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Project Summary

Fuzzy Logic Control of Electric Motors and Motor Drives: Feasibility Study

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Electric motors use 60% of the electrical energy generated in the U.S. An improvement of 1% in all electric motors' operating efficiency could result in reduced coal combustion of 6.5 to 10 million tons* per year. New techniques are required to extract the ultimate performance from modern motors.

This study examined the feasibility of Fuzzy Logic Motor Control (FLMC). The investigation included 1) reviews of existing applications of fuzzy logic, of motor operation, and of motor control; 2) a description of motor control schemes that can use FLMC; 3) selection of a motor stator voltage control scheme to minimize motor input power at specified speed/torque conditions; and 4) development and demonstration of software to simulate both ac motor performance and a fuzzy logic controller for optimized motor efficiency. Simulated FLMC results compared favorably with other motor control approaches. Potential emissions reductions were quantitated based on preliminary predictions of FLMC performance.

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, 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).

(*) 1 ton = 907 kg.

Introduction

Fuzzy logic motor control (FLMC) is a promising technique for extracting maximum performance from modern motors. Electric motors use over 60% of the electrical power generated in the U.S. More efficient motors can significantly reduce energy consumption and help mitigate environmental problems such as acid rain and global warming.

The application of FLMC is timely because, following the advent of solid-state adjustable-speed motor drives (ASDs), improved motor control has reached a point requiring either 1) highly accurate simulation of the complex, non-linear system (with some uncertain parametric relationships) or 2) an alternate mechanism for predicting and optimizing controlled motor system behavior. Fuzzy logic has been chosen here to fill the latter role.

Motors and Drives

The most important challenge to reducing motor power consumption is to properly vary the shaft speed of motors that are designed as constant-speed machines. Manufacturing machines, compressors, pumps, fans, and most other motor drive loads vary with time of day, season, and production requirements. The efficiency of a constant-speed induction motor can drop drastically under reduced loads, especially loads below 50% of the rated torque. Flow control by throttling not only wastes power in constant-speed motors, but also increases fan, compressor, or pump system friction losses.

To minimize power losses, it is necessary to control motor speed and thereby

match motor speed to load requirements. The most recent, universal, and successful approach is the ASD. ASDs use semiconductors and switching circuits to vary the voltage and frequency of a motor's power supply. ASDs essentially operate on the principle of rectifying ac input (line) voltage, filtering the signal, and then switching the dc power on and off in an inverter section to form a variable frequency ac power output to the motor. A microprocessor control block modifies the inverter switching characteristics so that the connected motor speed may be controlled to satisfy the process requirements. The rectifier voltage or current is also directly controlled in conjunction with frequency. FLMC is being developed as the core of the ASD control block, to analyze system feedback and select frequency/voltage/current combinations to optimize energy efficiency.

An embedded fuzzy logic controller can be added to conventional ASDs. ASDs have now been applied to over 1% of the motors larger than 7.5 hp (5.6 kWe) in the U.S. and over 10% of motors larger than 200 hp. At least 85% of the energy that could be saved by better motor control would be associated with motors larger than 5 hp.

A system with the ASD converter, microprocessor, and motor is a highly nonlinear control system. The complexity of the system model and uncertain parametric relationships mean that an accurate system model for simulation, performance prediction, and control is very difficult to achieve. This is especially true considering the precision and accuracy needed to obtain the last few percent of efficiency from a motor system.

Efficiency Optimization

A motor drive may be controlled according to a number of performance functions, such as input power, speed, torque, airgap flux, stator current, power factor, and overall calculated motor efficiency. Normally in a drive system, the machine is operated with the flux maintained at the rated value or with the voltage to frequency ratio (V/Hz) held essentially constant in relation to the value at rated conditions. This allows speed control with the best transient response. The constant V/Hz approach is used wherever actual shaft speed is not measured; i.e., in open loop speed control.

