Fuzzy Logic Enhanced Speed Control of an Indirect Field-Oriented Induction Machine Drive

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***Abstract*— Field orientation control (FOC) of induction machines has permitted fast transient response by decoupled torque and flux control. However, field orientation detuning caused by parameter variations is a major difficulty for indirect FOC methods. Traditional probability density function (PID) controllers have trouble meeting a wide range of speed tracking performance even when proper field orientation is achieved. PID controller performance is severely degraded when detuning occurs. This paper presents a fuzzy logic design approach that can meet the speed tracking requirements even when detuning occurs. computer simulations and experimental results obtained via a general-purpose digital signal processor (DSP) system are presented.**

***Index Terms*—AC motor drive, field orientation control, fuzzy logic, induction machine, speed control.**

I. Introduction

With the field orientation control (FOC) method, induction machine drives are becoming a major candidate in high-performance motion control applications, where servo quality operation is required. Fast transient response is made possible by decoupled torque and flux control. However, conventional proportional integral derivative (PID) control has difficulty in dealing with dynamic speed tracking, parameter variations, and load disturbances. As a result, the motion control system must tolerate a certain level of performance degradation.

Fuzzy control (FC) provides a systematic way to incorporate human experience in the controller. Recent literature has paid much attention to the potential of fuzzy control in machine drive applications [1]–[5]. The authors of [1] and [2] present a unique real-time adaptive fuzzy controller for a doubly excited reluctance machine in and a typical FC for the same machine. In [2], the well-known model reference adaptive control method is combined with the principles of fuzzy logic. Fuzzy logic is applied to an induction machine in [3] where the gains of a PI controller are varied by the fuzzy controller. Though this approach did show better performance, it is, however, more complex in that there are essentially two controllers. Furthermore, the authors did not address performance when machine parameters change. In [4], the authors presented two FC's to achieve position control with an indirect FOC induction machine. The first FC provides coarse control and the second FC performs fine control. Hence the transient response and steady-state error are improved by the coarse and fine FC's, respectively. The paper addresses robustness when both disturbances as well as small parameter changes (i.e., 10%) occur.

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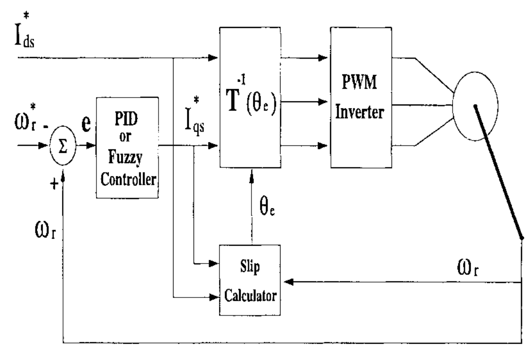

Fig. 1. Indirect field orientation control block diagram.

This paper presents a single, *relatively simple*, FC that is robust in terms of speed tracking, disturbance rejection, and parameter variations without the need for complex adaptive control techniques. This is achieved by carefully designing the rule base as opposed to using a typical symmetric rule base as the authors did in [1]–[4].

II. FC: Principle and Design

Aside from all the *hype* generated over FC, it is recognized that fuzzy logic offers a convenient way of designing controller nonlinearities from one's experiences and expert knowledge about the process being controlled. This heuristic approach can enhance the performance, reliability, and robustness of the closed-loop system more so than conventional linear controllers. In fact, a linear controller that works well over a small operating range can be included in the FC and then nonlinear effects can be added which boosts performance over a much larger range.

A block diagram of an indirect field orientation controlled (IFOC) induction machine is shown in Fig. 1. Note that either a conventional PID controller or a fuzzy controller can be used for the speed control loop. The block diagram showing the implementation of the FC is illustrated in Fig. 2. The actual inputs to the fuzzy system are, e_1 and e_2, which are a scaled version of the speed error and the change in speed error as defined by (1) and (2). The gains, G_1 and G_2, can be varied to tune the fuzzy controller for a desired performance. The output gain, G_u, can also be tuned

$$e_1 = G_1(\omega_r - \omega_r^*) = G_1 e \quad (1)$$

$$e_2 = G_2 \dot{e}. \quad (2)$$

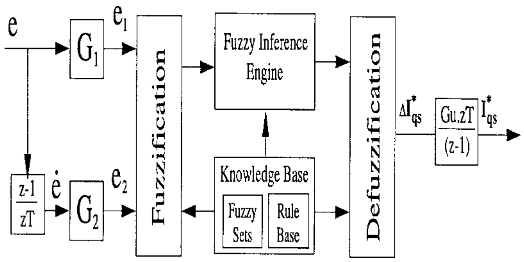

Fig. 2. Fuzzy controller block diagram.

