



## Project Summary

# Efficiency Optimization Control of AC Induction Motors: Initial Laboratory Results

M.W. Turner, V.E. McCormick, and J.G. Cleland

**A fuzzy logic, energy optimizing controller has been developed to improve the efficiency of motor/drive combinations which operate at varying loads and speeds. This energy optimizer is complemented by a sensorless speed controller which maintains motor shaft revolutions per minute (rpm) to produce constant output power. Efficiency gains of from 1 to 20% are obtained from laboratory demonstration with commercial motors and drives. Motor shaft rpm is controlled to within 0.5%. The energy optimizing controller used for "vector control" adjustable speed drives is complemented by a torque pulsation control scheme to rapidly damp vibrations.**

***This Project Summary was developed by EPA's National Risk Management Research Laboratory's Pollution Prevention and Control Division, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).***

### Introduction

Electric motors use over 60% of the electrical power generated in the U.S. The U.S. population of approximately 1 billion ( $10^9$ ) motors consume over 1700 billion kWh per year. Each year, 140 million new motors are sold. More than 80% of the electricity used by motors is consumed by less than 1% of the motor population [motors greater than 20 hp (142 kW)]. Each 1% improvement in motor efficiency could result in savings of over \$1 billion per year in energy costs, 6-10 million tons (5.4-9.1 million tonnes) less per year of combusted coal and approximately 15-20

million tons (13.6-18.1 million tonnes) less carbon dioxide released into the atmosphere.

Adjustable speed drives (ASDs) are power electric devices which allow control of the speed of rotation of electric motors. ASDs can provide a significant savings in energy for motors which spend a portion of their duty cycle operating at less than their rated speed and torque. Prior to the introduction of ASDs, control of motor-driven devices such as fans and pumps were always controlled by valves, vanes, dampers, and other mechanical devices, which are inherently inefficient.

Conventional ASDs do not optimally minimize motor input power at any given motor speed and load torque. *The objective of the research described in this report has been to improve ASDs by adding controls which optimize the ASD on the basis of energy efficiency.* The research and development program was defined by the following precepts:

- New controls must work with commercial ASDs. Controllers should be able to be added to existing ASDs and/or integrated into new ASD designs.
- Motors of interest are those rated from 5 to 5000 hp (3.7 to 3730 kW).
- *Steady-state operation* of large motors is emphasized.
- Simple, low-cost design is emphasized.
- The controllers must reduce energy consumption "significantly." A reduction in overall energy use of 2% is targeted for motors with rated efficiencies above 85% (large motors).

Controls are physically integrated into the motor/ASD configuration as shown in Figure 1. The qualitative interactive performance of these components is the same at essentially any scale. Energy optimizing controllers interface with the ASD to minimize line power consumption. In actual applications, the direct-current (dc) brake is replaced by an actual load such as a pump or conveyor belt. The dynamometer is a research tool used to measure and maintain a specific simulated load.