However, in light-load conditions, this approach causes the motor's "core loss," or "iron loss," to be excessive compared to the "copper loss," giving non-optimum efficiency conditions. This means that reduced flux operation is desirable for opti-

mum efficiency, especially in the many applications where rapid transient response is not very important.

Various motor control schemes (including both open- and closed-loop control) were assessed. Control approaches that this study describes include 1) motor slip control, 2) inverter stator voltage or current control, 3) combined frequency and voltage (or current) control, 4) "vector" motor control, 5) rotor speed perturbation control, and 6) input power minimization for efficiency optimization.

A scheme of input power minimization using fuzzy logic was chosen to optimize motor efficiency at reduced loads. The input power, P_{in}, is measured (line value or rectifier output), and then one or more parameters (and ultimately, the flux) are varied from their initial setting (for the typical ASD this initial setting is the constant, rated V/Hz ratio, with voltage lowered in proportion to some required motor speed below rated RPMs).

The input power is measured again and compared (using fuzzy logic) with the previous value, and another perturbation of parameters is initiated, until a minimum input power is reached. This technique is powerful and reasonably simple to implement. The scheme is independent of system parameters and the search algorithm can be applied universally.

The efficiency optimization approach of perturbing stator voltage to reach an input power minimum at a given output is illustrated by data (Figure 1) from the fuzzy controller. Note that as stator voltages, V_s (and consequently flux) are perturbed downward, core losses decrease and copper losses increase. Where the losses equilibrate, input power is minimized. During this control, it was possible to maintain the desired output torque and rotor speed almost constant.

Steady state motor performance was mathematically modeled using the equivalent electrical circuit and mechanical relationships for an ac motor. The simulator was combined with the FLMC power minimization control scheme and performance tested.

Fuzzy Logic Controller

The fuzzy logic controller was developed for the control approach described which involves perturbation of the single variable, V_s. The fuzzy logic controller has been designed to the following guidelines:

1. Assess the direction of change of the input power to the motor, and vary V_s in the corresponding direction for reducing input power;

2. Sense when input power was minimized to the extent that further

variations in V_s produce negligible results;

3. Control the step size for varying V_s so that convergence on the optimum operating point is accelerated; and

4. Limit perturbations to avoid insufficient torque or excess speed (typical limits were -5% and +5% respective variations off the initially specified values).

The above objectives demonstrate the development technique and prove that FLMC can be implemented successfully to control a motor in simulation. These were the goals of this study.

To gain perspective on how the rules in the fuzzy rule base should be formulated, the modeled system's response to changes in V_s was analyzed. The magnitude of P_{in} was evaluated fuzzily and compared to the previous value, P_{old} (see Figure 2). The selected operating torque and speed, and corresponding input voltage, were set for the motor under investigation and V_s was varied by a set number of volts. ΔP_{in1} and ΔP_{in2} were then observed as functions of the corresponding ΔV_{old} and ΔV_{new}.

Based on trends observed among the fuzzy variables, three fuzzy sets (N standing for negative, P for positive, and Z for zero) were chosen to relate the fuzzy variables, along with the following simple set of rules:

1. If ΔP_{in} is N and ΔV_{old} is N, then ΔV_{new} = N.

2. If ΔP_{in} is N and ΔV_{old} is P, then ΔV_{new} = P.

3. If ΔP_{in} is P and ΔV_{old} is N, then ΔV_{new} = P.

4. If ΔP_{in} is P and ΔV_{old} is P, then ΔV_{new} = N.

5. If ΔP_{in} is Z and ΔV_{old} is any, then ΔV_{new} = Z.

Rule 5 is needed for convergence on an optimum input power; i.e., the point where any small change in voltage results in a negligible change in input power.

To allow adjustment of step size (for faster convergence with no overshoot), additional linguistic variables (e.g., positive medium, PM, and negative medium, NM) were added. A set of 13 rules was found to be adequate to relate the variables for the simple control problem.