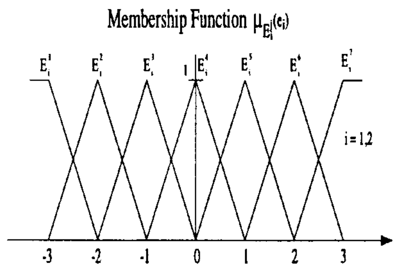

Fig. 3. Input membership functions.

A. Fuzzification, Inference, and Defuzzification

The fuzzification process maps a *crisp* input to a fuzzy set with a degree of certainty determined by the associated membership function, where the input membership functions, $\mu_{E_i^j}(e_i), i = [1\ 2]$, are shown in Fig. 3. The linguistic values for each fuzzy set E_i^j, in order from $j = 1, \cdots, 7$, are: negative large (-3), negative medium (-2), negative small (-1), zero (0), positive small (1), positive medium (2), and positive large (3). Note that "-3," "-2" etc., are linguistic values that classify *how negative* a crisp value is.

The inference engine, based on the input fuzzy sets, uses the appropriate IF–THEN rules in the knowledge base to make decisions, where the product operation is used for the premises and the Min operation is used for the implication. Note that

$$\text{Product} \quad \mu_{A*A'}(a) = \mu_A(a)\mu_{A'}(a), a\epsilon A$$
$$\text{Min} \quad \mu_{A*A'}(a) = \min\{\mu_A(a), \mu_{A'}(a)\colon a\epsilon A\}.$$

The inference engine produces an implied output fuzzy set, $\hat{U}^j$, corresponding to the output membership functions, $\mu_{U^j}(u)$ shown in Fig. 4. The implied fuzzy set is transformed to a crisp output by the center of gravity defuzzification technique as defined by (3), where c^j is the center of the jth output membership function. The summation is from one to R, where R is the number of rules that apply for the given fuzzy inputs. The output of the fuzzy controller is integrated such that the input to the current regulated PWM (CRPWM) inverter is given by (4)

$$y = \frac{\sum_{j=1}^{R} c^j \int \mu_{\hat{U}^j}(u)\,du}{\sum_{j=1}^{R} \int \mu_{\hat{U}^j}(u)\,du} \tag{3}$$

$$I_{qs}^* = I_{qs}^* + G_u \Delta I_{qs}^*. \tag{4}$$

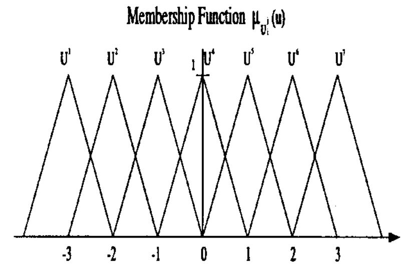

Fig. 4. Output membership functions.

Rule Base		E_2^j (ė)						
	U	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**
E_1^j (e)	**-3**	3	3	3	2	2	2	1
	-2	3	3	2	2	2	0	-3
	-1	3	2	2	2	1	-1	-3
	0	3	2	1	0	-1	-2	-3
	1	3	1	-1	-2	-2	-2	-3
	2	3	0	-2	-2	-2	-3	-3
	3	-1	-2	-2	-2	-3	-3	-3

Fig. 5. Fuzzy controller rule base.

Hence, the *effective* output of the FC is the incremental current command (ΔI_{qs}^*).

B. The Fuzzy Rule Base

The fuzzy controller's strongest asset is its knowledge base. By carefully designing the knowledge base, the expert's experience is incorporated into the fuzzy controller. This experience is synthesized by the choice of the input–output (I/O) membership functions and the rule base. Typically, uniformly distributed triangular membership functions are used in order to simplify the digital implementation. This paper uses uniformly distributed triangular membership functions for both the input and output membership functions. The range for the input and output membership functions are as shown in Figs. 3 and 4, respectively. However, by changing the gains G_1, G_2, and G_u, the range can either be increased or decreased (i.e., the triangles are either stretched or compressed). For this particular application, G_u was set to unity and then G_1 and G_2 were varied until the desired response was achieved.

