Fuzzy Logic Control of Food Frying Process: Efficiency and Energy Optimization of Food Frying Process

P.B. Osofisan, Ph.D.* **and M.O. Falodun, B.Sc.(Eng.)**

Department of Electrical engineering, University of Lagos, Lagos State, Nigeria.

*E-mail: tosofisan@yahoo.com
famikecontrols@hotmail.com

ABSTRACT

A fuzzy logic controller for energy optimization was developed to improve the efficiency of motor/ conveyor belt combinations, which operate, at varying loads and speeds during the food frying process. A sensorless speed controller that maintains a constant motor shaft speed (revolutions per minute) which produces constant power output complements this energy optimizer.

Such an implementation leads to a more effective control design with improved system performance and robustness. Conventional control allows basic different design objectives such as steady state and transient characteristics of the closed loop system. Fuzzy logic is integrated to overcome the problems with uncertainties in the plant parameters and structure encountered in the classic model-based design. Induction motors that control the food frying conveyor belts system are characterized by complex, highly non-linear and time-varying dynamics and inaccessibility of some states and outputs for measurements

This fuzzy logic approach was developed and applied to adjust the speed of the conveyor belts system for optimal performance of food frying process control.

(Keywords: fuzzy logic, optimization,
conveyor speeds, adjustable speed drives, ASD,
variable structure systems, VSS)

INTRODUCTION

There are two distinctive dynamic effects in modern conveyor belt design that are governed by nonlinear processes, namely transverse belt vibrations and longitudinal wave motion induced in the belt on starting and stopping. Fuzzy logic has been implemented in this development to improve the motor/conveyor speed control of food frying process for efficiency optimization because: Fuzzy logic overcomes the mathematical difficulties of modelling highly non-linear systems; it responds in a more stable fashion to imprecise readings of feedback control parameters, such as the DC link current and voltage; and Fuzzy logic control mathematics and software are simple to develop and flexible for each modification.

The nonlinear characteristics of a DC motor such as saturation and friction could degrade the performance of conventional controller [1-3]. Many advanced model-based control methods such as variable-structure control [7] and model reference adaptive control [3] have been developed to reduce these effects. However, the performance of these methods depends on the accuracy of system models and parameters. Generally, an accurate non-linear model of an actual DC motor is difficult to find, and parameter values obtained from system identification may be only approximated values.

Emerging intelligent techniques (e.g. fuzzy logic) have been developed and extensively used to improve, or replace, conventional control techniques because these techniques do not require an intensive mathematical model.

Heuristic knowledge is applied to defined fuzzy membership functions and rules. The membership functions and rules are modified after initially borrowing the knowledge from a P-I controller developed from a simple linear model [5,8].

Figure 1 shows the structure of direct fuzzy controller.

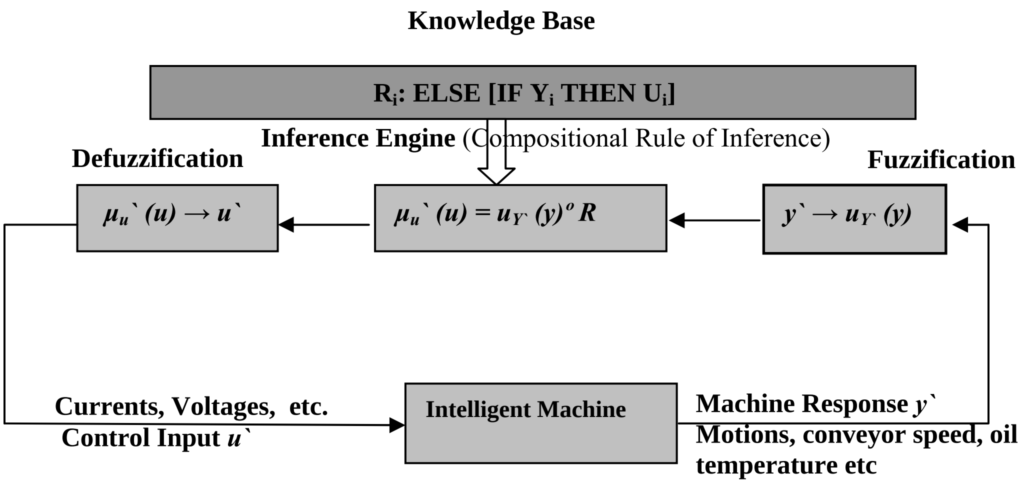


Figure 1: Structure of Direct Fuzzy Controller.

