Fuzzy logic based Improvements in Efficiency Optimization of Induction Motor Drives

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Abstract

Induction motor are, without any doubt, the most used in industry. Motor drive efficiency optimization is important for two reasons: economic saving and reduction of environmental pollution. In this paper, advantages of using fuzzy logic in steady-state efficiency optimization for induction motor drives are described. Experimental results of a fuzzy logic based optimum flux search controller are presented. For transient states, a new original idea is introduced: a fuzzy logic based controller, actuating as a supervisor, is proposed to work with reduced flux levels during transients to optimize efficiency also in dynamic mode. Two different rule tables are designed, for torque transitions and for reference speed changes. With this controller, efficiency can be improved in transients, and also search controller convergence speed is increased. Experimental results with a 1.5 kW induction motor drive demonstrate the validity of the proposed methods.

1. Introduction

It is estimated that more than 50% of the world electric energy generated is consumed by electric machines [1]. Improving efficiency in electric drives is important, mainly, for two reasons: economic saving and reduction of environmental pollution [2], [3].

Induction motors have a high efficiency at rated speed and torque [4]. However, at light loads, iron losses increase drastically, reducing considerably efficiency [5].

The main induction motor losses are usually split into 5 components: stator copper losses, rotor copper losses, iron losses, mechanical and stray losses. To improve the motor efficiency, the flux must be reduced, obtaining a balance between copper and iron losses [6].

Basically, there exist two different approaches to improve efficiency [7]:

A. Loss Model based approach

If a motor loss model is available [7], [8], [9], the loss minimization optimum flux is computed analytically. The main advantage is the simplicity of this method, not requiring extra hardware. However, it is mandatory an accurate knowledge of motor parameters, which change considerably with temperature, saturation, skin effect, etc.

B. Power Measure based approach

An optimum flux search algorithm is used, and the drive power consumption is measured [2], [7], [10], [11], [12]. Obviously, this approach does not require the knowledge of motor parameters. However, it is only efficient at steady-state condition and with high powers the method has convergence problems.

In this work, advantages of using a fuzzy logic based search controller to optimize efficiency at steady state are described [2]. For transients, a fuzzy logic based controller, actuating as a supervisor, is proposed to optimize efficiency with reduced flux levels in dynamic mode. Experimental results with an indirect field oriented control are obtained using a standard 1.5 kW induction motor at our laboratory.

2. Philosophy of search controllers

At steady state, the input power of an induction motor drive is a flux dependent convex function. The philosophy of search controllers is to decrease the motor flux as a function of the power consumption until the minimum loss point is found (point A in Fig. 1), obtaining a balance between copper and iron losses.

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Figure 1 shows the experimental results obtained using this approach with an indirect field oriented control for a 1.5 kW induction motor drive. At steady state, (speed and torque constant), the flux current i_{sd}^{*} is decreased gradually, while the torque current is increased, until the optimum flux is found.

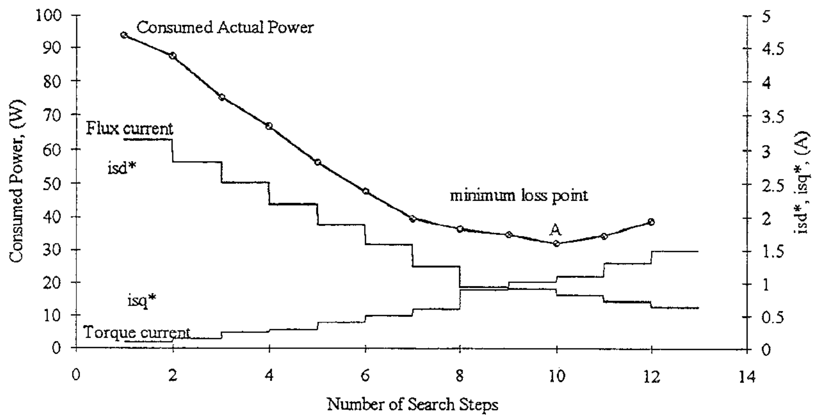

Figure 1. Philosophy of search controllers Experimental results at 25% rate speed with no load.

