Induction Motor Slip Control with Efficiency Optimization Using Fuzzy Logic Techniques

Jaime Fonseca, João Afonso, Júlio Martins and Carlos Couto
Department of Industrial Electronics, University of Minho
Largo do Paço, 4700 - Braga, PORTUGAL
(E-mail: ccouto@dei.uminho.pt)

Abstract

This paper describes a fuzzy logic based slip controller for an induction motor, with efficiency optimization for steady state operation. The speed control is accomplished through a Mandani type fuzzy controller, with 11 rules, taking *speed error* (built with 5 Membership Functions - M.F.) and *speed error variation* (3 M.F.) as inputs, to produce the *slip increment* (5 M.F.). The average motor input power is computed and used to decrement the motor voltage until minimum input power is found, optimizing the efficiency. A Mandani type fuzzy controller, with 5 rules, was devised for this purpose using the *input power variation* (5 M.F.) as input, to produce the *voltage decrement* (5 M.F.).

Matlab/Simulink and its Fuzzy Logic Toolbox were used to design the controllers under simulation environment. Simulation results are presented comparing the fuzzy logic controller with a traditional approach, using a PI with antiwindup mechanism for slip control. Experimental results obtained with standard hardware are also shown.

1. Introduction

Fuzzy logic is a superset of conventional (Boolean) logic that has been extended to handle the concept of partial truth (truth values between "completely true" and "completely false"). It was introduced by Dr. Loft Zadeh of UC/Berkeley in 1960's as a mean to model the uncertainty of natural language, but only recently its use has spread over a large range of engineering applications. Fuzzy logic techniques attempt to simulate human thought processes, even in technical environments. In doing so, the fuzzy-logic approach allows the designer to handle efficiently very complex closed-loop control problems, reducing engineering time and costs [1, 2].

Fuzzy control supports non-linear design techniques that are now being exploited in motor control applications [3-7]. Examples include the ability to vary gain over a range of the inputs in order to not saturate the control capability.

Matlab/Simulink was used as a simulation tool. Matlab is an integrated technical computing environment that combines numeric computation, advanced graphics visualization, and a high-level programming language. Simulink is built on top of Matlab, and is an interactive environment for modelling, analyzing and simulating a wide variety of dynamic systems.

In this paper we try to show, through simulation studies validated by laboratory tests, that the use of fuzzy logic techniques can be advantageous, even in cases where the classical approaches can be used and perform well. Fuzzy logic is used in a slip control scheme for a three-phase induction motor fed by a voltage-source inverter.

2. Induction Motor Slip Control

Figure 1 presents a conventional slip control scheme for an inverter fed induction motor which is used for low performance variable speed drives [8]. Traditionally, the speed error (ω_e) is input to a PI controller (block A) that sets the motor slip frequency (ω_l). Stator frequency (ω_s) is obtained by adding slip frequency to rotor speed (ω), and stator voltage (U_s) is set accordingly to a pre-defined $U_s/\omega_s \approx constant$ law (block B), so that motor flux is kept at its nominal value. Slip frequency must be limited, setting (indirectly) a limit to both peak torque and stator current. Voltage and frequency values are then input to the voltage source inverter (block C).

Keeping flux at nominal value allows motor to develop its rated torque but does not guarantee that it operates with good efficiency. In fact it can be shown that, specially for small motors and light loads, efficiency can be improved by reducing motor flux [8, 9]. Therefore, the conventional slip control scheme can be improved, so that at steady state, stator voltage (and so motor flux) is reduced to minimize motor losses.

