *Negative Small*, then the output δT_{r1} should be *Positive Small*. In other words, T_r should be continuously increased a little bit in each step. The final output of FLC_2 is expressed in

$$\Delta T_{r1}(k) = \Delta T_{r1}(k-1) + T \cdot \delta T_{r1}(k). \tag{12}$$

C. FLC_3: Slip Compensator for Constant-Speed Mode

According to the previous discussion, FLC_2 modifies T_r only when a dynamic speed-tracking error $(e_3 \neq 0)$ is detected. Then, both FLC_1 and FLC_2 are active to reduce speed error to zero, and T_r is kept constant thereafter. However, T_r may not be an optimum value even if the speed error is zero. Equivalently, the induction machine may still be in a slightly detuned condition, which leads to additional copper losses and lower peak torque capability. To further tune up field orientation and improve performance, another slip compensator FLC_3 is added to solve the detuning problem when the machine operates in a constant-speed mode.

Suppose that detuning occurs slowly due to thermal effects. The speed controller will then demand more torque current i_{qs}^* to maintain the constant speed. In such a case, detuning effects may actually be exist, but are concealed by the zero-speed error. As a result, detuning of an IFO places the induction machine in a high-slip high-current low-flux condition if T_r used in the slip calculator is less than its actual value. Conversely, detuning results in a low-slip low-flux condition if T_r in the slip calculator is greater than the actual one. For small machines, the detuning effects are similar except that the current is always higher [1]. Fig. 6 shows the i_{qs}^* curve for a 5-hp induction machine measured in the laboratory.

To overcome detuning of field orientation under the conditions of zero-speed error, the principle of minimizing input current with an unchanged speed response can be applied. In effect, the analysis results and experimental experiences are

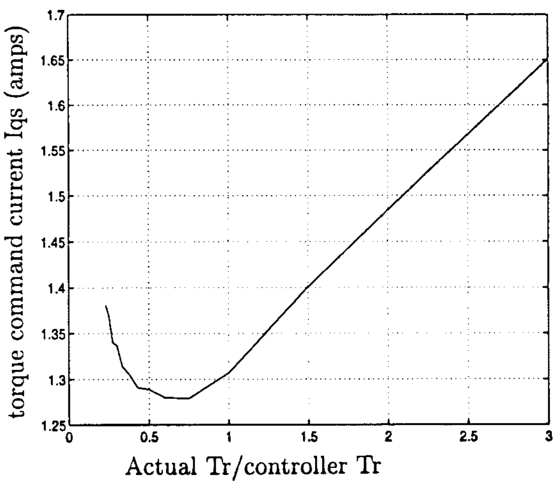

Fig. 6. Torque command current curve when detuning occurs.

integrated to form the knowledge base for FLC_3. Specifically, FLC_3 is designed to minimize i_{qs}^* for a given load (speed-torque) by modifying T_r in the slip calculator. Although the approach may not place the machine in the condition of $\frac{T_{r,\text{actual}}}{T_{r,\text{controller}}} = 1$, the machine will always work in the peak torque/ampere state, thus, optimizing the machine current. For small and medium machines, this approach results in the ideal field-oriented condition. The inputs of FLC_3, e_5, and e_6 are defined in (13) and (14). The output δT_{r2} is defined in

$$e_5(k) = G_5 \left| \omega_r(k) - \omega_r^*(k) \right| \tag{13}$$

$$e_6(k) = G_5 \frac{\left(i_{qs}^*(k) - i_{qs}^*(k-1)\right)}{T} \tag{14}$$

$$\Delta T_{r2}(k) = \Delta T_{r2}(k-1) + T \cdot \delta T_{r2}(k). \tag{15}$$

For the inputs, seven fuzzy sets are defined with triangular-type membership functions. The input gains G_5 and G_6 are defined similarly as done in the FLC_1 and FLC_2. Zadeh's compositional rule of inference and COG defuzzification are used in this fuzzy compensator. Note that only the positive part of the membership functions is used since e_5 is always "positive," so the negative part of E_5^j in the rule base has been removed. On the other hand, since a big speed change is always accompanied by a large current change, it is difficult to tune T_r to minimize i_{qs} in this case. Therefore, when speed error is too big, which is always true for a dynamic speed command, FLC_3 is not allowed to work, and the corresponding rules in *positive medium and positive large* areas are not applicable. The linguistic rules of FLC_3 are shown in Fig. 7.

The linguistic rules can be interpreted as follows.

1) IF the speed error is "Zero" and the current error is "Negative," THEN δT_{r2} should be increased, i.e., "Positive."
2) IF the speed error is "Zero" and the current error is "Positive," THEN δT_{r2} should be decreased, i.e., "Negative."
3) IF the speed error is NOT "Zero" and the current error is either "Negative" or "Positive," THEN δT_{r2} should be decreased, i.e., "Negative."