The linguistic rules are contained in Fig. 5, where "3" corresponds to positive large and "2" to positive medium, etc. Given these rules and membership functions, the fuzzy controller produces the crisp and continuous nonlinear I/O map shown in Fig. 6 when all the tuning gains are unity.

The I/O map for a PI controller would be a smooth surface, perhaps, with the end points saturated due to physical current limits. This fuzzy map (Fig. 6) indicates that numerous nonlinearities are designed to enhance the controllers ability to drive the system to a set point. Note that near the center of the map, the surface appears to be smooth which means that for a small operating range of the fuzzy controller behaves like a linear controller.

Most FC's have a diagonal row of zeros (i.e., outputs are "0") in the rule base, that separate positive output from negative output. This FC does not. The square at the center of the table represents that when the error and change of error are zeros, $\Delta I_{qs}^* = 0$. Moving away from the center, in any direction, causes the FC to increment or decrement I_{qs}^*. For example, the rule

IF "e" is "-3" and "$\dot{e}$" is "3" THEN ΔI_{qs}^* is "1"

applies for the case when ω_r is much less than ω_r^* and is accelerating quickly toward ω_r^*. Most FC's would conclude that ΔI_{qs}^* should be "0". However, this FC decides to slightly increase the torque causing the machine to accelerate even faster. The *brakes* are applied when the linguistic value of the error becomes "-2" by the rule

IF "e" is "-2" and "$\dot{e}$"' is "3" THEN ΔI_{qs}^* is "-3".

Hence, the current command is quickly reduced so that the speed does not overshoot the command speed. The above example can be visualized graphically on the I/O map (Fig. 6). Starting on the negative error axis and moving to the right along the front, the map falls sharply as the error becomes smaller, i.e., the brakes are applied easing the speed to the commanded value.

The rules in Fig. 5 were designed to take full advantage of the decoupling of torque and flux such that the actual speed can reach the command speed as quick as possible (within drive limitations) without overshoot. Based on engineering experience, the authors *know* that if the machine is properly field oriented, the torque can be changed almost instantaneously without oscillations by the CRPWM inverter. Therefore, the extremes of the FC's I/O map were designed to have abrupt changes, as the above two rules show (i.e., the current command changed from a positive "1" to a negative "3"). A typical FC rule base would have a smoother I/O map at the endpoints. As a result, these rules at the extremes were designed to improve the transient capability of the drive system.

The rules near the center are also different from a typical fuzzy controller. In particular, the rules $(\mathrm{e} = -1$ and $\dot{e} = 1)$ and $(\mathrm{e} = 1$ and $\dot{e} = -1)$ would have a zero for the output with a typical FC, however, this rule base outputs a "1" or a "-1," respectively. This changes the current command just enough to drive the error to zero faster than a zero output would. Consequently, these rules near the center reduce the error more effectively, thus improving the steady-state performance.

In summary, the rule base was designed to have large changes in the current command when the error and/or the change of error are large. This makes better uses of the torque capabilities of the FOC drive. When the error and change of error are zero the fuzzy controller has reached the command speed and is holding at the speed. If any disturbance occurs, the rules near the center quickly change the current to keep the speed at the reference speed.

III. Indirect Field Orientation Detuning

This section presents a brief discussion of the effects of a detuned IFOC machine. Note that in [6]–[8], a thorough