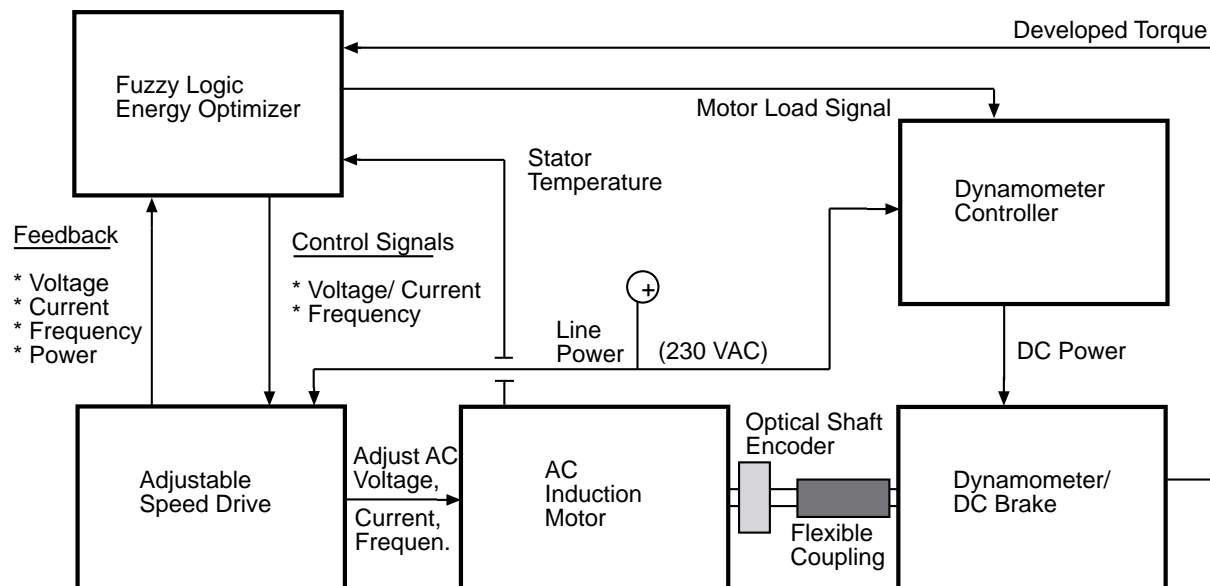
Controllers that have been developed under this project for two kinds of adjust-

able speed drives used with ac induction motors are

1) **ASD Type 1:** These ASDs control the frequency and *voltage* supplied to a motor by maintaining a ratio of voltage to frequency that is the same as the ratio at the motor's rated conditions (e.g., 208V at 60 Hz, 104V at 30 Hz). These drives are best for steady-state operation (where load or speed fluctuations are only occasional or the dynamics are slow--on the order of minutes rather than milliseconds or seconds).

2) **ASD Type 2:** These ASDs control frequency and *current* by indirect vector control. These drives are better for dynamic operation and controlling speed under rapidly changing load conditions, such as control of smaller motors in manufacturing, positioning, and computer-aided design/manufacturing machining.