Rule Base U_3		E_6^j (e_6)						
		-3	-2	-1	0	1	2	3
E_5^j (e_5)	0	3	2	1	0	-1	-2	-3
	1	-1	-1	-1	-2	-2	-2	-3
	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	3	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Fig. 7. Knowledge base of FLC_3.

TABLE I

220 Volts	14.8 Amps	5HP
$L_{ls} = L_{lr} = 1.9\text{mH}$	$L_m = 41.2\text{mH}$	1800 RPM
$R_s = 0.6\ \Omega$	$R_r = 0.412\ \Omega$	4 poles

IV. Experimental Results

In order to verify the effectiveness of the proposed on-line tuning scheme, a laboratory induction machine drive system is configured according to the block diagram as already shown in Fig. 1. The testing setup consists of a 5-hp cage-rotor induction machine, pulse-width modulation (PWM) inverter, and high-speed Motorola DSP56001-based controller. The specifications and parameters of the induction machine are listed in Table I.

Coordination between FLC_2 and FLC_3 is realized by the speed commands. That is, FLC_2 is automatically activated for variable-speed tracking commands and FLC_3 for constant-speed commands.

A. Speed Performance with FLC_1

The step-speed response of the fuzzy-controlled induction machine is shown in Fig. 8. The command speed is a step function with steady-state speed at 1250 rpm. As seen from the figure, the fuzzy controller drives the machine to the command speed in 0.68 s without any overshoot and steady-state error.

Speed-tracking performance is shown in Fig. 9. The command speed is trapezoidal. As expected, the fuzzy controller shows sharp tracking of command with a negligible amount of overshoot at the speed break points.

Fig. 10 shows the torque disturbance rejection capability with fuzzy control scheme. For the torque-disturbance rejection test, a constant command speed (1250 rpm) is applied to the machine. When the machine operates in steady state, a torque disturbance is applied to the machine. As seen in Fig. 10, fuzzy-controlled drive responds with a quick torque current, and the speed shows almost no change.

Note that in the above tests, only one fuzzy controller FLC_1 is used to handle both step command and speed-tracking command with very good performance in terms of overshoot, steady-state error, torque disturbance, and sharp speed tracking.

B. Speed Tracking with On-Line Fuzzy Tuning

The tracking performance with detuning and on-line fuzzy tuning is presented in Fig. 11. The top waveforms are the

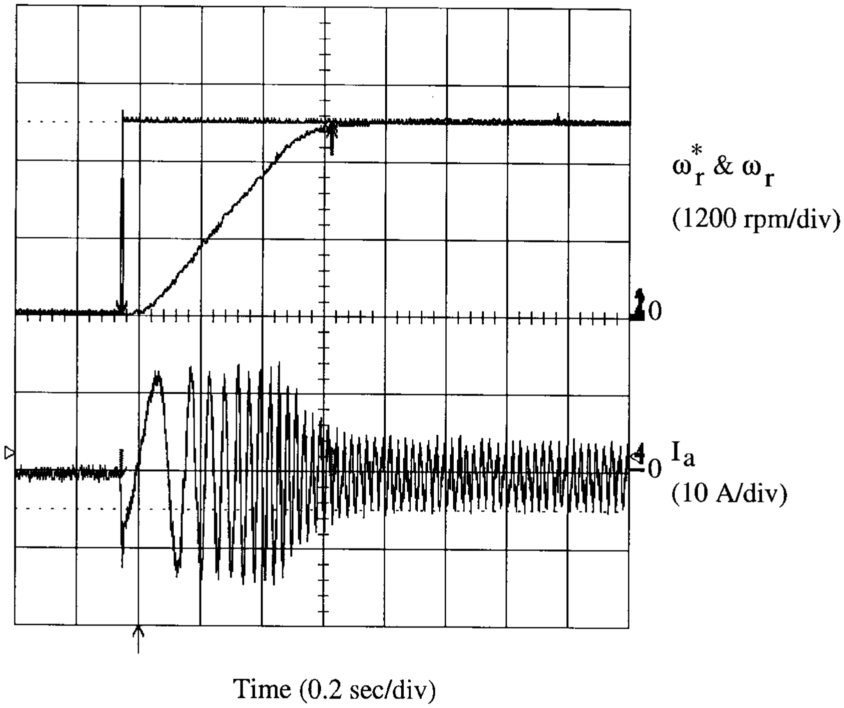

Fig. 8. Step response with fuzzy control scheme.