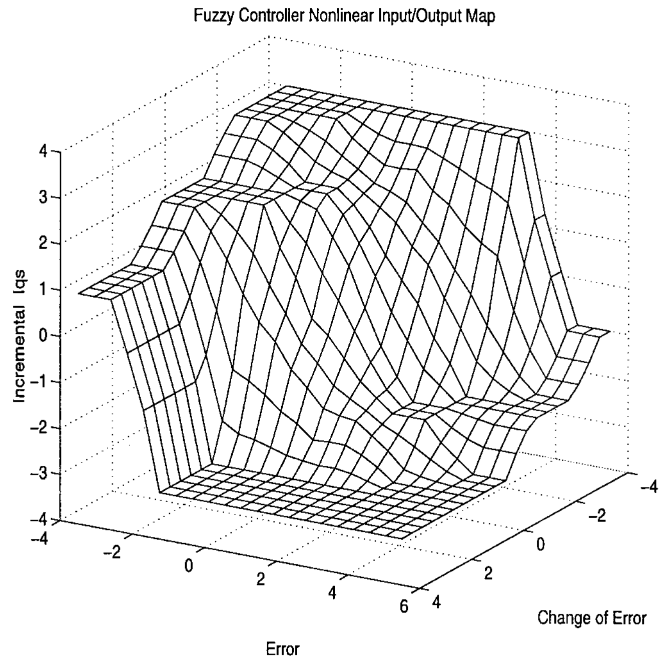

Fig. 6. *Crisp* I/O map.

development of this topic was presented. The success of FOC is based on the proper division of stator current into two components. Using d-q axis theory, these two currents are I_{ds}^* which specifies the magnetizing flux and I_{qs}^* which specifies the torque where "*" denotes command quantities.

The indirect FOC method uses a feedforward *slip* calculator (Fig. 1) to partition the stator current. The slip speed is calculated by

$$\omega_s = \frac{L_m I_{qs}^*}{T_r \lambda_r} \tag{5}$$

where T_r is the rotor time constant (L_r/R_r) and $\lambda_r = L_m I_{ds}^*$. Clearly the slip calculation is sensitive to parameter changes. Under ideal field orientation, torque and flux production are decoupled, hence a change in I_{qs}^* will not disturb the flux and instantaneous torque control is achieved.

However, when parameters change, due to saturation and/or heating, the slip calculator will produce incorrect slip commands and the stator current will not be properly partitioned. For typical machines, the steady-state result is either a low-slip high-flux high-current mode or a high-slip low-flux high-current mode. No matter which mode occurs the following is true.

1) The torque/ampere capability is reduced.
2) Steady-state copper losses are increased.
3) Instantaneous torque control is lost.

Since the FC designed in this paper includes many nonlinearities, which affect the command current, I_{qs}^*, as well as the slip calculation the speed performance is less sensitive to the parameter variations. In addition, when detuning is detected by the fuzzy inputs, the fuzzy output tends to manage the available current from the power converter more effectively, thus the closed-loop speed performance is still improved.

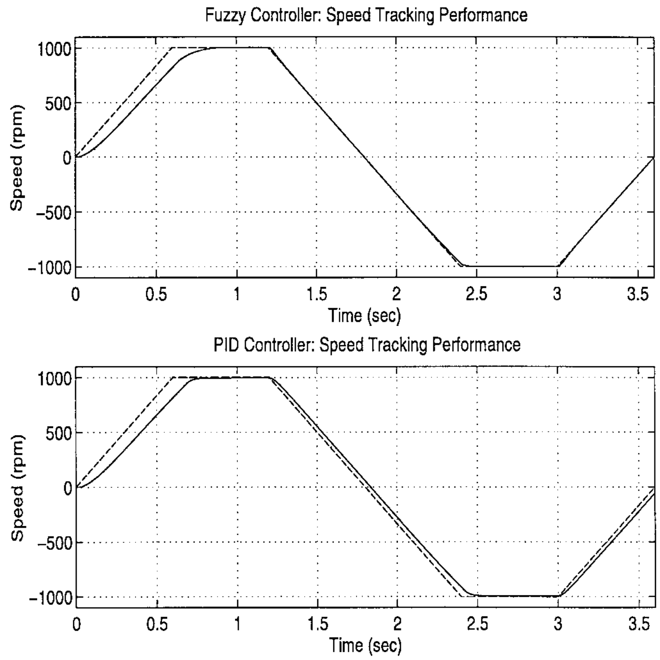

Fig. 7. IFOC speed tracking (no detuning).