All efficiency optimization under this project is based on a fundamental approach--the voltage (for ASD Type 1) or



**Figure 1.** Motor research laboratory main component layout.

the current (for ASD Type 2) is perturbed in a manner that decreases the motor's input power while the motor output power is maintained constant. By these means, the core losses of the machine decrease while the copper losses increase until the combined core and copper losses reach a minimum value, as shown in Figure 2.

### Fuzzy Logic and Control Designs

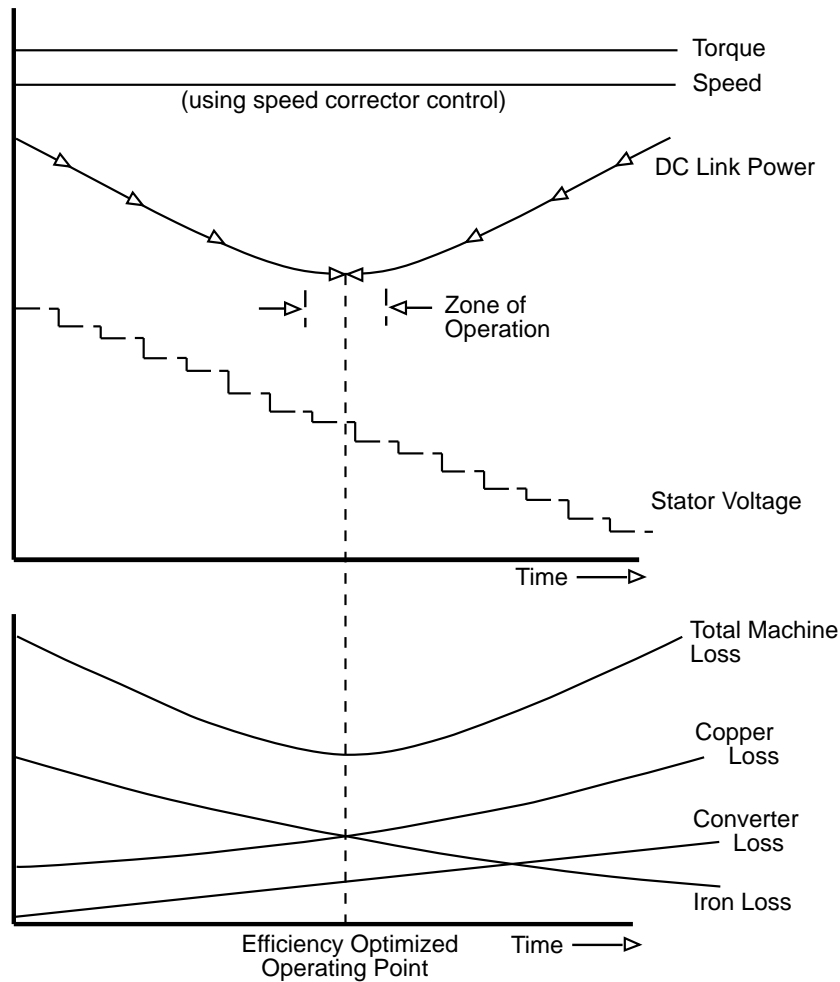
The mathematical technique called fuzzy logic offers a new approach to improving ASD voltage/frequency/current control. Fuzzy logic has evolved from an esoteric branch of mathematics into a useful engineering tool. By virtue of its adaptability, it can be applied to problems whose non-