The fuzzy sets (e.g., P,N,Z) were defined for each fuzzy variable by assigning triangular membership functions. Working sets of membership functions were refined through testing of the combined control scheme and motor simulator. An example is shown in Figure 3. The optimal
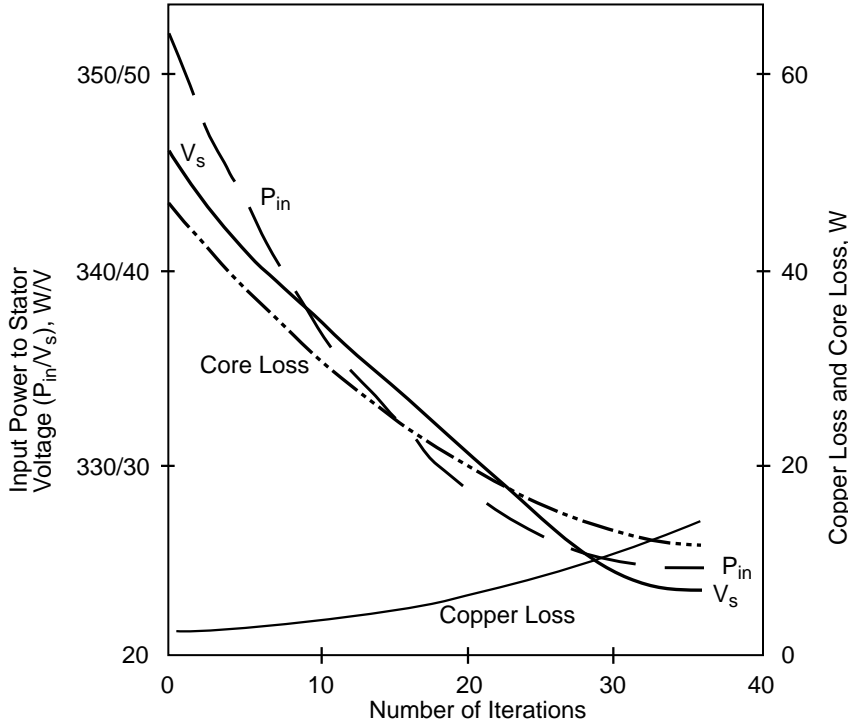
Figure 1. Behavior of perturbed stator voltage, input power, and losses during FLMC simulation.

Figure 2. Diagram of the linked controller model.

overlapping of membership functions was addressed during the course of controller simulation. Experimentation is required because the desired result cannot be defined a priori for each range of input values.

Improvements were made to the fuzzy controller as different torque/speed requirements and different sizes of motors were modeled. Frequent modifications were made to the width of the Z membership function for ΔP_{in} and its overlap with the NM and PM functions. Both the max-dot and the max-min inference methods commonly used for fuzzy logic solutions were applied, with the max-dot proving superior. The centroid defuzzification method was selected and yielded a fast executable code.

Simulated Performance

The preliminary, single-variable (V_s), open-loop fuzzy logic controller was demonstrated by computer simulation. Results show improvement in motor efficiency using FLMC while maintaining good performance in other areas; e.g., maintaining desired torque and speed at steady levels.

For example, Figure 4 compares the efficiency of a motor over a broad range of loads and operating under both conventional constant V/Hz control and FLMC control. The load torque relation to rotor speed simulates the behavior of pump or fan loads, where load torque is proportional to the square of the rotor speed. FLMC performs better than constant V/Hz control at all speed/torque combinations.