VARIABLE STRUCTURE SYSTEMS [7]

The basic control law of Variable Structure Systems (VSS) is given by:

$$u = -K\text{sgn}(S) \qquad \textbf{(1)}$$

Where K is a constant parameter, sgn (·) is the sign function and S is the switching function defined by:

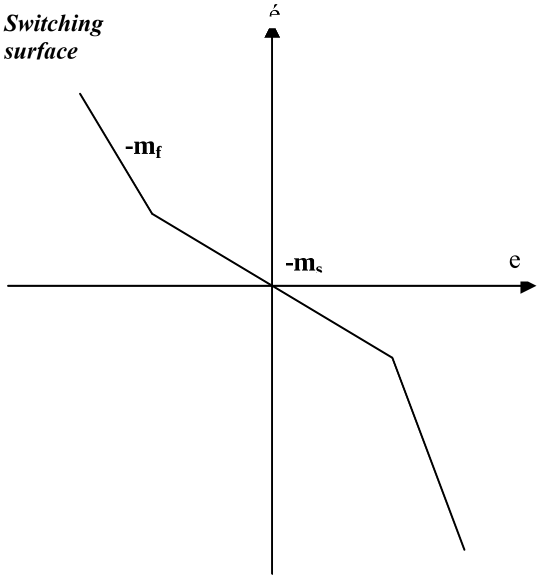


Figure 2: Membership Functions Adjustment with m_s and m_f [7].

$$S = f^T x. \qquad \textbf{(2)}$$

When S = 0, this represents the switching surface and gives the desired dynamics. Similarly, the fuzzy rules

$$R_i : \text{IF } A_i \text{ AND } B_i \text{ THEN } C_i \qquad \textbf{(3)}$$

may be interpreted as a control structure that is switched according to the system states. Hence fuzzy controllers can be viewed as a class of variable structure controllers.

Let the desired dynamics of the drive system be specified in terms of the switching surface as shown in Figure 2. The error trajectory approaches the switching surface gradually with the slopes $-m_f$ and $-m_s$ corresponding to fast and slow dynamics, respectively.

With reference to Figure 2, the slopes of the error trajectory are obtained as

$$m_s = \frac{L_{de0}\, m_e}{L_{e0}\, m_{de}} \qquad \textbf{(4)}$$

$$m_f = \frac{L_{de0} - \dfrac{L_{de0}}{m_{de}}}{L_{e0} - \dfrac{L_{e0}}{m_e}} = \frac{L_{de1} - \dfrac{L_{de1}}{m_{de}}}{L_{e1} - \dfrac{L_{e1}}{m_e}} \qquad \textbf{(5)}$$

By specifying the desired m_s and m_f, and assuming the range of the error signal {Le, me}, the membership functions related to the error and its change of triangular shape chosen here is adjusted by the following relationships:

$$M_{de} = \frac{L_{de0}\, m_e}{m_s\, L_{e0}} \qquad \textbf{(6)}$$

$$L_{dei} = m_f L_{ei} - (m_f - m_s)\,\frac{L_{e0}}{M_e}, \quad I = 0,1 \qquad \textbf{(7)}$$

The controller structure is Proportional-Integral (PI) and is illustrated in Figure 3.

Here $K_P = K_u R(K_{de})$ **(8)**

and $K_I = K_u R(K_e)$ **(9)**

are the controller proportional and integral gains, and R(·) is defined by the controller rule base which is summarized in Table 1.

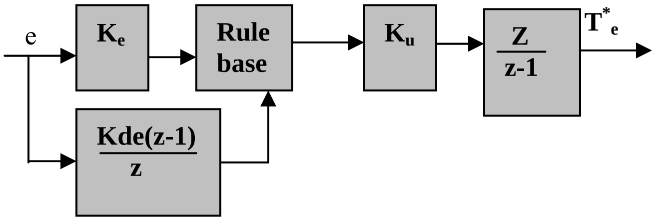


Figure 3: Fuzzy PI Controller Structure.