linearity and dynamic nature makes them intractable to solution via classical control methods. Motor control has all of the attributes of this class of problems. Fuzzy logic has been implemented in this development of improved motor control because:

- 1) Fuzzy logic overcomes the mathematical difficulties of modeling highly non-linear systems;
- 2) Fuzzy logic responds in a more stable fashion to imprecise readings of feedback control parameters, such as the dc link current and voltage; and
- 3) Fuzzy logic control mathematics and software are simple to develop and flexible for each modification.

Three interactive efficiency-optimizing (input power minimizing) controllers have been developed for Type 1 ASDs. These controllers are 1) voltage perturbation for input power minimization, 2) speed correction, and 3) slip compensation.

The *voltage perturbation controller* is based on changes in input power and stator voltage. Fuzzy logic control has been emphasized for voltage perturbation. The fuzzy logic membership functions for both inputs and the output are partitioned using five fuzzy sets. The input variables are  $\Delta V_{s_{old}}$  and  $\Delta P_{in}$ ; the output variable is  $\Delta V_{s_{new}}$ . Triangular fuzzy sets are used for



**Figure 2.** Changes in core and copper losses with changing flux.

both inputs and outputs, with a restriction that the output fuzzy sets must be isosceles to simplify defuzzification.

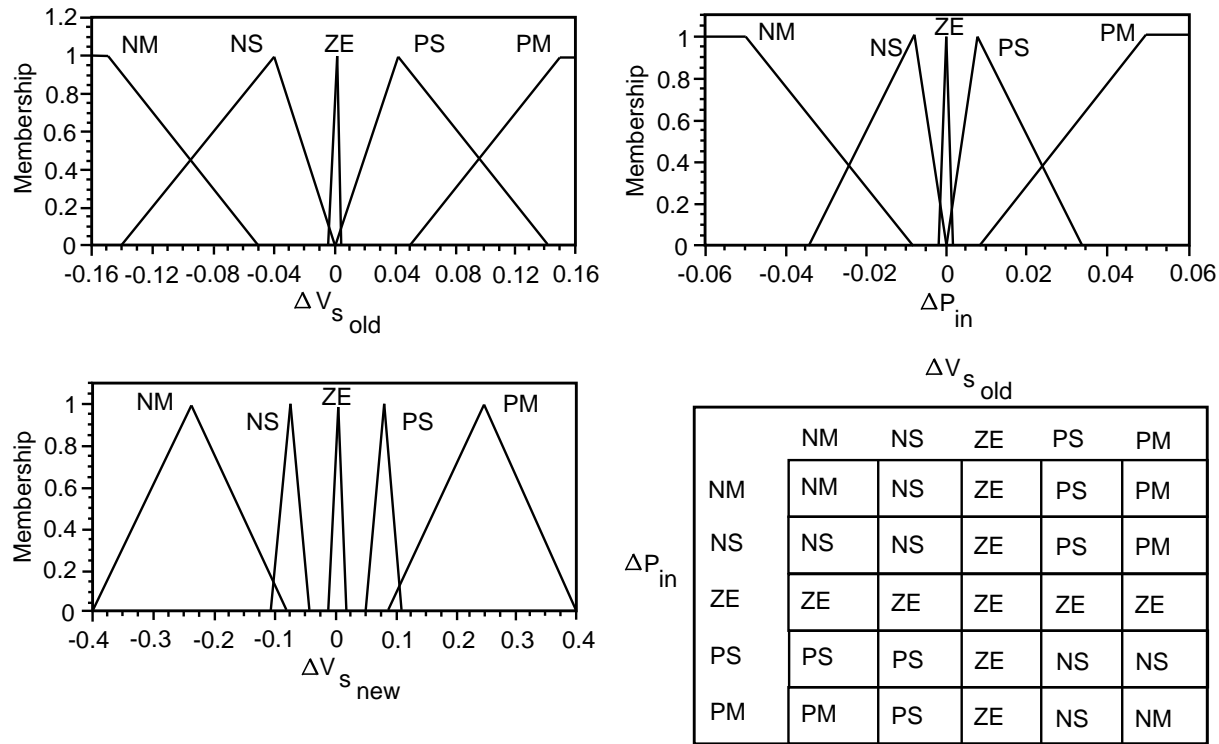
Membership functions and the associated rule set are shown in Figure 3, where input and output values are represented linguistically (i.e., NM=negative medium, NS=negative small, ZE=zero, PS=positive small, and PM=positive medium). The rule base table can be read according to the following example: If the last voltage change ( $\Delta V_{s_{old}}$ ) is a “positive small” value and the

measured input power change ( $\Delta P_{in}$ ) is a “negative small” value, then  $\Delta V_{s_{new}}$  is “positive small.”

*Speed correction control* is needed because the perturbation approach alters motor speed and output power. The motor's output rotor speed should be maintained as constant as possible. For Type 1 ASDs, a fuzzy logic speed corrector controller was designed to correct for the speed change with voltage perturbation. The fuzzy speed controller uses voltage, commanded speed,

measured frequency, and measured voltage to estimate the best new frequency setting.

*Slip compensation*, has also been developed to further reduce motor power consumption. For many motor ASD applications, whenever the frequency is set, a higher than desired rotor speed results, using more power. For example: If an operator wishes to reduce speed to 50% of the rated value, the operator sets the frequency from 60 to 30 Hz. However, with