As stator frequency and rotor slip frequency are automatically adjusted by the speed control loop, the motor operating point is maintained (speed and output power are kept constant). At the same time, an average motor input power can be computed so that voltage is decreased until minimum input power is found, in a efficiency optimization process.
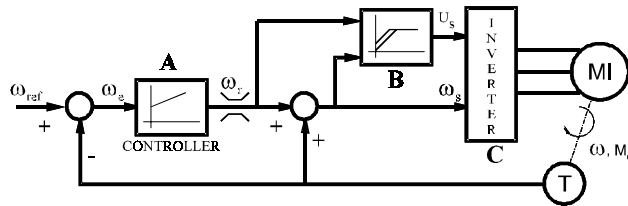

Figure. 1.   Slip control for an induction motor voltage-source inverter drive.

3. Fuzzy Logic Controllers Design

Figure 2 presents the system block diagram in the Matlab/Simulink environment. Block A is a masked block that implements the fuzzy slip controller. Block B is another masked fuzzy controller block, responsible for the motor efficiency optimization process. Block C decides if motor runs in transient or in steady-state regime, allowing switching from a "constant flux" to a "flux reduction" law.

The Fuzzy Logic Toolbox used to develop blocks A and B covers all steps of fuzzy logic design, from the project definition to the definition of membership functions and rules [10].
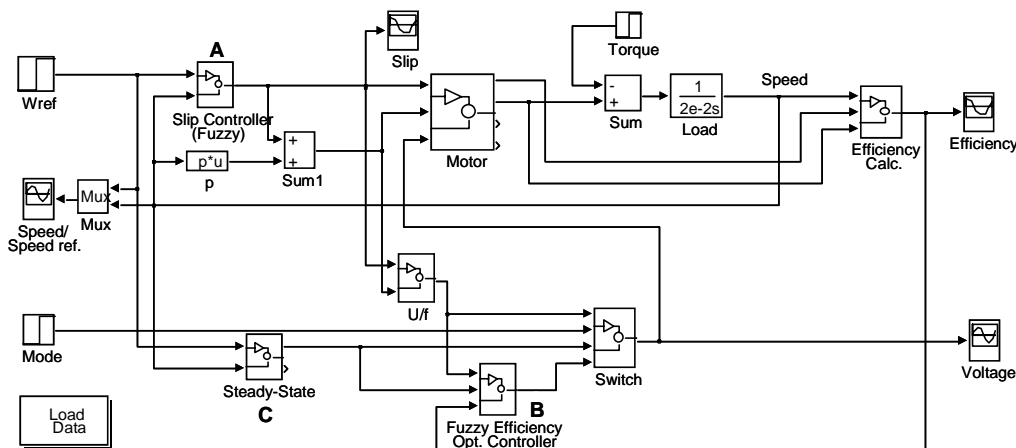

Figure 2. The fuzzy approach - system block diagram.

The first step is to define the structure of the controller by means of the "Fuzzy Inference System (FIS) Editor". The FIS Editor displays the control structure and permits to adjust the fuzzy inference functions, such as the defuzzification method. The FIS Editor also allows the designer to directly access the "Membership Function Editor", the "Rule Editor", the "Rule Viewer" and the "Surface Viewer". The second step of the controller design is the definition of the membership functions. The graphic interface of the development tool allows the designer to easily create the most suitable membership functions and the linguistic variables for the application.

The slip controller has two inputs (*speed error* and *speed error variation*) and one output (*slip increment*). The inputs and the output are described with triangular Membership Functions (M.F.). The *speed error variation* uses 3 M.F.: Negative (N), Zero (ZE) and Positive (P). The *speed error* is described with 5 M.F.: Negative Large (NL), Negative Small (NS), ZE, Positive Small (PS) and Positive Large (PL). The *slip increment* uses 7 M.F.: NL, Negative Medium (NM), NS, ZE, PS, Positive Medium (PM) and PL. It was used 11 rules to relate the inputs with the output of the slip controller (Table I).