Table 1: Fuzzy Rule for VSS.

				←	e	→		
		NB	**NM**	**NS**	**EZ**	**PS**	**PM**	**PB**
	PB	**Z**	PS	PM	PB	PB	PB	PB
↑	**PM**	NS	**Z**	PS	PM	PB	PB	PB
	PS	NM	NS	**Z**	PS	PM	PB	PB
de	**EZ**	NB	NM	NS	**Z**	PS	PM	PB
	NS	NB	NB	NM	NS	**Z**	PS	PM
↓	**NM**	NB	NB	NB	NM	NS	**Z**	PS
	NB	NB	NB	NB	NB	NM	NS	**Z**

Here NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Big) are linguistic variables.

CONTROLLER DESIGN

While conventional controllers depend on the accuracy 'of the system model and parameters', FLCs use a different approach to control the DC motor speed. Instead of using a system model, the operation of a FLC is based on heuristic knowledge and linguistic description to perform a task. The effects from inaccurate parameters and models are reduced because an FLC does not always require a system model. However, building an FLC from the base may not provide good results or sometime even a worse result than a conventional controller if there is not enough knowledge of the system.

ENERGY AND EFFICIENCY OPTIMIZATION OF MOTOR SPEED CONTROL

A motor drive may be controlled according to a number of performance functions, such as input power, speed, torque, air gap flux, stator current, power factor, and overall calculated motor efficiency. Normally in a conveyor belt 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. 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 Adjustable Speed Drive (ASD) this initial setting is the constant, rated V/Hz ratio, with voltage lowered in proportion to some required motor speed below rated RPMs)[4].

The input power is measured again and compared 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 4) from the fuzzy controller. Note that as stator voltages, Vs (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. The simulator was combined with the FLMC (Fuzzy Logic Motor Controller) power minimization control scheme and performance tested.

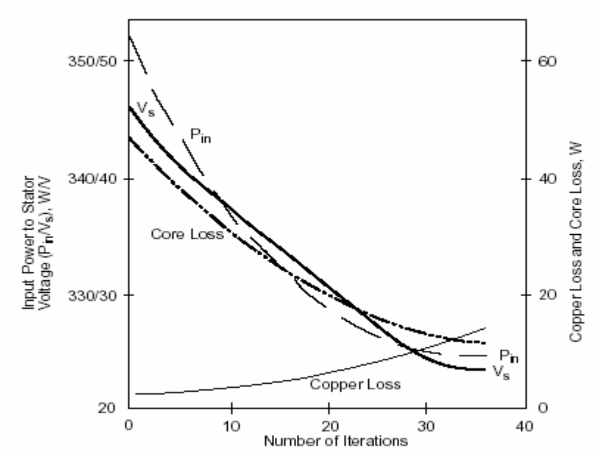


Figure 4: Behavior of Perturbed Stator Voltage, Input Power, and Losses During FLMC Simulation (John G. Cleland and M. Wayne Turner, 1996) [4].

EFFICIENCY OPTIMIZATION OF MOTORS FOR FOOD FRYING PROCESS CONTROL

Three interactive efficiency-optimizing controllers have been developed. The optimization is effected through minimization of the input power. These controllers are: (1) voltage perturbation for input power minimization, (2) speed correction, and (3) slip compensation (Figure 5). The voltage perturbation controller is based on changes in input power and stator voltage. Fuzzy logic control has been used for voltage perturbation. The fuzzy logic membership functions for both inputs and the output are partitioned using five fuzzy sets. The input variables are ΔVs_{old} and ΔP_{in}; the output variable is ΔVs_{new}. Triangular fuzzy sets are used for 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 6, 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 (ΔVs_{old}) is a "positive small" value and the measured input power change (ΔP_{in}) is a "negative small" value, then ΔVs_{new} is "positive small."

Speed correction control is needed because the perturbation approach alters motor speed and output power. The output rotor speed of the motor should be maintained as constant as possible. A fuzzy logic speed corrector controller was designed to correct 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 (Adjustable Speed Drive) 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 the frequency change, the slip, s, of the motor also changes. Slip is defined as the ratio of Rotor speed/Frequency.

In this paper, the slip compensation control mathematically estimates the slip, which will result from a given change in frequency, and adjusts frequency to give the desired percent speed.