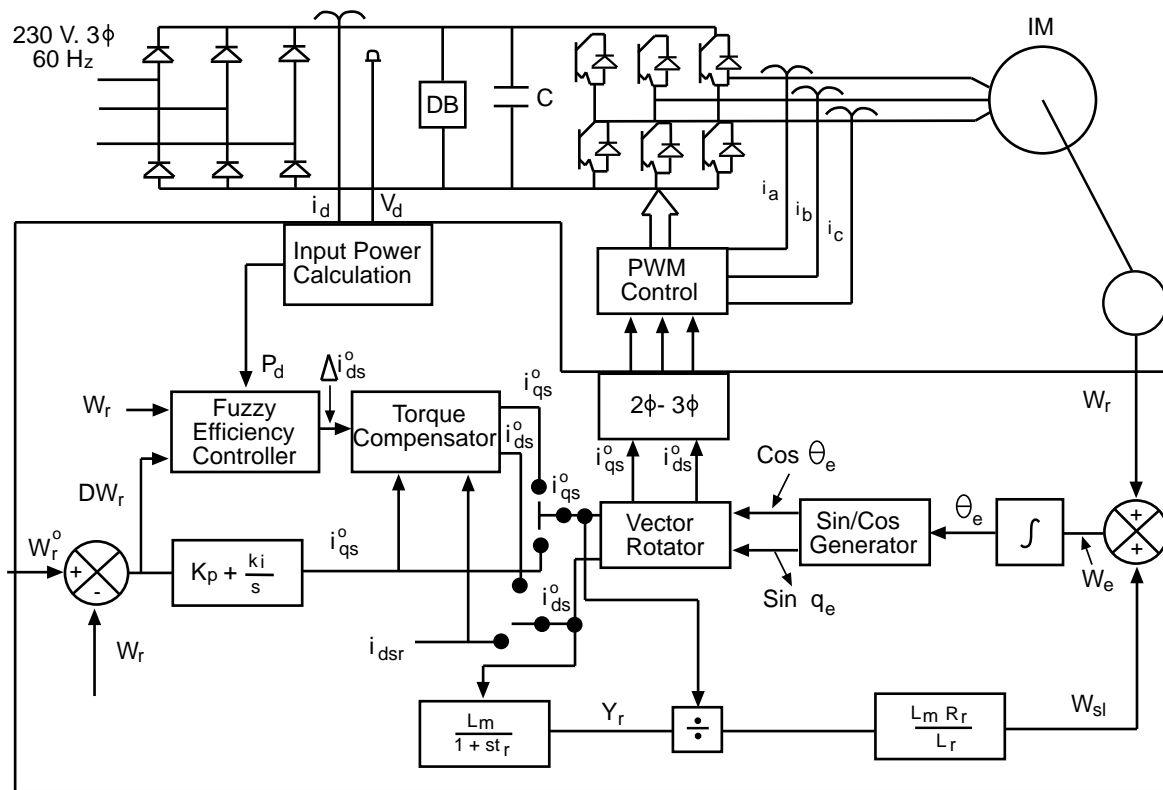


**Figure 3.** Membership functions and rule set for fuzzy voltage perturber.

An indirect vector controlled induction motor drive with an efficiency optimization controller is shown in Figure 4. All the control functions indicated by the dashed outline are implemented in real time by a single digital signal processor. The feedback speed control loop generates the active or torque current command  $i_{qs}^*$ . The vector rotator receives the torque and excitation current commands

A *feed-forward pulsating torque compensator* has been developed to prevent speed ripple and mechanical resonance during transient operation. As the excitation current is reduced in adaptive steps by the fuzzy controller, the rotor flux decreases exponentially. The decrease of flux causes loss of torque, which normally is compensated for slowly by the speed control loop.

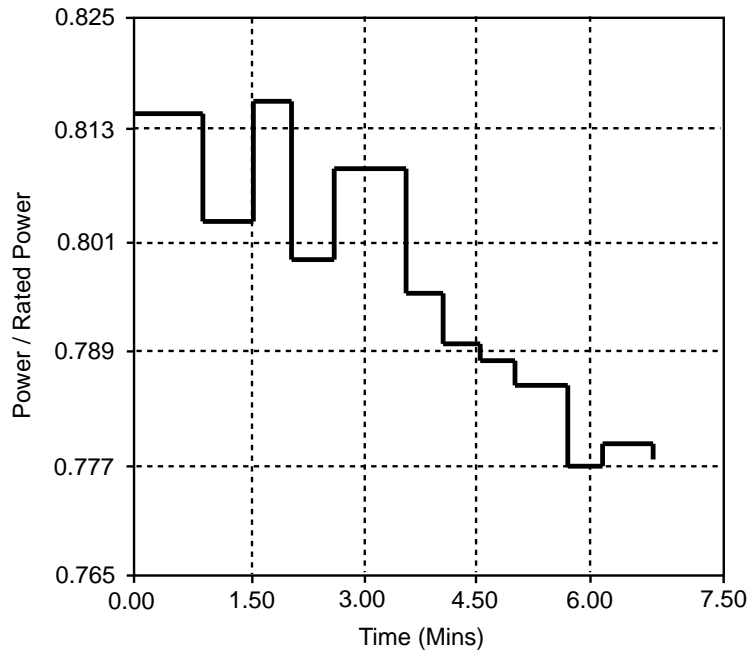
advantage of this control mode is that the transient response becomes sluggish. For any change in load torque or speed command, fast transient response capability of the drive can be restored by establishing the rated flux. Therefore, for ASD Type 2, the system starts in efficiency optimization and then switches to transient response optimization in the event of a load disturbance or a change in set speed. During non-steady-state conditions, the system establishes the rated magnetizing current (Figure 4 switch in Position 1).