3. Experimental equipment

The experimental equipment (Fig. 2) used in the implementation consists of a power converter and a 1.5 kW induction motor. The rectifier is based on power diodes and the three-phase inverter is a MOSFET current-controlled voltage converter. The induction machine is coupled to a DC generator with an electronic load, working as brake.

The power measurement is done at the drive input, sampling ac voltage and current with a transformer and a Hall-effect current sensor, respectively. A software routine computes the consumed power with a digital average. An 80486 microprocessor, running at 66 MHz, is the control computer.

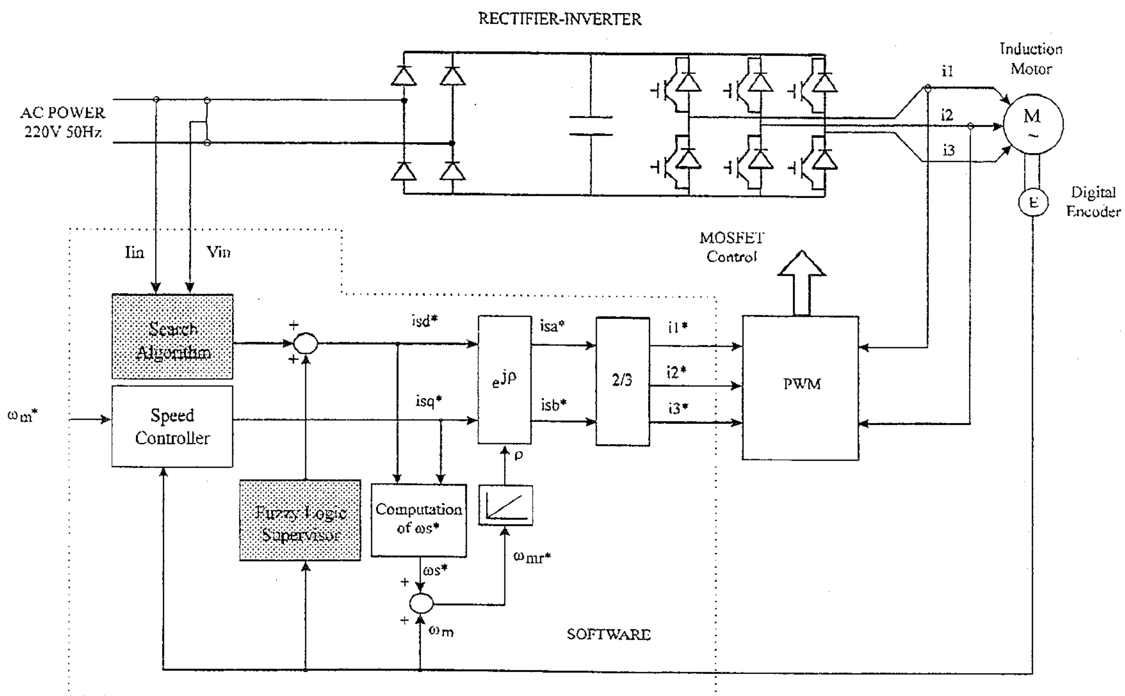

Fig. 2. Indirect vector-controlled induction motor drive with a search controller and a fuzzy logic based supervisor to optimize efficiency at steady state and dynamic mode.

4. Fuzzy logic applied to search controllers

There exist many search algorithms to optimize efficiency for induction motor drives using the power measure based approach [13]. Their main limitations are speed of convergence, perturbations in the electromagnetic torque and oscillations around the optimum flux.

Fuzzy logic can help avoid these problems, improving the performance of the search controller. This idea of using fuzzy logic for search controllers was recently reported in [2].

The FL controller antecedents are the power change ΔP_n and the last flux current change $\left(\Delta i^*_{sd}\right)_{n-1}$ and the consequent is the new flux change $\left(\Delta i^*_{sd}\right)_n$.(see [2] for more details).

$\Delta P_n \backslash \left(\Delta i^*_{sd}\right)_{n-1}$	N	P
PB	PM	NM
PM	PS	NS
PS	PS	NS
ZE	ZE	ZE
NS	NS	PS
NM	NM	PM
NB	NB	PB

PB: Positive Big
PM: Positive Medium
PS: Positive Small
ZE: Zero
NB: Negative Big
NM: Negative Medium
NS: Negative Small

Table 1. Fuzzy rules to find the optimum flux (output $\left(\Delta i^*_{sd}\right)_n$).