FLMC OF V_{P1} AND V_{P2}

Fuzzy logic motor control (FLMC) is a promising technique for extracting maximum performance from modern motors, which is an alternate mechanism for predicting, optimizing, and controlled motor system behavior. 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.

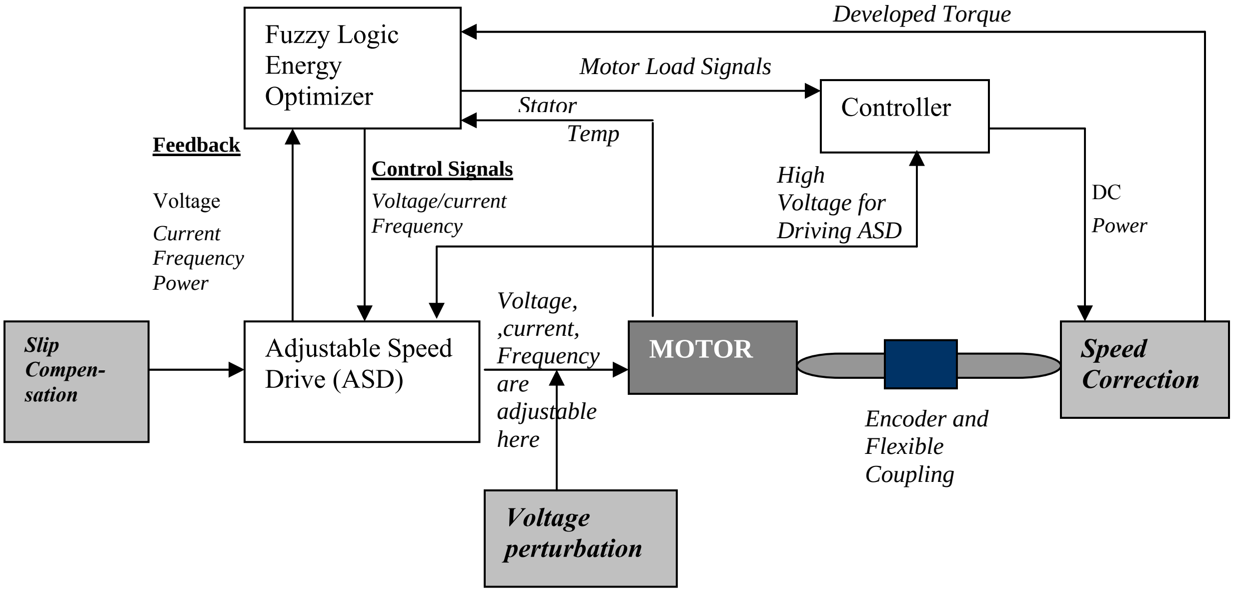
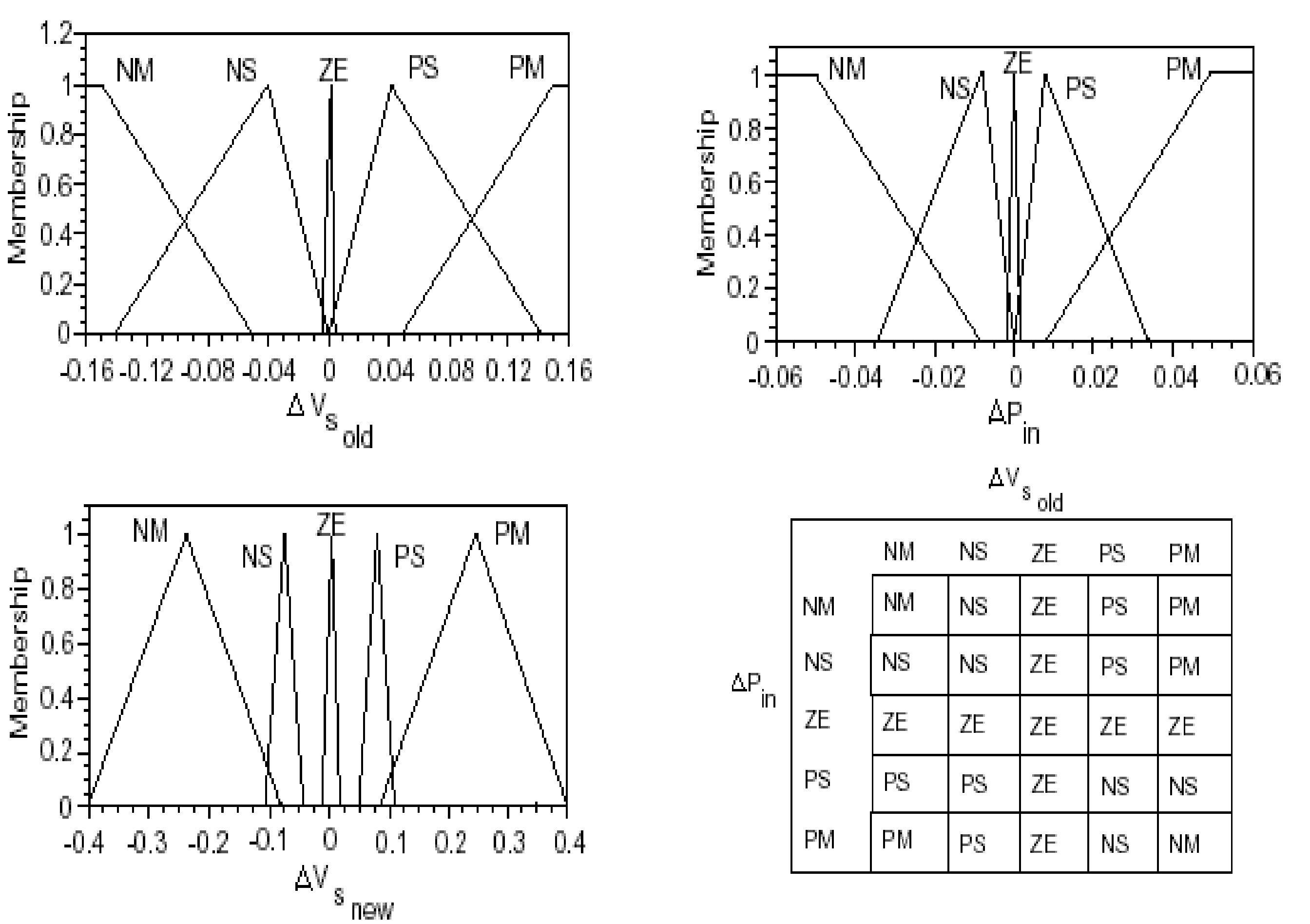