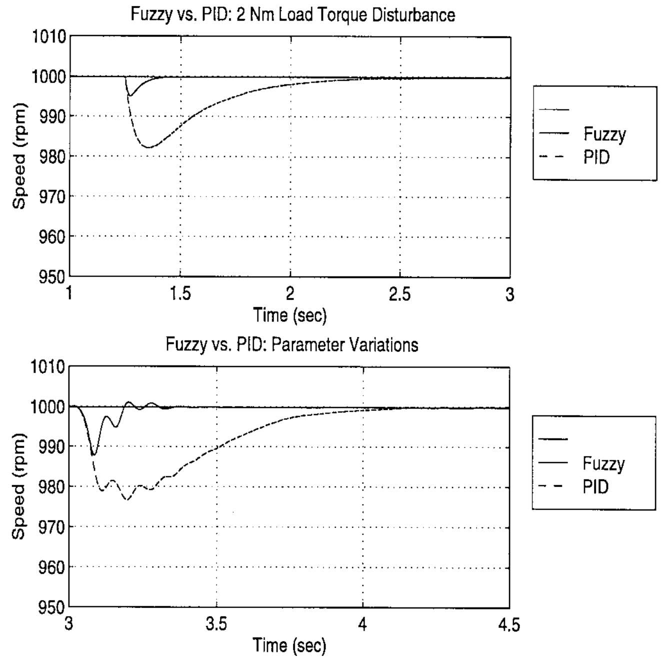

Fig. 8. IFOC disturbance rejection.

IV. Simulation Results

Computer simulations for a 5-hp cage rotor induction machine, using the fuzzy controller described in Section II, shows performance enhancements for the case when the machine is properly field oriented and when it is detuned. The machine parameters are listed at the bottom of the page, and the simulation used a CRPWM scheme with current limits.

Fig. 7 shows the speed tracking performance, under no load, for both fuzzy and PID controllers. The slope of the trapezoidal command speed is 1666 r/min/s. Initially, both the controllers have difficulty in following the command because of the current limit and the time needed to build up the flux. Once the flux is established, the PID controller tracks the command speed reasonably well with a small steady-state error. The FC tracks the ramp with no steady-state error as expected.

The second simulation, Fig. 8, examines the disturbance rejection capabilities of each controller when a load is suddenly applied and when the machine becomes detuned. Initially the machine's speed is 1000 r/min. At 1.25 s, a 2-Nm load is applied to the shaft (top). The fuzzy controller quickly returns the speed to the command speed within 0.25 s with a maximum drop of 5 r/min. The PID controller takes about 1.25 s to return the speed to 1000 r/min and has a maximum dip of 18 r/min. Next, the rotor's resistance is doubled at 3.0 s while the machine is still loaded (bottom). As expected, the field orientation detuning problem causes the greatest degradation in performance. When the rotor's resistance is doubled, the speed becomes oscillatory indicating that the flux and torque current commands are no longer decoupled. Despite the loss of decoupling, the FC manages to return the speed to 1000 r/min within 0.5 s with a maximum dip of about 11 r/min. The PID controller performs poorly taking 1.0 s to restore the speed with a dip around 22 r/min.

From our simulation experience, the PID controller's disturbance rejection performance can be improved by readjusting the gains at the expense of speed tracking performance. For example, larger integral gains can be used to reduce the errors, but will cause serious speed overshoots and long settling times.

V. Experimental Results

The laboratory test setup consists of a 5-hp cage rotor induction machine and a high-speed Motorola DSP56001 DSP application development system. The DSP system uses a Sine-Δ PWM current regulation method with a sampling rate of 75 μs. The speed control loop has a sampling rate of 500 μs.

Both the PID controller and the FC are implemented digitally. Implementing the PID controller is relatively straightforward. However, the FC does need a more complex algorithm more RAM, and more execution time (as expected). Fortunately, the modern DSP technology makes all these possible

Machine Parameters

	Stator	Rotor	Magnetizing Branch
3 phase, 60 Hz	$R_s = 0.600\ \Omega$	$R_r = 0.4120\ \Omega$	$L_m = 41.500$ mH
220 volts, 15 amps	$L_s = 43.4420$ mH	$L_r = 43.4420$ mH	$R_m = 1.769\ \Omega$
5 hp, 1720 r/min	$L_{ls} = 1.9417$ mH	$L_{lr} = 1.9417$ mH	

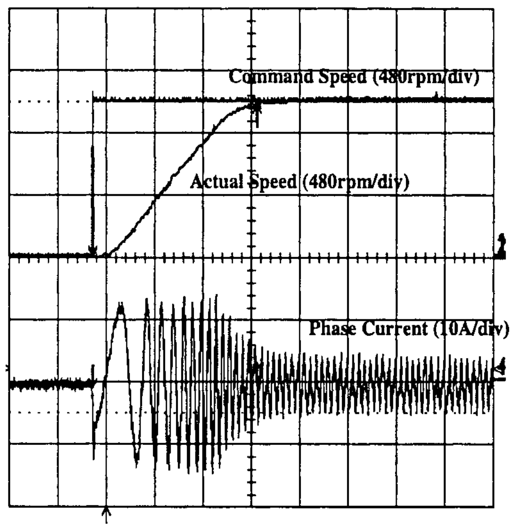

Fig. 9. PID step response: speed (top) 480 r/min/div, phase current (bottom) 10 A/div, time 0.2 S/div.