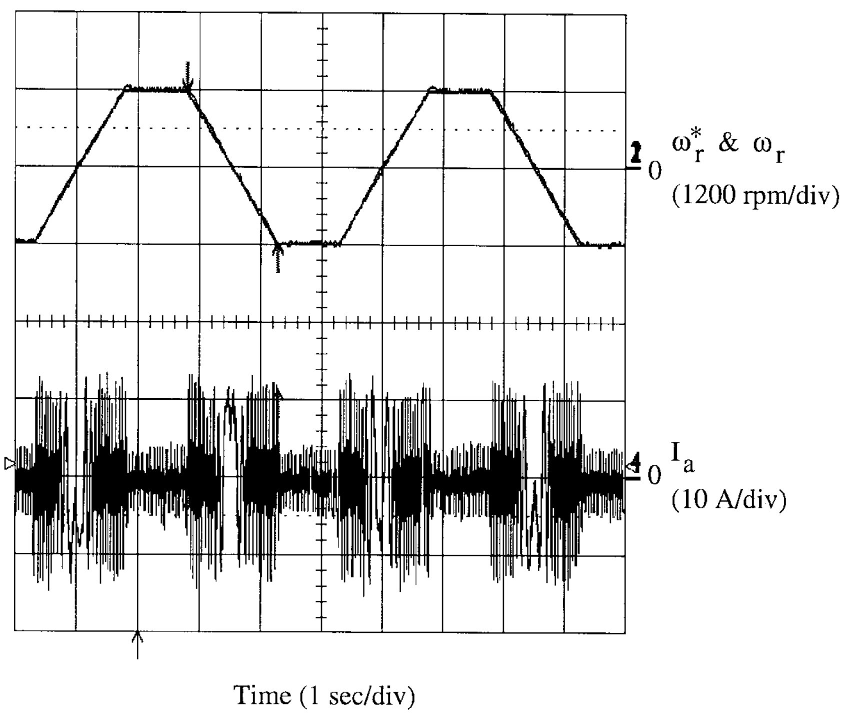

Fig. 9. Speed-tracking performance with fuzzy control scheme.

command and actual rotor speeds, the middle one is $\frac{1}{T_r}$ used in the slip calculator, and the bottom one is the machine phase current.

As seen from the figure, when T_r is reduced on purpose to half of the normal value (i.e., $\frac{1}{T_r}$ is doubled) in the slip calculator, a significant speed error occurs. Then, FLC_2 is connected to the system, which modifies the T_r by δT_{r1} according to the error. Finally, good speed-tracking performance is restored in 1.3 s.

C. Optimal Torque Per Ampere Control by On-Line Fuzzy Tuning

The optimal torque per ampere control at constant speed is shown in Fig. 12. Here, T_r in the slip calculator is intentionally set to twice of the normal value initially. The machine operates with a light load torque at 1200 rpm (top). Note that no speed error exists, and the torque command current (middle) is stable at 1.5 A. Then, FLC_3 is connected to the system. After 1.7 s,

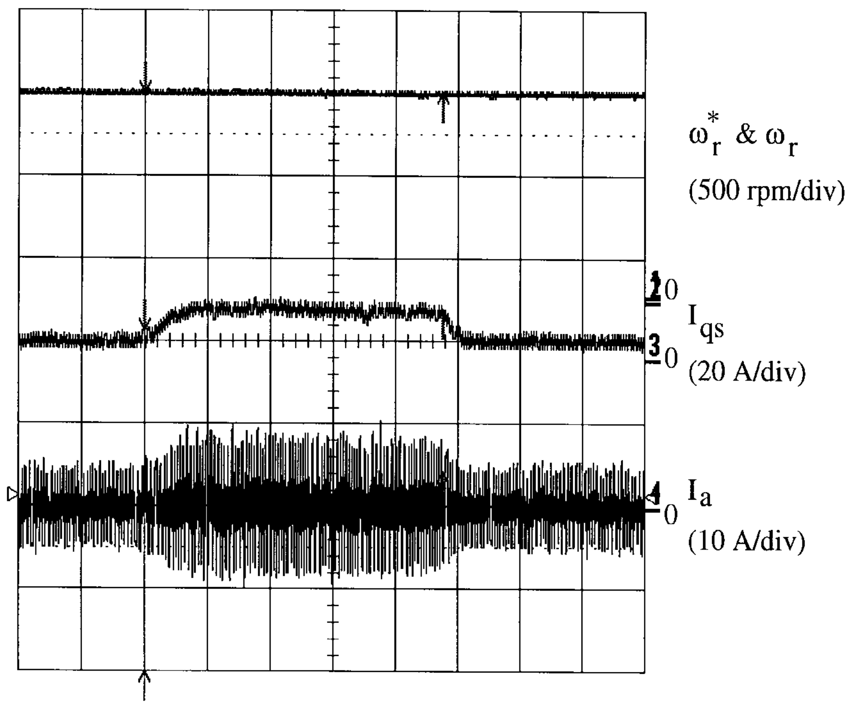

Fig. 10. Torque disturbance rejection capability with fuzzy control scheme.