Figure 5: Layout of Main Component Responsible for Interactive Efficiency-Optimization of Food Frying Process Control [4].



ΔP_{in} \ $\Delta V_{s\,old}$	NM	NS	ZE	PS	PM
NM	NM	NS	ZE	PS	PM
NS	NS	NS	ZE	PS	PM
ZE	ZE	ZE	ZE	ZE	ZE
PS	PS	PS	ZE	NS	NS
PM	PM	PS	ZE	NS	NM

Figure 6: Membership Functions and Rule Set for Fuzzy Voltage Perturber.

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. 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 (Adjustable Speed Drives) control block, to analyze system feedback and select frequency/voltage/current combinations to optimize energy efficiency.

The fuzzy logic controller was developed for the control approach described which involves perturbation of the single variable, Vs. 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 Vs in the corresponding direction for reducing input power; (2) Sense when input power was minimized to the extent that further variations in Vs produce negligible results; (3) Control the step size for varying Vs 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).

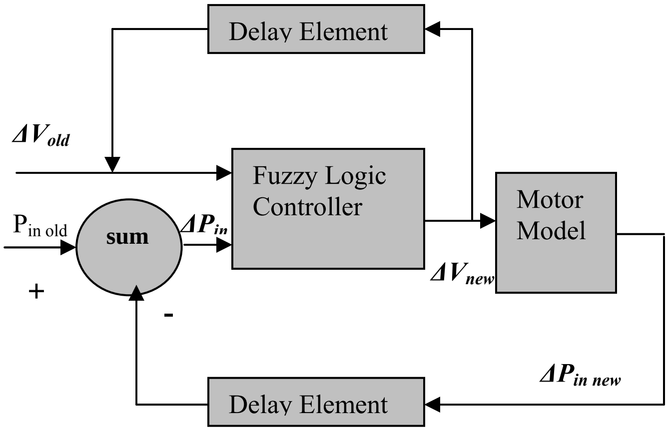


Figure 7: Diagram of the Linked Controller Model [4].