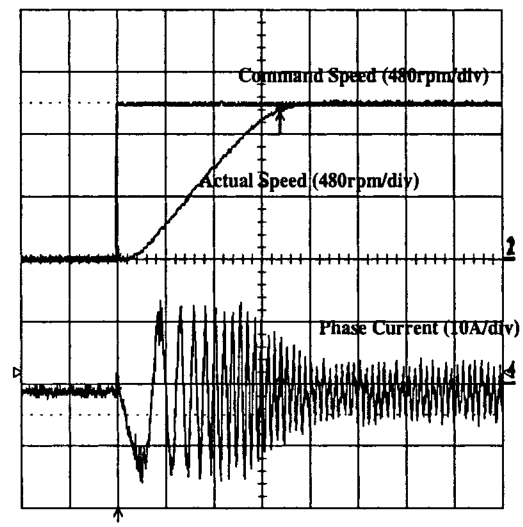

Fig. 10. Fuzzy step response: speed (top) 480 r/min/div, phase current (bottom) 10 A/div, time 0.2 S/div.

at a reasonable cost. First, the rule base is stored as a look-up table in RAM where the rows and columns correspond to the address of the fuzzified inputs. Next, the centers for the input and output membership functions are stored in RAM. Since, the membership functions are triangles, it is possible to write a simple equation to define each (note the endpoints of the input membership functions are a special case).

After the inputs have been scaled by the appropriate gains, they are processed through a series of conditional statements (e.g., IF–THEN tests). This determines which fuzzy set the input belongs to and assigns the essential address to the sampled points. The degree of certainty is calculated by the equation for the triangle membership function. Then the value in the rule base, at the address of the fuzzy inputs, corresponds one of the centers of the output membership function. Finally, the proper weighting is applied to each rule and the output is defuzzified to a crisp output.

This implementation is not the simplest but does provide the greatest flexibility because the engineer can change any block in the fuzzy controller. A more practical approach would be to store the I/O map (Fig. 6) in memory. Then after the inputs are scaled, a two-dimensional (2-D) interpolation routine would output a crisp value. This approach could be implemented in a low cost microprocessor and execute rather quickly, but the ability to change rules and membership functions is lost.

A. Normal Operation

The step speed responses for the PID and FC's are shown in Figs. 9 and 10, respectively. The top trace shows the command speed and the actual speed and the bottom shows the resulting phase current (480 r/min/div and 10 A/div). Each controller was tuned to reach 1200 r/min in about 0.68 s with no overshoot. For both controllers, these settings are kept constant for the following experiments as a basis for comparison.

Figs. 11 and 12 show the loading effect for the PID and FC, respectively. The PID controller has a 7% r/min dip when the load is applied and a 7% r/min overshoot when the load is removed. The nonlinear I/O capabilities of the fuzzy controller allows for the current to be changed very quickly resulting in almost no speed variation. The PID controller has a sluggish reaction because the gains were tuned to have no overshoot for step commands.

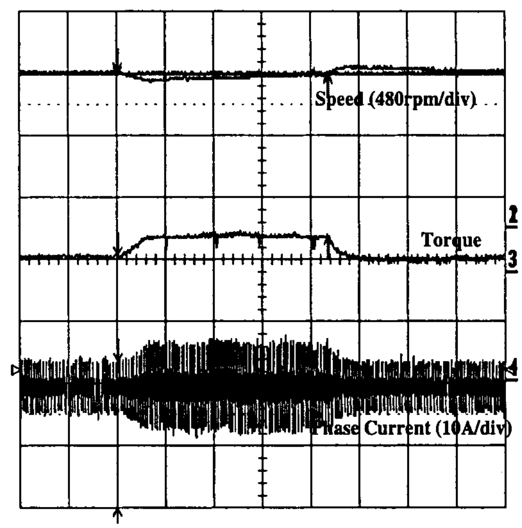

Fig. 11. PID controller: speed (top) 480 r/min/div, Q-axis current (middle), phase current (bottom) 10 a/div, time 1 S/div.