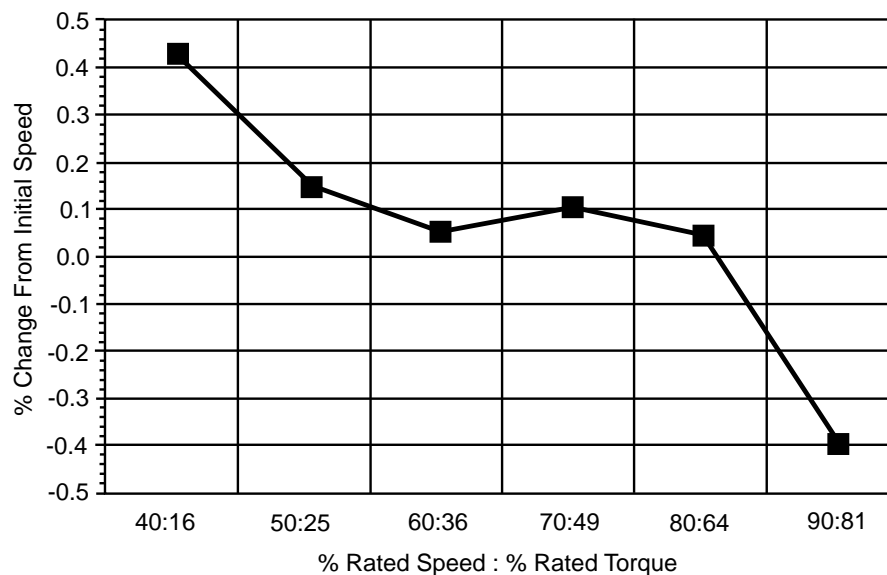
5

Figure 5 is a captured screen from a real-time demonstration of the optimizing and speed controllers for a Type 1 ASD. The motor load being measured and controlled simulates a pump or fan running at 90% of rated speed and 81% of rated torque. At each step, a speed correcting

The speed controller has been shown to hold speed during efficiency optimization to within 0.5%. Figure 6 illustrates controller



**Figure 5.** Efficiency optimization results for 90% speed and 81% torque.



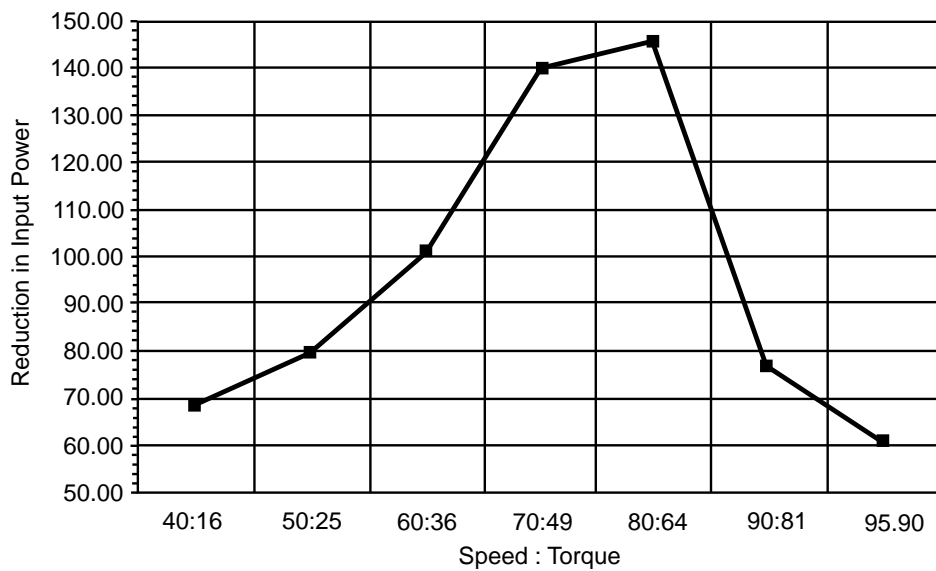
**Figure 6.** Percent change in motor speed from initial motor speed, without slip compensation.