The above objectives demonstrate the development technique and prove that FLMC can be implemented successfully to control a motor in simulation, most especially as applied to submerged conveyor speed, V_{p1} and takeout conveyor speed, V_{p2} of food frying process control. To gain perspective on how the rules in the fuzzy rule base should be formulated, the modeled system's response to changes in Vs was analyzed. The magnitude of P_{in} was evaluated and compared to the previous value, $P_{in\ old}$ (Figure 7).

The selected operating torque and speed, and corresponding input voltage, were set for the motor under investigation and Vs 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 $\Delta V_{new} = N$.
2. If ΔP_{in} is N and ΔV_{old} is P, then $\Delta V_{new} = P$.
3. If ΔP_{in} is P and ΔV_{old} is N, then $\Delta V_{new} = P$.
4. If ΔP_{in} is P and ΔV_{old} is P, then $\Delta V_{new} = N$.
5. If ΔP_{in} is Z and ΔV_{old} is any, then $\Delta V_{new} = Z$.

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. Figure 8 shows the final membership functions for the fuzzy variable ΔV_{new}.

A set of 13 rules was found to be adequate to relate the variables for the simple control problem. The rules are:

If ΔP_{in} is NM and ΔV_{old} is NM, then ΔV_{new} = NM
If ΔP_{in} is NM and ΔV_{old} is NS, then ΔV_{new} = NS
If ΔP_{in} is NM and ΔV_{old} is PS, then ΔV_{new} = PS
If ΔP_{in} is NM and ΔV_{old} is PM, then ΔV_{new} = PM
If ΔP_{in} is NS and ΔV_{old} is NM, then ΔV_{new} = NS
If ΔP_{in} is NS and ΔV_{old} is NS, then ΔV_{new} = NS
If ΔP_{in} is NS and ΔV_{old} is PS, then ΔV_{new} = PS
If ΔP_{in} is NS and ΔV_{old} is PM, then ΔV_{new} = PM
If ΔP_{in} is PS and ΔV_{old} is PS, then ΔV_{new} = NS
If ΔP_{in} is PS and ΔV_{old} is PM, then ΔV_{new} = NS
If ΔP_{in} is PM and ΔV_{old} is PS, then ΔV_{new} = NS
If ΔP_{in} is PM and ΔV_{old} is PM, then ΔV_{new} = NM

If ΔP_{in} is ZE and ΔV_{old} is any, then ΔV_{new} = ZE

(The last rule is needed for convergence on P_{in})

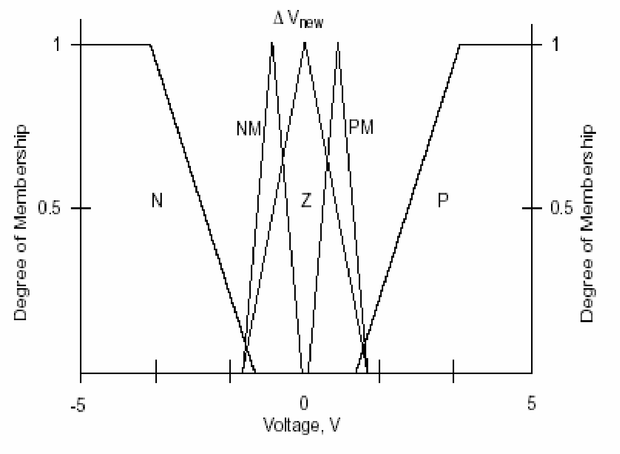


Figure 8: Final Membership Functions for the Fuzzy Variable $\Delta V_{new.}$

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.

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.. The centroid defuzzification method was selected and yielded a fast executable code. The preliminary, single-variable (V_{as}), 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.

Figure 9 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 conveyor belt 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 [6].

