# 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 PID controllers have trouble meeting a wide range of tracking performance even when proper field orientation is achieved. PID performance is severely degraded when detuning occurs. This paper presents a Fuzzy Logic design approach that will meet the speed tracking requirements even when detuning occurs. Experimental results obtained via a general purpose DSP system is presented along with computer simulations.*


## I. Introduction

With field orientation control methods, 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 PID control has difficulty dealing with dynamic speed tracking, parameter variations, and load disturbances. As a result, the motion control system must tolerate a certain level of control 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]. Industry has also shown an interest because of the relative ease of implementation of a fuzzy controller. This paper introduces a fuzzy controller that enhances indirect field orientation control for both the ideal and the detuned conditions. Computer simulations along with experimental results, obtained with a general purpose DSP, will be presented.



## II. Fuzzy Control: Principle and Design

Aside from all the *hype* generated over Fuzzy Control, 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 designed in the fuzzy controller 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 speed regulation. 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 equations. (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.

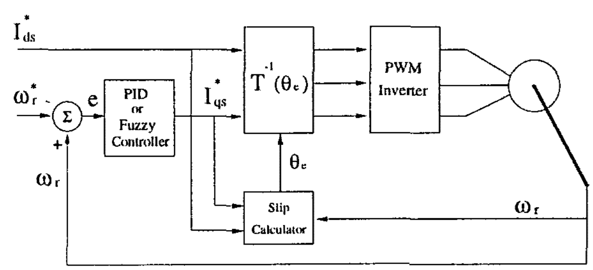


**Figure 1:** Indirect Field Orientation Control Block Diagram

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

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

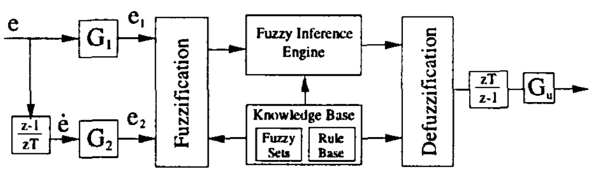


**Figure 2:** Fuzzy Controller Block Diagram

### *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, ... , 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.

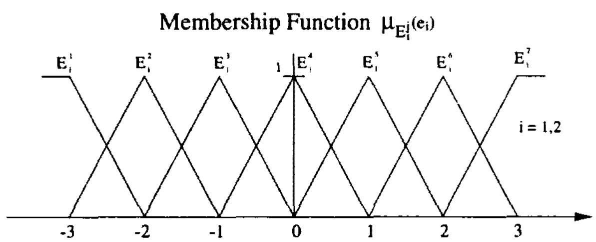


**Figure 3:** Input Membership Functions

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 premise and the Min operation is used for the implication. Note that:

$$-Product \quad \mu_{A*A'}(a) = \mu_A(a)\mu_{A'}(a), \; a \in A$$
$$-Min \quad \mu_{A*A'}(a) = min\,\{\mu_A(a), \mu_{A'}(a) : \; a \in A\}$$

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. The output of the controller is integrated such that the input to the CRPWM inverter is

$$I_{qs}^* \;=\; I_{qs}^* \;+\; G_u \Delta I_{qs}^* \qquad (3)$$

hence, the *effective* output of the FC is the incremental command current ($\Delta\; I_{qs}^*$).

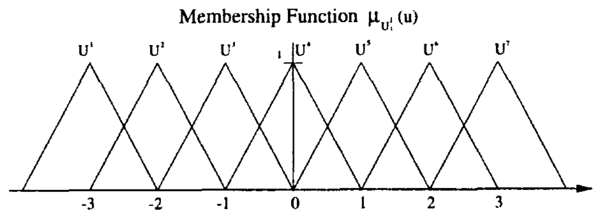


**Figure 4:** Output Membership Functions

### *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 membership functions and the rule base. Typically, uniformly distributed triangular membership functions are used, as is the case for this paper. 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.

| 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 |

**Figure 5:** Fuzzy Controller Rule Base

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

Most fuzzy controllers have a diagonal row of zero's (i.e. "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 the error and change of error are zero, so $\Delta\; I_{qs}^* = 0$. Moving away from the center, in any direction, causes the fuzzy controller to increment or decrement $I_{qs}^*$. For example the rule