Table I - Slip Controller Rules

IF		THEN	
ErrorVar	SpeedError	DoS	Slip_Inc
N	ZE	1.00	NS
ZE	ZE	1.00	ZE
P	ZE	1.00	PS
N	PS	1.00	NM
ZE	PS	1.00	PS
P	PS	1.00	PM
N	NS	1.00	NM
ZE	NS	1.00	NS
P	NS	1.00	PM
	NL	1.00	NL
	PL	1.00	PL

The efficiency optimization process controller was implemented in a similar way. It has one input *(input power variation)* and one output (*motor input voltage increment*) described with five triangular membership functions: NM, NS, ZE, PS and PM. It uses five rules to relate the input with the output (Table II).

Table II - Optimization Rules

IF	THEN	
Input Power Variation	DoS	Voltage Decrement
NM	1.00	PM
NS	1.00	PS
ZE	1.00	ZE
PS	1.00	NS
PM	1.00	NM

In the development of both controllers each rule output was determined by "MIN-MAX" inference and the each crisp output was generated by "centroid" (COG) defuzzification.

The sampling time used in the slip controllers simulations (fuzzy and PI) was 5.1 ms. The efficiency optimization process used a 0.1 s time interval between voltage decrements.

4. Efficiency Optimization Process Results

Figure 3 illustrates the efficiency optimization process, implemented with fuzzy logic. Motor is started-up and after speed reaches steady state the efficiency optimization process controller begins to act, reducing motor voltage, what leads to flux reduction and increment of the slip. This process permits an efficiency improvement, which is greater than 5% in this case.
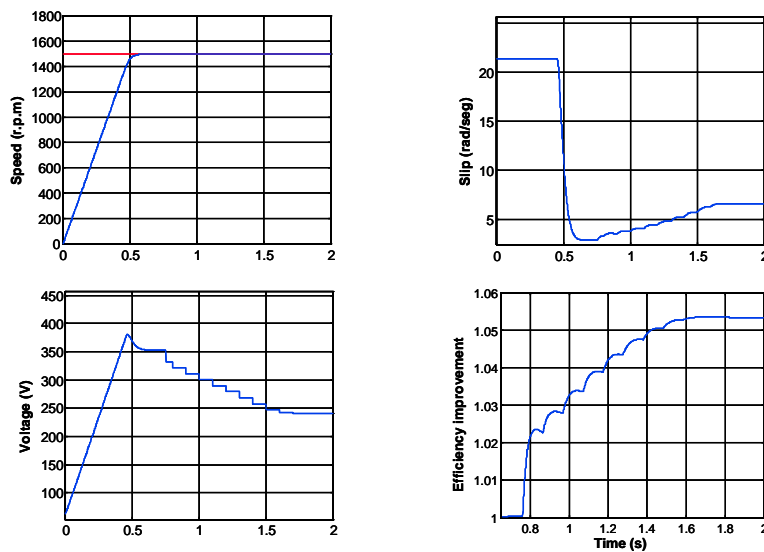

Figure 3.   Efficiency optimization process: (a) Speed; (b) Slip; (c) Voltage; (d) Efficiency Improvement.

5. Fuzzy and PI Slip Controllers Comparation

Figure 4 compares simulation results of the fuzzy slip controller and of a PI with antiwindup controller [11]. Note that it is not possible to tune a conventional PI controller because of the slip limitation. This figure shows both controllers behaviour during start-up and then in response to a sudden load change from zero to 100% of the nominal torque, for two different load inertia values, $J = 2.10^{-2}$ kg.m^2 and $J = 20.10^{-2}$ kg.m^2 . The PI controller parameters were optimized for the first inertia value using Matlab Non-Linear Control Design Toolbox.