Typical power savings due to slip compensation for a 10 hp motor are shown in Figure 7. A total of 1-2% of rated power is saved.

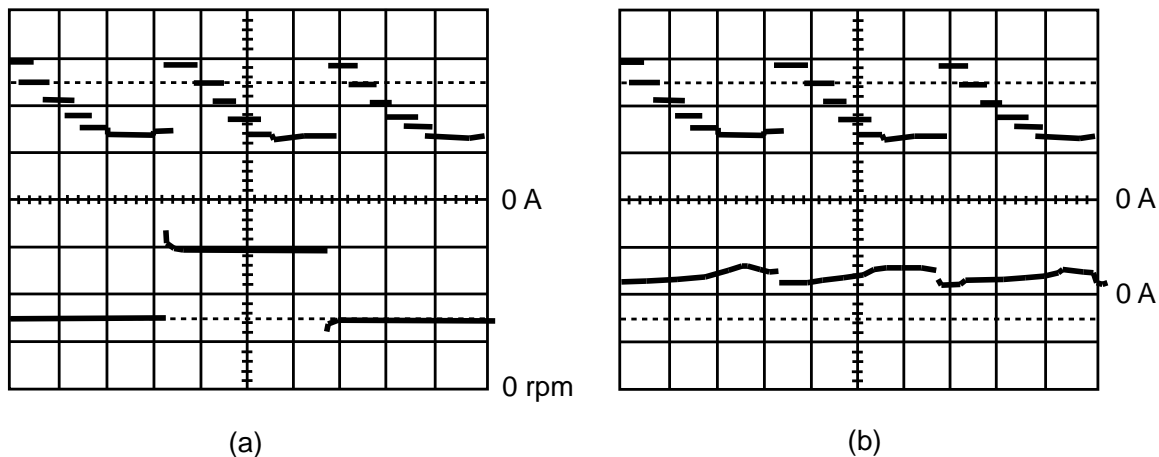
The operation of the pulsating torque compensation scheme for the indirect vec-

tor control drive system is illustrated in Figure 8. An ASD initially operating in a steady-state mode has its command speed changed from 450-900 rpm. At 3 seconds, the system has already reached a new steady-state mode with rated current rees-

tablished. A new search for the optimum efficiency point is initiated. The drive speed response demonstrates the adequacy of the method for fast transient applications.



**Figure 7.** Power reduction in watts due to slip compensation (rated input power = 8477W).



**Figure 8.** Drive performance in time domain with sudden changes in command speed.

a) Top: current (3.33 A/div.); Bottom: speed (3.5 rpm/div.).

b) Top:  $i_{ds}^*$  (3.33 A/div.); Bottom:  $i_{qs}^*$  (3.33 A/div.).

Time scale: 5 sec./div.

Figure 9 contains efficiency curves for the Type 2 ASD, where the dotted curves are results obtained by optimal control with the fuzzy controller and the solid curves represent standard drive control. At light load torque, efficiency gains on the order of 15% may be obtained.

For ASD Type 1, Figures 10 and 11, it is seen that Motor A exhibits less gain from efficiency optimization in the 50 to 60% speed range than at the highest and lowest output powers. The test data also show that, in this operating range, voltage perturbation for optimization reverses its direction; *i.e.*, at the higher speed/torque combinations, voltage perturbation results in voltage increases until  $P_{in}$  is minimized. At