With this mentioned controller, some improvements may be obtained (see Figs. 3.a, 3.b). First, the speed of convergence increases due to the adaptive size of the flux steps imposed to the machine. Moreover, when we are approaching to the optimum flux, the step size is reduced drastically, avoiding unnecessary movements around the minimum loss point.

Finally, the fuzzy logic based search is infinitum, i.e., the algorithm is always working, avoiding deviations of the optimum flux due to motor parameter changes by temperature effect, and so on.

It can be demonstrated that the fuzzy logic based search method consists of a gradient based search [13] with adaptive flux steps and infinitum search with non-null flux step around the minimum loss point.

The only drawback of this approach is that the search controller requires adjustable gains (speed and torque dependent), which depend on the motor power.

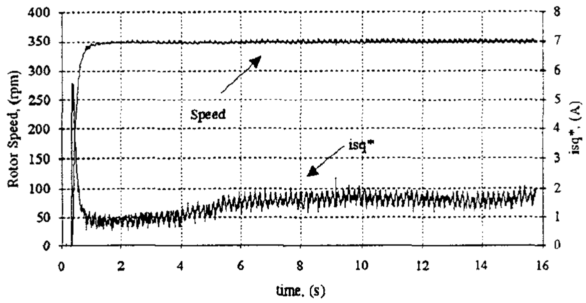

Fig. 3.a. Rotor speed and reference torque current i^*_{sq} evolution. (Experimental results using the FL search controller).

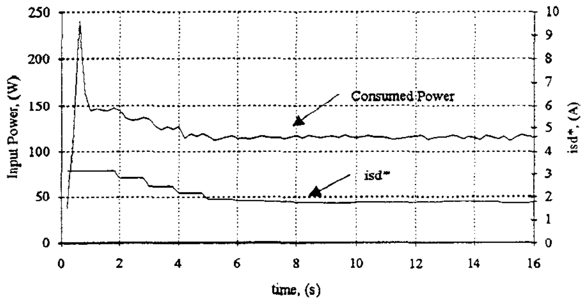

Fig. 3.b. Consumed input power and reference flux current i^*_{sd}.(Experimental results using the FL search controller).

5. Fuzzy logic applied to efficiency optimization in transients

So far, we have been only considering optimization at steady-state condition. The above fuzzy logic based search controller is only effective with constant speed and torque. When a torque perturbation or command speed change is produced, the search process stops. All the works in recent literature [2], [10], [11], [12] propose to establish the rated flux during a dynamic transition. This permits to have the maximum torque capability in order to get the optimum transient response.

However, the transient torque and speed response may not be so important for some practical applications (it is the case of an elevator or a crane). For example, if the process has many small load torque perturbations. In these cases, efficiency optimization can take priority. In this paper, we propose to work with reduced flux levels during dynamic transitions, optimizing power in the dynamic mode and accelerating the search process at steady state. For this, a fuzzy logic controller, actuating as a supervisor, is designed. During transients, the controller increases the flux, depending on the speed error and its derivative. If the transient is very large or the speed error is very large, the flux is established at rated level, in order to let the drive track the reference command.

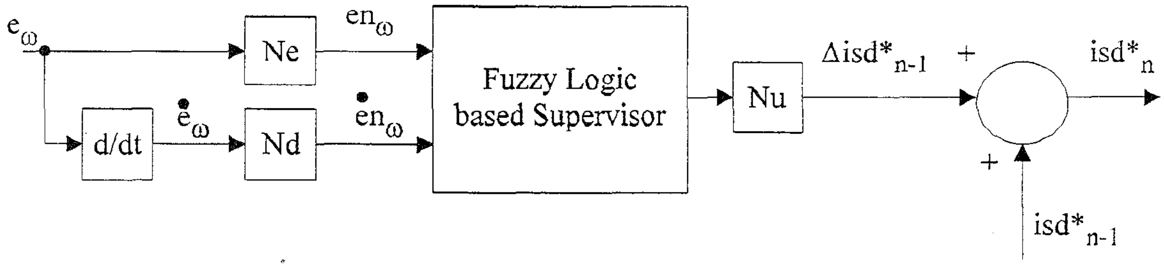

Fig. 4. Diagram of the proposed fuzzy logic supervisor to increment the flux current.