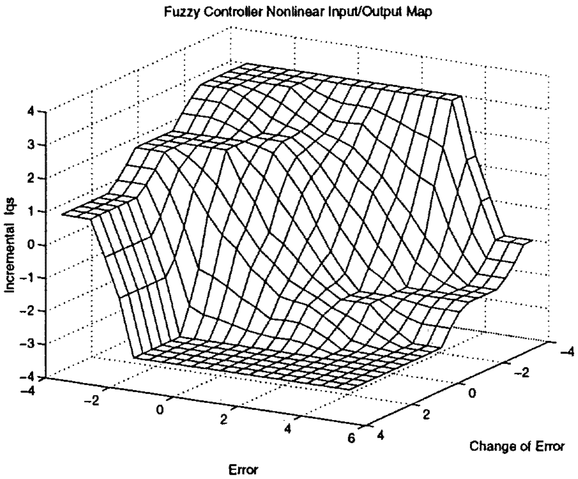


**Figure 6:** *Crisp* Input/Output Map

IF "e" is "-3" and "ė" is "3" THEN $\Delta\ I^*_{qs}$ is "1".

applies for the case when $\omega_r$ is much less than $\omega^*_r$ and is accelerating quickly towards $\omega^*_r$. Most FC's would conclude that $\Delta\ I^*_{qs}$ is "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 "ė" is "3" THEN $\Delta\ I^*_{qs}$ is "-3".

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, hence the brakes are applied easing the speed to the command speed.

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. Furthermore, the incremental output makes linear speed tracking, with zero steady state error, possible.

## III. Indirect Field Orientation Detuning

This section presents a brief discussion of the effects of a detuned indirect field orientation controlled machine. Note that in [6], a thorough development of this topic was presented. The success of field orientation control 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

$$\omega_s \;=\; \frac{L_m\ I^*_{qs}}{T_r\ \lambda_r} \qquad (4)$$

where $T_r$ is the rotor time constant $(\frac{L_r}{R_r})$ 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 and
(3) instantaneous torque control is lost.

Since the fuzzy controller designed in this paper includes many nonlinearities, the speed performance is less sensitive to the loss of instantaneous torque control. 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 acceptible.

## IV. Simulation Results

Computer simulations for a 5 hp cage rotor induction machine, using the fuzzy controller described in Section II, show performance enhancements for the case when the machine is properly field orientated and when it is detuned. The machine parameters are listed in the appendix. A current regulated PWM scheme with current limits is used.

Figure 7 shows the speed tracking performance, under no load, for both controllers. The slope of the trapezoidal command speed is 1666 rpm/s. Initially both the fuzzy and PID controller have trouble 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 reasonably well with a small steady state error. The fuzzy controller tracks the ramp with no steady state error as predicted.

The second simulation, Fig. 8, examines the disturbance rejection capabilities of each controller. Initially the machine's speed is 1000 rpm. At 1.25 seconds a 2