To test the simulator for consistency, equivalent circuit values of other higher horsepower motors were introduced into the model. Comparisons were also made with results from other more complex motor efficiency optimization control approaches involving speed feedback control and a lookup table approach for optimizing induction motor slip. The qualitative behavior of FLMC was consistent with other techniques, and efficiency reduction was favorable for FLMC. FLMC was also compared with a constant-step-size voltage perturbation approach that was shown to require 2 to 5 times as many iterations as FLMC to reach the optimum point.
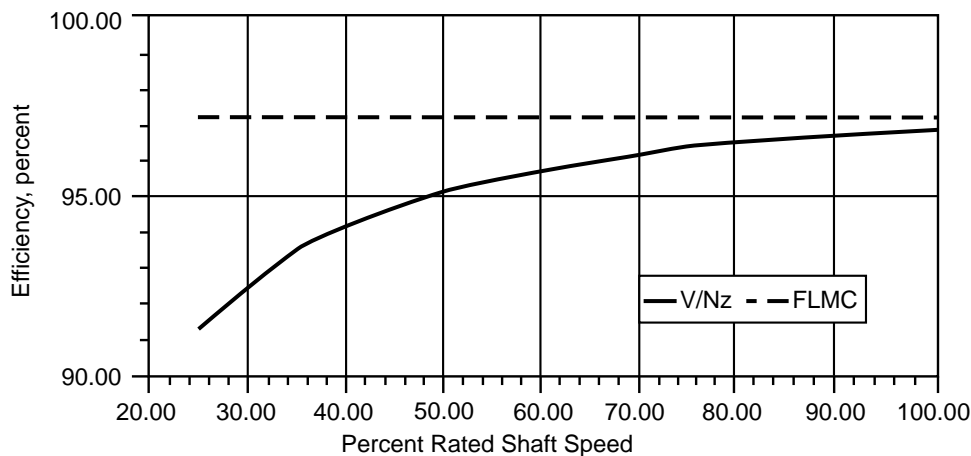
Conclusions

Relative efficiency improvements by FLMC over V/Hz for the motors examined range from about 0.2 to 14%. Median savings over V/Hz open-loop control using the preliminary FLMC for a 10-hp motor could conservatively be expected to be about 3%, or roughly 1,800 kWh/yr