The speed tracking performance is presented in Figs. 13 and 14 for the PID and FC, respectively. As expected the PID controller cannot follow the 1600-r/min/s acceleration profile showing a 0.12-s delay. However, the FC shows sharp tracking of the command with a little overshoot at the corners. Note the speed scale is 1200 r/min/div. Again, experimental tests showed that PID performance could be improved by changing the gains at the expense of serious overshoots and oscillations for step inputs.

B. Detuned Operation

As discussed, the indirect FOC method uses a feedforward slip calculation that depends on accurate parameter identifica-

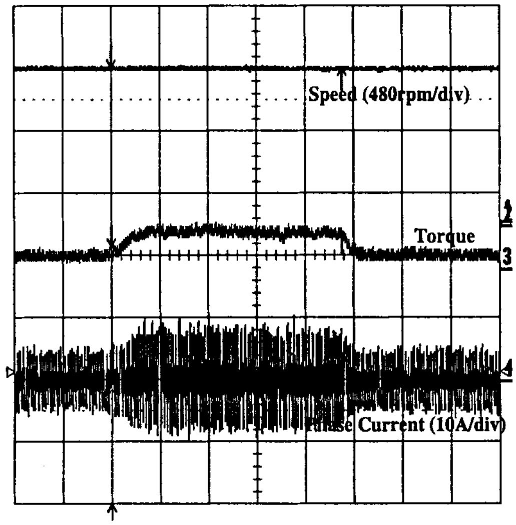

Fig. 12. Fuzzy controller: speed (top) 480 r/min/div, Q-axis current (middle), phase current (bottom) 10 a/div, time 1 S/div.

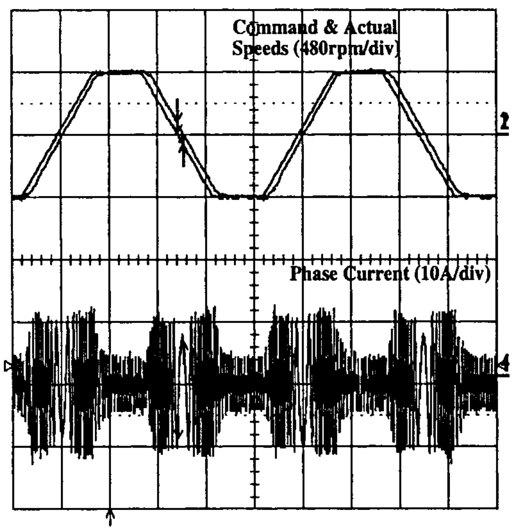

Fig. 13. PID tracking: speed (top) 1200 r/min/div, phase current (bottom) 10 a/div, time 1 S/div.

tion. However, heating and saturation effects will cause the parameters to fluctuate which will deteriorate the closed-loop speed tracking.

Figs. 15 and 16 show the tracking performance when the rotor's resistance is doubled for the PID controller and the FC, respectively (cursors mark the onset of detuning). The PID controller performs extremely poor when the system becomes detuned. The FC does not track the command as sharply as before, but it still follows the trapezoidal profile.

Looking at the phase current, it is clear that each controller tries to increase the current to compensate for the reduced torque capabilities caused by the detuning. During acceleration, both controllers reach the current limit, however, the FC relies on its ability to quickly raise and lower the current and thus utilizes a longer period of the maximum current output. Therefore, the FC has improved the transient performance due to the rules near the extremes (see Fig. 5).

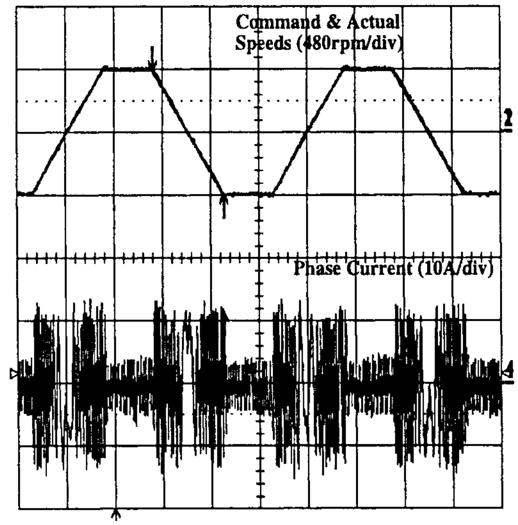

Fig. 14. FC tracking: speed (top) 1200 r/min/div, phase current (bottom) 10 a/div, time 1 S/div.