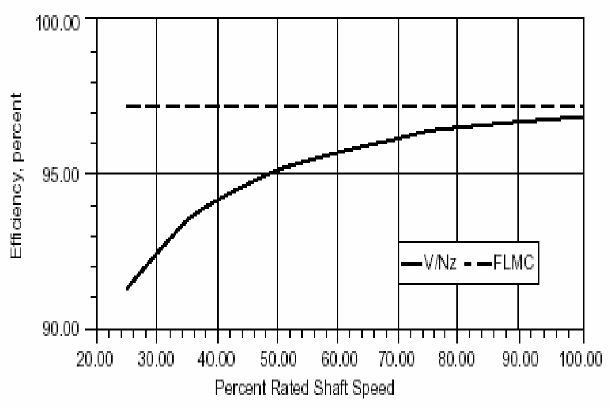


Figure 9: FLMC vs. V/Hz Control for a 100 HP Motor (John G. Cleland and M. Wayne Turner, 1996).

RESULTS

Figure 10 is a captured screen from a real-time demonstration of the speed controllers. The motor load being measured and controlled simulates conveyor belts running at 90% of rated speed and 81% of rated torque.

At each step, a speed-correcting controller compensates for changes in speed with changes in input frequency. Ultimately, the input power is reduced from about 81 to about 78% of rated input power. The speed controller has been shown to hold speed during efficiency optimization to within 0.5%. Typical power savings due to slip compensation for a 10 hp motor are shown in Figure 11. A total of 1-2% of rated power is saved.

Figure 12 shows the measured real speed and estimated speed of the sensorless drive to a 1000 rpm step command. The rise time is about 200 msec under a 20 A current limit on the torque current command. Experimental results have shown the closeness between the measured and estimated rotor speed. Figure 13 shows the step responses of the Digital Signal Processing (DSP) -based vector controlled induction drive with and without encoder feedback. Although the dynamic response of a sensorless drive is inferior to a drive with encoder feedback, however, its response is also much superior than the conventional open-loop controlled PWM inverter drive.

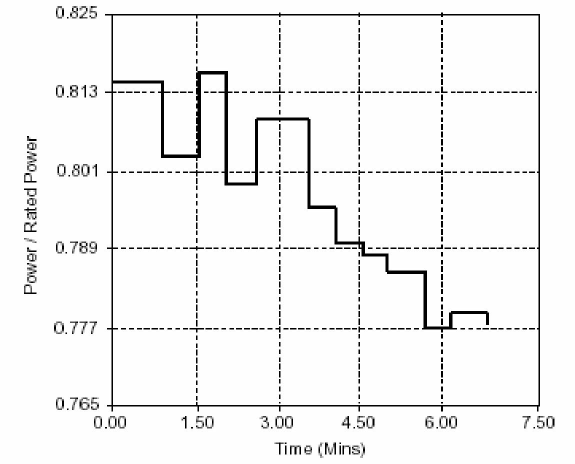


Figure 10: Efficiency Optimization Results for 90% Speed and 81% Torque.

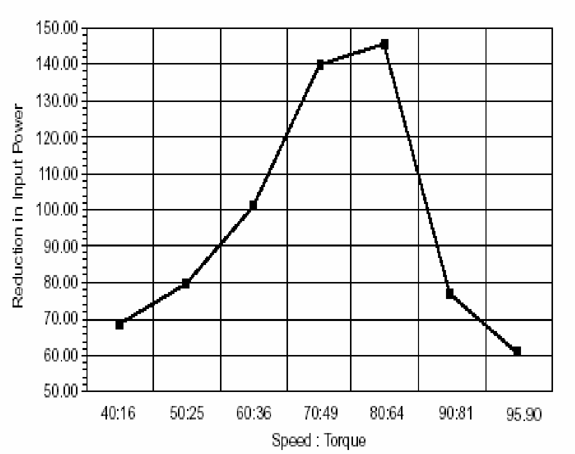


Figure 11: Power Reductions in Watts due to Slip Compensation (rated input power = 8477W).