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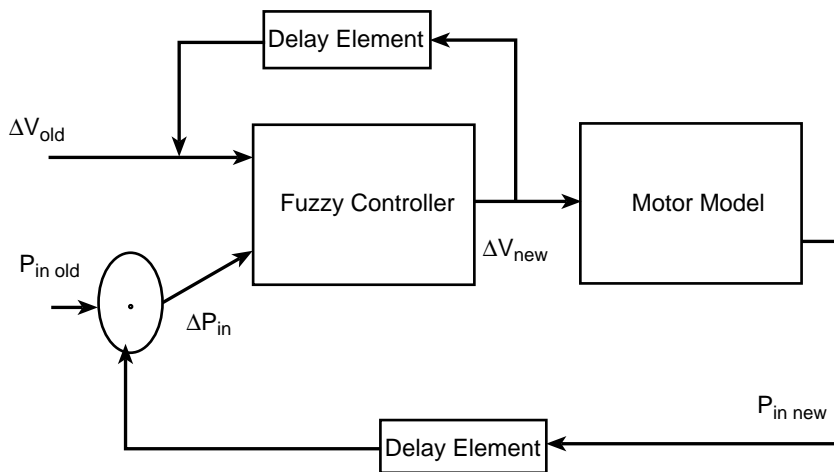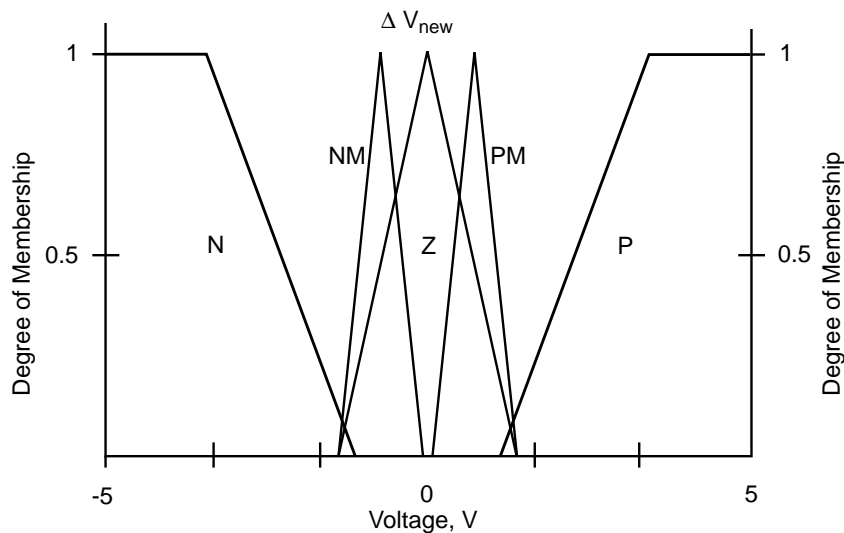
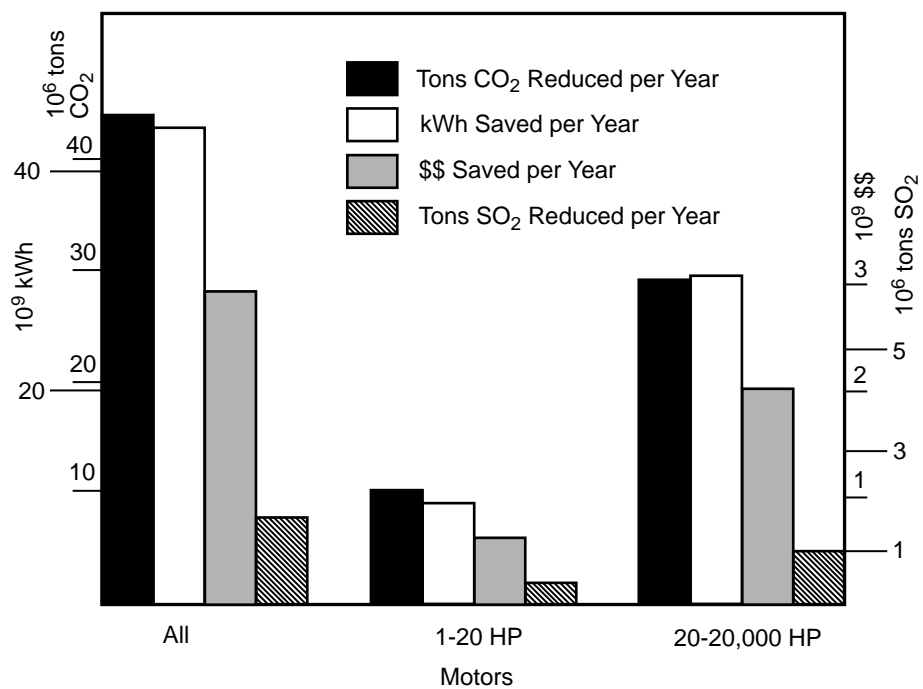**Figure 3**. Final membership functions for the fuzzy variable ΔV_{new}.

Figure 4. FLMC vs. V/Hz control for a 100 hp motor with torque α speed[2].

($55 to $95); for a 25-hp motor, 1.7%, 2,500 kWh/yr ($75 to $130); and for a 100-hp motor, 1.4%, 8,500 kWH/yr ($250 to $450), all derived from a commercial sector delivered power cost of 3 to 5.3 ¢/kWh.

Results indicate that FLMC can consistently improve motor efficiency over conventional speed control techniques by increments of 1 to 4%. Figure 5 illustrates potential pollution abatement implications as well as energy savings from FLMC based on conservative estimates of average energy savings for major classes of motors (using study results, data on U.S. motor usage, and typical coal-fired power plant heat rates and emissions).

Future Developments

The full potential of FLMC is not realized by this first simple controller. Future developments could include dual-variable (voltage or current, and frequency) FLMC, and a fuzzy speed estimator (rotor speed calculated from measured voltage and current) that will allow dual-variable control without a tachometer. An optimized controller could be transferred to an application specific integrated circuit (ASIC) chip set for ASD retrofit. Such developments would probably include motor simulation upgrades and extensive laboratory testing.

Figure 5. Projected savings from FLMC.

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