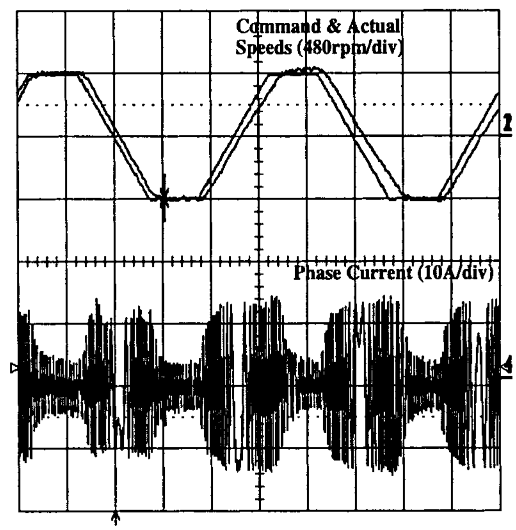

Fig. 15. PID detuned tracking: speed (top) 1200 r/min/div, phase current (bottom) 10 a/div, time 1 S/div.

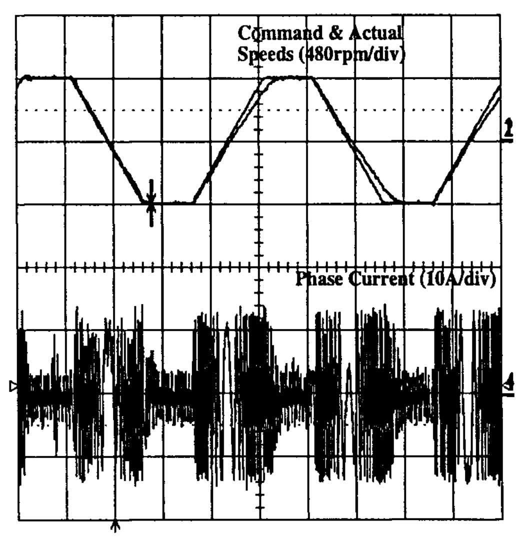

Fig. 16. FC detuned tracking: speed (top) 1200 r/min/div, phase current (bottom) 10 a/div, time 1 S/div.

VI. Conclusions

This paper has successfully demonstrated that a properly designed FC can outperform traditional PID controllers, both when the machine is properly field oriented and when it becomes detuned. Based on simulation results and experimental verification, the following conclusions are made.

1) The FC can be tuned to a *single* setting such that the speed will track trapezoidal and step commands with zero steady-state error and no overshoot for step commands. The PID controller needed to be retuned for different speed profiles.
2) The FC is more robust than the PID controller when load disturbances occurred.
3) The FC's performance when certain motor parameters were increased by a factor of two was still quite good and far better than the PID controller's performance when the same parameters doubled.
4) Proper design of the rule base makes the FC superior to traditional PI control techniques.
5) Tuning of a FC is more intuitive because of the direct *meaning* associated with each gain. The FC required about five trials to get a fast step response with no overshoot, plus the final setting tracked the trapezoidal command with no steady-state error. The PID controller required numerous trials and constant retuning to get reasonable performance.

Fuzzy logic provides a means for synthesizing a controller from engineering experiences that can be more robust, have better performance, and reduce cycle times. This paper has integrated a single FC with the popular FOC technique with promising results. A modified version of this FC is under development that uses stator current information to adjust the slip gain to counter the detuning effect. Future work includes developing an adaptive FC to increase the reliability and robustness plus identify the onset of detuning.

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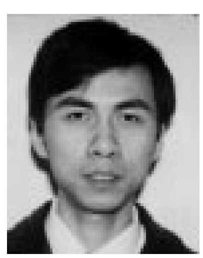

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Dr. Tang is a Member of Industrial Drives Committee the and Electric Machines Committee of the IEEE Industry Applications Society.