The slip response when $J = 2.10^{-2}$ kg.m^2 is almost the same for both controllers, so the speed response (not showed) is equal to the two controllers in this condition. When the inertia is increased the controllers response become worse, but as can be concluded from the graphics, the PI controller dynamic response is more dependent on load inertia than the fuzzy controller, since the oscillations with PI increased more than with fuzzy.
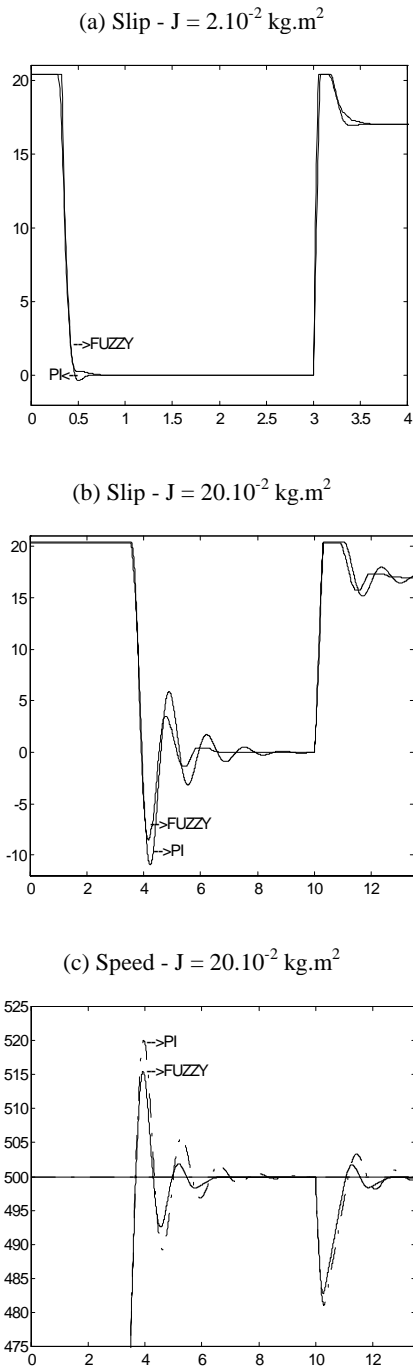
(a) Slip - $J = 2.10^{-2}$ kg.m^2

(b) Slip - $J = 20.10^{-2}$ kg.m^2

(c) Speed - $J = 20.10^{-2}$ kg.m^2

Figure 4. Fuzzy and PI controllers comparation.

6. Hardware Implementation Results

An 1 kW three-phase induction motor fed by a voltage source IGBT power module was used in the experiments. No fuzzy processors or any other specific hardware was used to implement the fuzzy logic controller. A standard Intel 80C196KC microcontroller performs the control algorithm and generates the PWM waveforms for the IGBT motor drive inverter. The control algorithm runs within a 5.1 ms loop (the same time used in the simulations sampling time). A digital implementation of sinusoidal pulse width modulation (SPWM) with harmonic addition to maximize the output voltage and minimize distortion is used [8, 12].

Implementation of the fuzzy controller made use of the fuzzyTech software tool to produce C code for the microcontroller. The generated code takes about 2.5 ms to run in the 80C196KC with a 16 MHz clock.

Figure 5 shows experimental results of the fuzzy logic controlled induction motor drive. The motor is started-up unloaded, and reaches the reference speed without overshoot. When time is nearly 1.7 s a nominal load torque is applied, and motor speed decreases 5.1% before the effective actuation of the fuzzy controller, that increases slip and recovers speed to the reference value.
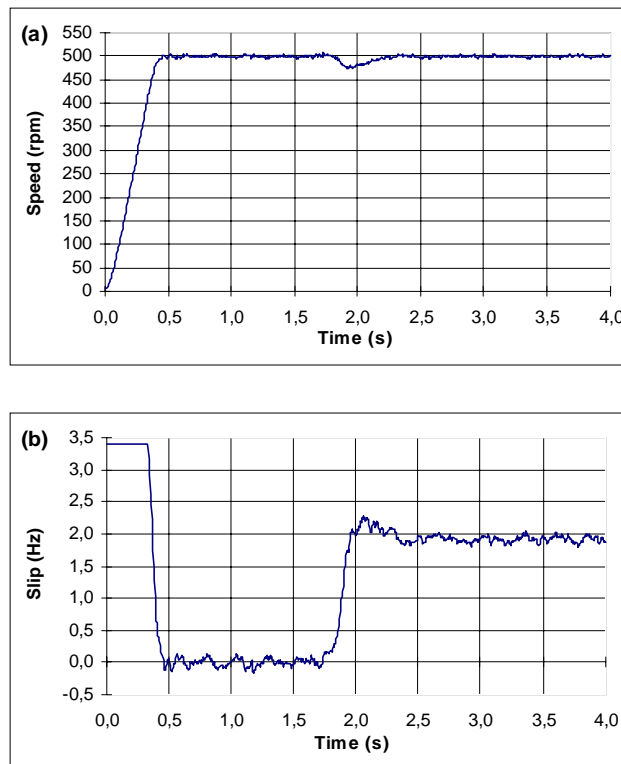