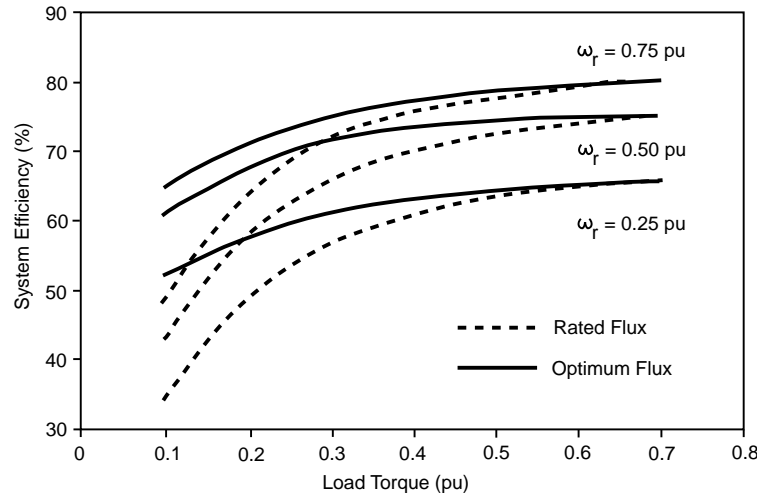
lower speed/torque combinations, voltage decreases to optimize. Motor B results are more common during efficiency optimization, with almost no improvement at rated conditions (100:100). Motor A behavior suggests that the optimum slip of a motor does not necessarily occur at rated conditions. The finding is significant because it implies that, for some motors, input power can be reduced significantly near rated output power operation.

Recommendations for continuing efforts related to the efficiency optimization controllers include:

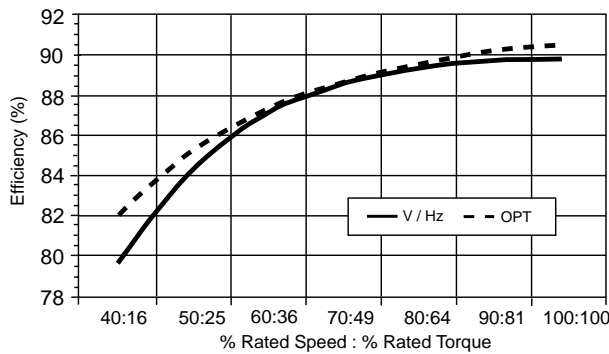
- Final hardware implementation of a microprocessor integrating all control-

lers into ASD circuitry, and testing of the hardware configuration.

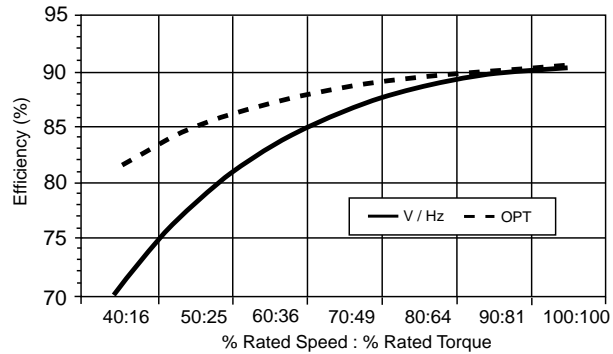
- Further investigation of the influence of motor design and fabrication on the operating conditions where maximum efficiency gains are found during application of the new controllers.
- Demonstration of the hardware-implemented controllers in an industrial setting.



**Figure 9.** Experimental system efficiency curves.



**Figure 10.** V/Hz and optimum efficiencies--Motor A.



**Figure 11.** V/Hz and optimum efficiencies--Motor B.



---

*M.W. Turner, V.E. McCormick, and J.G. Cleland are with Research Triangle Institute, Research Triangle Park, NC 27709.*

**Ronald J. Spiegel** is the EPA Project Officer (see below).

*The complete report, entitled "Efficiency Optimization Control of AC Induction Motors: Initial Laboratory Results," (Order No. PB96-153 424; Cost: \$21.50, subject to change) will be available only from:*

*National Technical Information Service*

*5285 Port Royal Road*

*Springfield, VA 22161*

*Telephone: 703-487-4650*

*The EPA Project Officer can be contacted at:*

*Air Pollution Prevention and Control Division*

*National Risk Management Research Laboratory*

*U.S. Environmental Protection Agency*

*Research Triangle Park, NC 27711*

United States  
Environmental Protection Agency  
National Risk Management Research Laboratory (G-72)  
Cincinnati, OH 45268

Official Business  
Penalty for Private Use \$300

EPA/600/SR-96/008

BULK RATE  
POSTAGE & FEES PAID  
EPA  
PERMIT NO. G-35