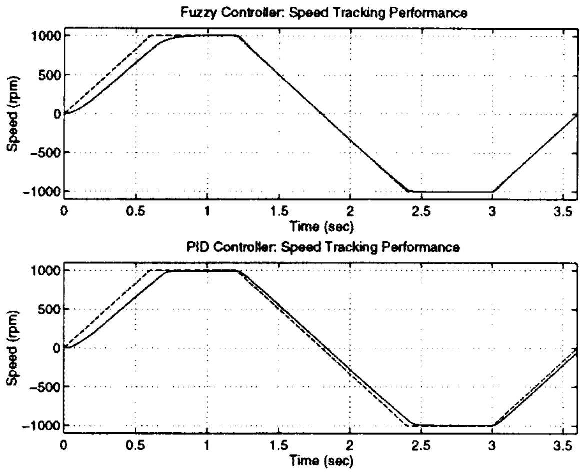


**Figure 7**: I.F.O.C. Speed Tracking (no detuning)

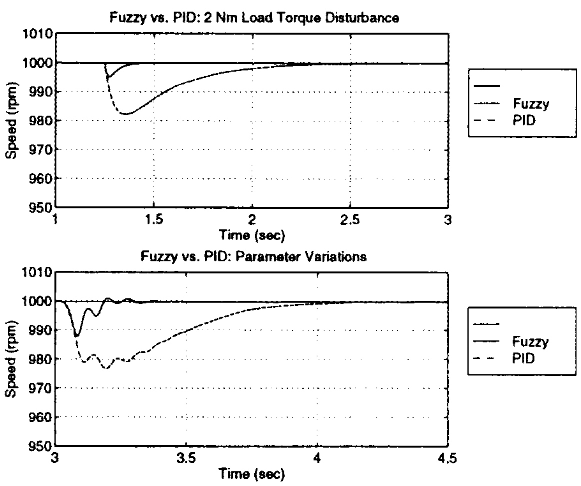


**Figure 8**: I.F.O.C. Disturbance Rejection

Nm load is applied to the shaft (top). The fuzzy controller quickly returns the speed to the command speed within 0.25 sec with a maximum drop in speed of 5 rpm. The PID controller takes about 1.25 sec to return the speed to 1000 rpm and has a maximum dip of 18 rpm. Next, the rotor's resistance is doubled at 3.0 sec while the machine is still loaded (bottom). As expected, the indirect 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 fuzzy controller manages to return the speed to 1000 rpm within 0.5 sec with a maximum dip of about 11 rpm. The PID controller performs poorly taking 1.0 seconds to restore the speed with a dip around 22 rpm.

From simulation experience, the PID controller's disturbance rejection performance can be improved by adjusting the gains at the expense of speed tracking performance. For example, larger integral gains will reduce the errors but will cause 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 digital signal processing development system. The DSP system uses a Sine-$\Delta$ PWM current regulation method with a sampling rate of 75 $\mu$s.

### *A. Normal Operation*

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

Figures 11 and 12 show the loading effect for the PID and FC, respectively. The PID controller has a 7% rpm dip when the load is applied and a 7% rpm overshoot when the load is removed. The fuzzy controller performs much better showing almost no speed change. The PID controller has a sluggish reaction because the gains were tuned to have no overshoot for step commands.

The tracking performance is presented in Figures 13 and 14 for the PID and FC, respectively. As expected the PID controller cannot follow the 1600 rpm/s acceleration profile showing 0.12 sec delay. However, the Fuzzy controller shows sharp tracking of the command with a little overshoot at the corners. Note the speed scale is 1200 rpm/div. Again, experimental tests showed that PID performance could be improved by changing the gains at the expense of 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 identification. However, heating and saturation effects will cause the parameters to fluctuate which will deteriorate the closed loop speed tracking.

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

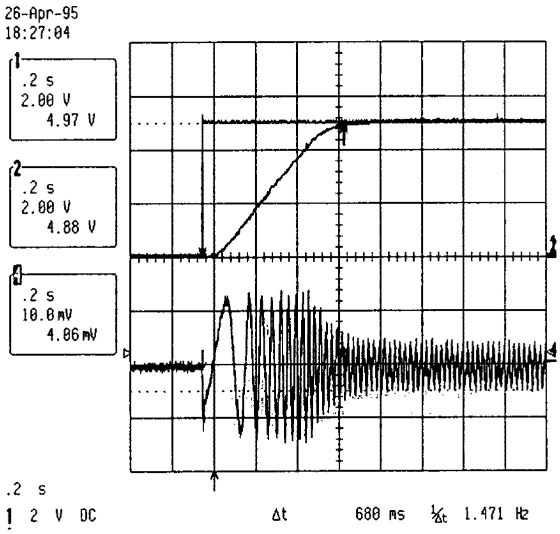


**Figure 9**: PID Step Response: Speed (top), Phase Current (bottom)

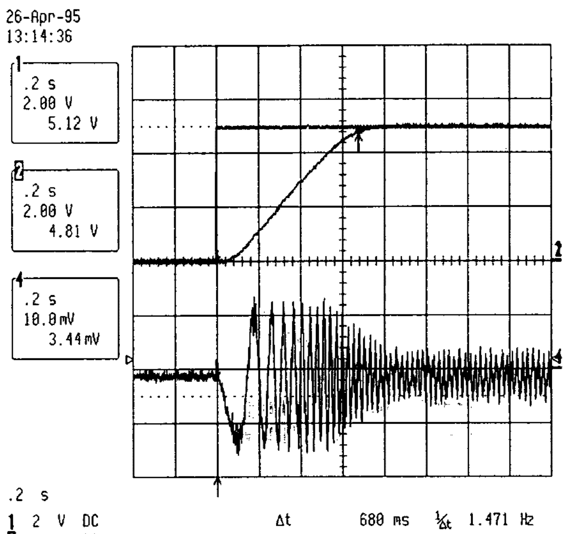


**Figure 10**: Fuzzy Step Response: Speed (top), Phase Current (bottom)

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 Fuzzy controller relies on its ability to quickly raise and lower the current and thus utilizes a longer period of the maximum current output.