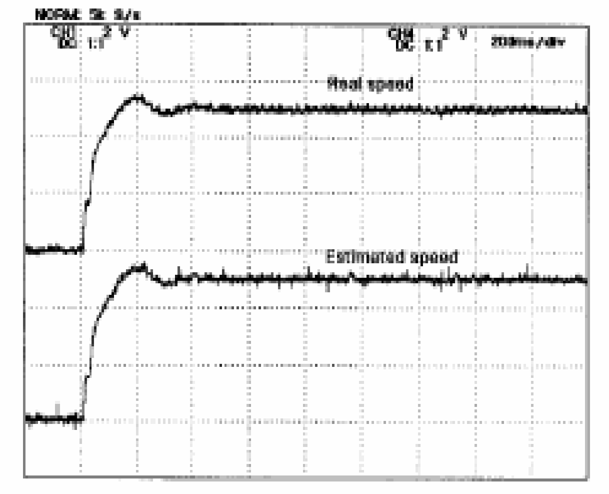


Figure 12: Dynamic Responses of the Sensorless Induction Drive to a 1000 RPM Step Input with Measured Rotor Speed and Estimated Rotor Speed.

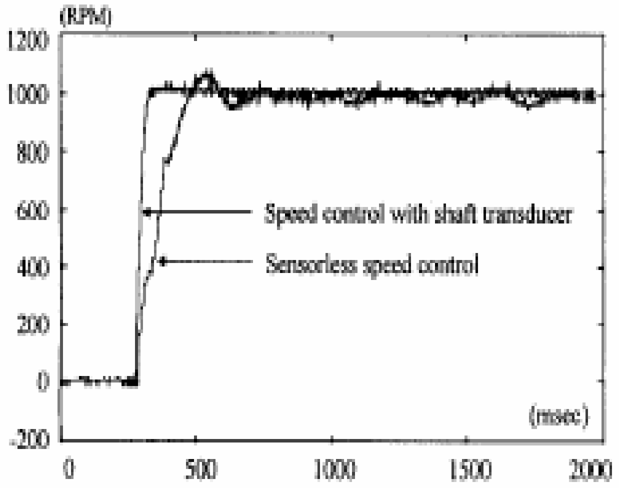


Figure 13: Step Responses of a Vector Controlled Induction Drive with and without Encoder Feedback.

The accuracy of the speed estimation algorithm is dependent on the induction motor modeling. Therefore, accurate parameter measurement or identification is necessary for good regulation and fast transient responses.

Experimental results show the proposed control scheme can achieve fast dynamic response speed control of the induction motor without any shaft transducers.

CONCLUSION

This paper presents some design approaches that lead to robust and easily tuned controllers, and are very well suited for systems with uncertain or unknown variations in plant parameters and structure. Designing effective controllers for induction motors used in the food frying process creates a challenging engineering problem. The performance and robustness of the proposed controllers have been evaluated under a variety of operating conditions of the drive system, and the results demonstrate the effectiveness, efficiency and energy optimization of these control structures.

Various studies of the control strategies in terms of performance and robustness have been conducted. The control techniques studied are very suitable for real time implementation due to their simplicity, robustness and ease of tuning.

The key to a successful implementation of sensorless induction drive depends not only on fast and accurate rotor speed estimation, but also requires a well-tuned decoupling control of the induction motor. In sensorless induction drives, speed estimation and decoupling control are always coupled together and they are dependent on the knowledge of related motor parameters, therefore, speed estimation with low sensitivity to motor parameter variations is especially important.

LIST OF SYMBOLS AND ABBREVIATIONS

ω	motor speed
Rs, Rr	stator and rotor resistances
V/Hz	voltage to frequency ratio
FOC	Field Orientation Control
P_{in}	input power
$V_{as}(V_s)$	single variable
P_{in}	input power
ΔP_{in}	change in input power
ΔVs_{old}	last voltage change
ΔV_{snew}	new voltage change
FLMC	Fuzzy Logic Motor Controller

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ABOUT THE AUTHORS

Dr. P.B. Osofisan, obtained his B.Sc.(Eng) and M.Sc.(Eng) in Electrical Engineering from the University of Stuttgart, Stuttgart, Germany. He earned his Ph.D. in Control Systems Engineering from the same University. He then worked in a cable manufacturing plant as the Production/Quality Control Manager for over 15 years, before he joined the University of Lagos as Senior Lecturer in Electrical and Electronics Engineering Department. His research interests include the application of Fuzzy Logic Theory and Neural Network in the process control of industrial processes.

Mr. M.O. Falodun, obtained his B.Sc.(Eng.) degree from the Federal University of Technology, Owerri in Imo State of Nigeria. He is currently concluding his M.Sc.(Eng.) program from the University of Lagos, Lagos, Nigeria.

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