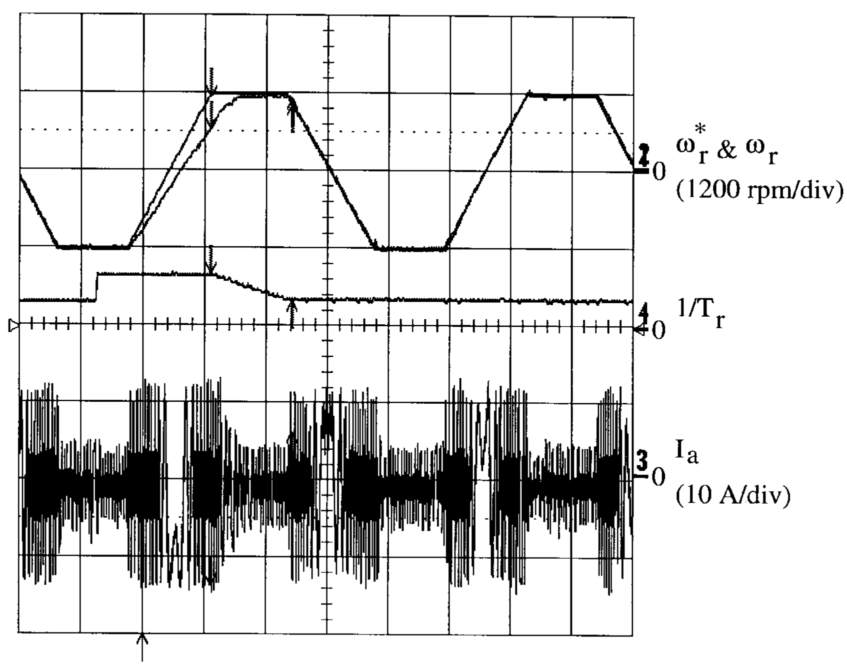

Fig. 11. Speed-tracking performance with FLC_2.

i_{qs}^* is reduced to 1.2 A, indicating that maximum torque per ampere operation is achieved.

V. Conclusion

A novel on-line fuzzy-tuning scheme is designed to enhance IFO induction machine drives. A fuzzy scheme is used to regulate the speed as well as correct detuning of field orientation for dynamic speed commands and constant-speed commands. This intelligent controller has systematically incorporated expert knowledge into the control scheme. The implementation does not require additional hardware or machine parameter information, making it applicable to any induction machine with only the need of a simple adjustment on input gains. Our laboratory experience shows that tuning these gains is usually about one fifth of the time spent on tuning the gains in a conventional PI controller. Extensive experimental results

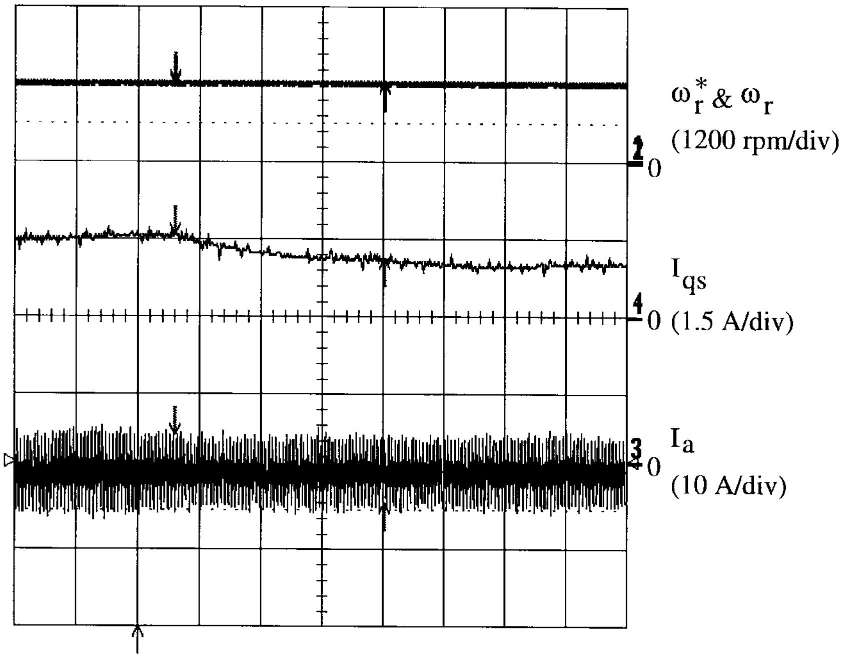

Fig. 12. Experimental result of detuning effect minimization with FLC_3.

show that the new control system can minimize the detuning effects and enhance the performance of an IFO induction machine drive effectively.

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