## VI. Conclusions

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

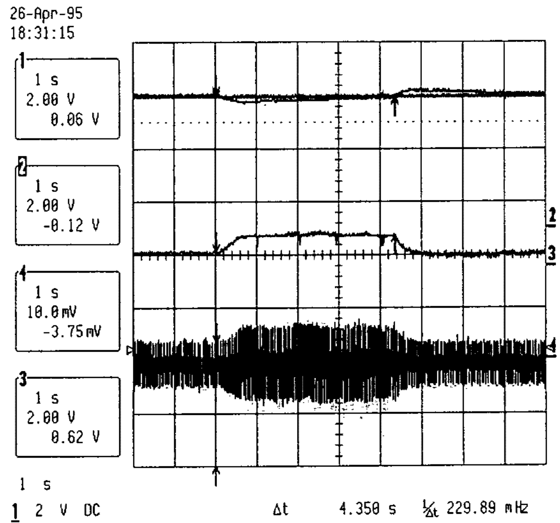


**Figure 11**: PID Controller: Speed (top), Q-axis Current (middle), Phase Current (bottom)

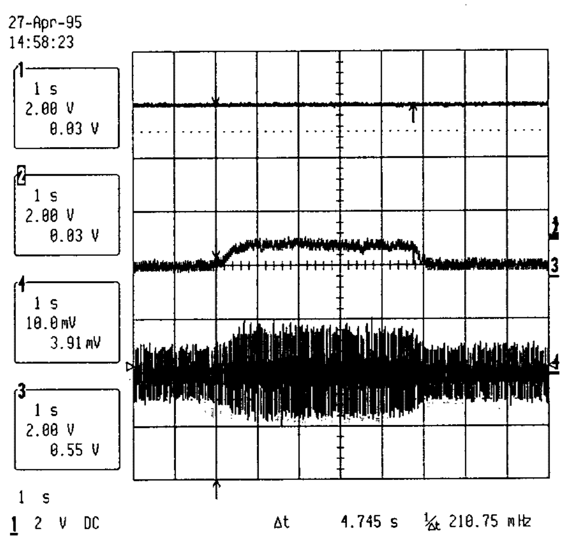


**Figure 12**: Fuzzy Controller: Speed (top), Q-axis Current (middle), Phase Current (bottom)

(1) The fuzzy controller can be tuned to a **single** setting such that the speed will track trapezoidal and step commands with zero steady state error and nó overshoot for step commands. The PID controller needed to be re-tuned for different speed profiles.

(2) The fuzzy controller is more robust than the PID controller during torque disturbances. The nonlinear I/O capabilities of the fuzzy controller allows for the current to be changed very quickly resulting in very accurate speed tracking. The PID controller reacts slower