Figure 5. Experimental results: (a) Speed; (b) Slip.

7. Conclusions

An evaluation of fuzzy logic techniques applied to the control of a three-phase induction motor was presented. Matlab/Simulink was used for controller design and for simulation of the whole system.

It was showed a simple process for efficincy optimization of an induction motor through decreasing its voltage during steady state operation.

Simulation results confirmed a slightly superior dynamic performance of fuzzy logic control against a more conventional scheme (PI with antiwindup controller), namely in terms of insensitivity to changes in model parameters.

Experimental results confirm the utilisation feasibility of standard hardware (80C196KC microcontroller) to the implementation of fuzzy logic controllers in fast processes, such motor control.

References

[1] René Jager, "Fuzzy Logic in Control", PhD Thesis, Delft University (Holland), 1995.

[2] Jerry M. Mendel, "Fuzzy Logic Systems for Engineering: A Tutorial", Proceedings of the IEEE, Vol. 83, No. 3, pp 345-377, 1995.

[3] G. C. Sousa, B. K. Bose and J. G. Cleland, "Fuzzy Logic Based On-Line Efficiency Optimization Control of an Indirect Vector Controlled Induction Motor Drive", IEEE Trans. Ind. Electronics , vol. 42, no. 2, pp. 192-198, April 1995.

[4] G. C. Sousa and B. K. Bose, "A Fuzzy Set Theory Based Control of a Phase-Controlled Converter DC Machine", IEEE Trans. Ind. Applicat., vol. 30, no. 1, pp. 34-44, Jan./Feb. 1994.

[5] P. Guillermin, "Fuzzy Logic Applied to Motor Control", IEEE Trans. Ind. Applicat., vol. 32, no. 1, pp. 51-56, Jan./Feb. 1996.

[6] S. A. Mir, D. S. Zinger and M. E. Elbuluk, "Fuzzy Controller for Inverter Fed Induction Machines", IEEE Trans. Ind. Applicat., vol. 30, no. 1, pp. 78-84, Jan./Feb. 1994.

[7] Jaime Fonseca, João L. Afonso, Júlio S. Martins, Carlos Couto, "Evaluation of Neural Networks and Fuzzy Logic Techniques Applied to the Control of Electrical Machines", Proceedings of the Mechatronics'96, July 1996.

[8] J. S. Martins, "Controlo de Velocidade do Motor de Indução Trifásico", PhD Thesis, Minho University (Portugal), 1993.

[9] C. Couto and J. S. Martins, "Control of a Voltage Source Inverter Fed Induction Motor with On-Line Efficiency Optimization", IEEE ICIT'94, Guangzhou, China, 1994.

[10] J.-S. Roger Jang and Ned Gulley, "Fuzzy Logic Toolbox For Use with MATLAB", The Math Works, Inc., 1995.

[11] Karl J. Astrom, "Computer Controlled Systems", Prentice-Hall, 1990.

[12] J. A. Houldsworth and D. A. Grant, "The Use of Harmonic Distortion to Increase the Output of a three-Phase PWM Inverter", IEEE Trans. Ind. Applicat., IA-20, Set./Out1984.