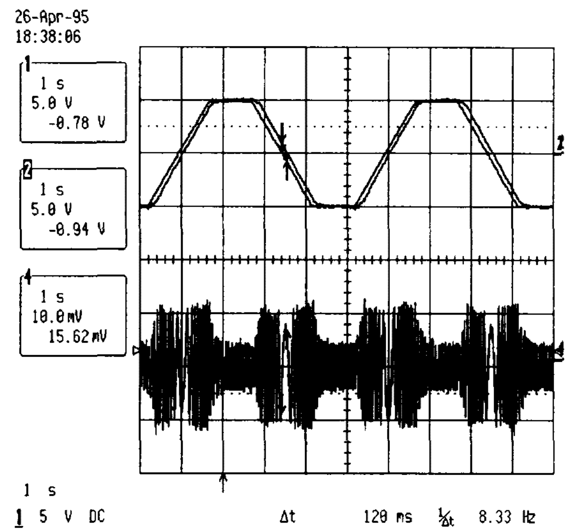


**Figure 13**: PID Tracking: Speed (top), Phase Current (bottom)

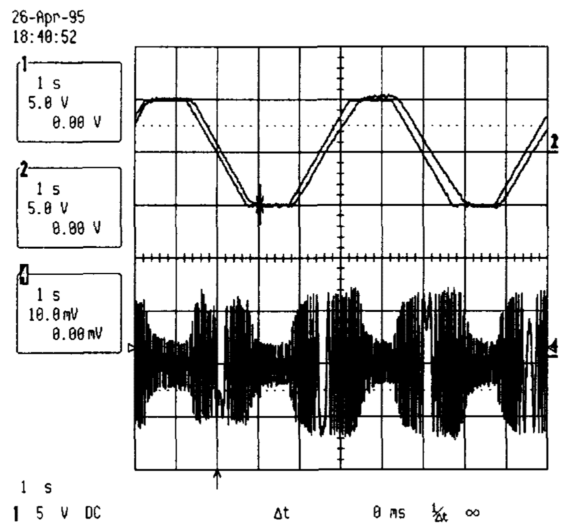


**Figure 15**: PID Detuned Tracking: Speed (top), Phase Current (bottom)

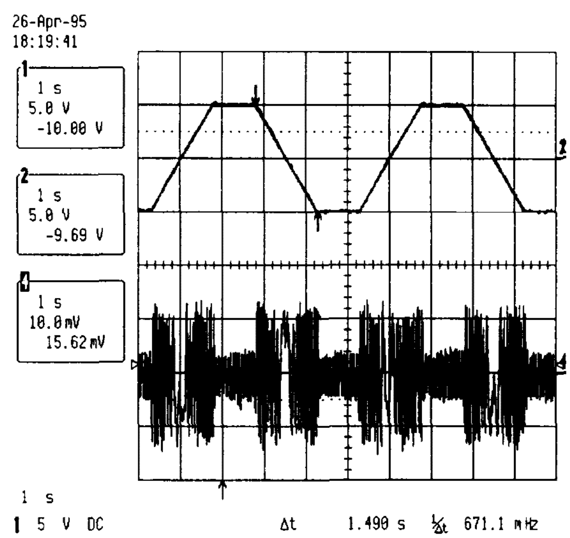


**Figure 14**: FC Tracking: Speed (top), Phase Current (bottom)

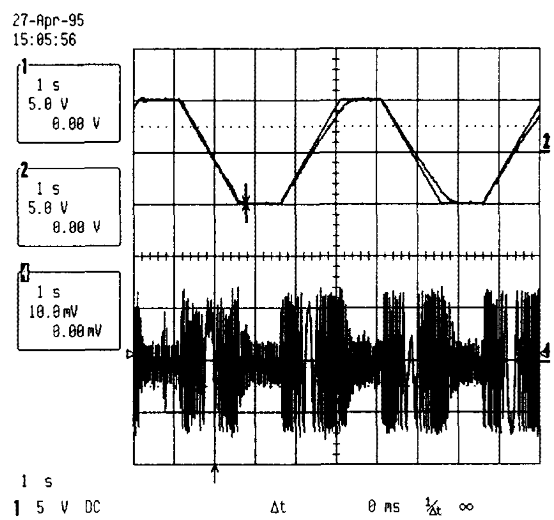


**Figure 16**: FC Detuned Tracking: Speed (top), Phase Current (bottom)

causing speed fluctuations.

(3) The speed performance of the fuzzy controller is less sensitive to parameters variations. Minimal degradation in performance was observed for the fuzzy controller whereas the PID controller suffered severely and needed to be re-tuned.

(4) Proper design of the rule base makes the fuzzy controller superior to traditional linear control techniques. For optimal performance, all of the possible rules should be utilized.

(6) The fuzzy controller's success is based on its ability to process, simultaneously, several rule implications thus producing a more complete output.

(7) Tuning of a fuzzy controller is more intuitive because of the direct *meaning* associated with each gain. The fuzzy controller required about 5 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 re-tuning 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 *PI like* fuzzy controller with the popular field orientation control technique with promising results. A modified version of this fuzzy controller is under development that uses stator current information to adjust the slip gain to counter the detuning effect. Future work includes developing an adaptive fuzzy controller to increase the reliability and robustness plus identify the onset of detuning.

## VII. Appendix

### Machine Parameters

| | |
|---|---|
| 3 phase | 60 Hz |
| 220 volts | 15 amps |
| 5 hp | 1720 rpm |

| Stator | Rotor |
|---|---|
| $R_s = 0.600\Omega$ | $R_r = 0.4120\Omega$ |
| $L_s = 43.4420mH$ | $L_r = 43.4420mH$ |
| $L_{ls} = 1.9417mH$ | $L_{lr} = 1.9417mH$ |

| Magnetizing Branch |
|---|
| $L_m = 41.500mH$ |
| $R_m = 1.769\Omega$ |

## VIII. Acknowledgments

A great amount gratitude is extended to Mr. Li Zhen for his persistent work implementing the Fuzzy Controller in the DSP development system.

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