The proposed controller is very simple, containing two tables of heuristic rules, distinguishing a torque transition and a reference speed change. The controller only provides positive flux increments, actuating as a supervisor, since it supervises the right command tracking, incrementing the flux if necessary.

The antecedents are the speed error e_ω and its derivative $\dot{e}_\omega$ and the consequent is the flux current increment Δi^*_{sd} (Fig. 4). Table 2 and 3 shows the rules for a positive torque transition and for a positive reference speed change, respectively.

$e_\omega \backslash \dot{e}_\omega$	**ZE**	**PS**	**PM**	**PB**
ZE	ZE	ZE	PS	PM
PS	PS	PS	PM	PB
PM	PM	PM	PB	PB
PB	PB	PB	PB	PB

Table 2. Rules for a positive torque transition.

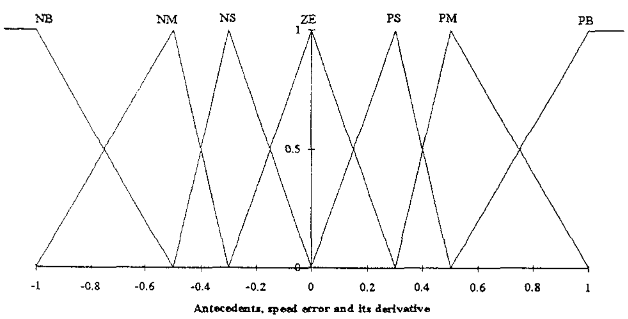

Fig. 5. Membership functions for the antecedents.

$e_\omega \backslash \dot{e}_\omega$	**NB**	**NM**	**NS**	**ZE**
ZE	ZE	ZE	ZE	ZE
PS	ZE	ZE	PS	PB
PM	PS	PS	PM	PB
PB	PS	PM	PM	PB

Table 3. Rules for a positive reference speed change.

The product-sum was used as inference method and the center of gravity was implemented as defuzzification method to get a fast algorithm in real time.

Figures 7, 8, 9, 10 show the advantages of using the fuzzy logic supervisor during a torque transition. As can be seen, efficiency during the transient is improved considerably, although the transient speed response is not so good and fast (Fig. 8).

During the transient due to a change in speed command (Figs. 11, 12), energy can also be optimized (Figs. 13, 14) by using the fuzzy logic supervisor, demonstrating the validity of the proposed method for transients.

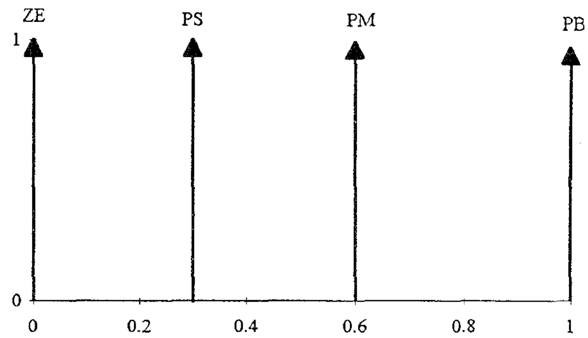

Fig. 6. Membership functions for the consequent.

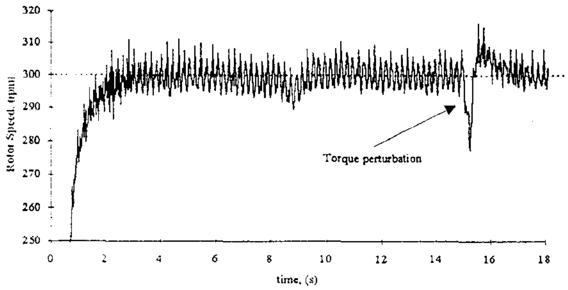

Fig. 7. Speed evolution with a torque perturbation using rated flux in the transition.

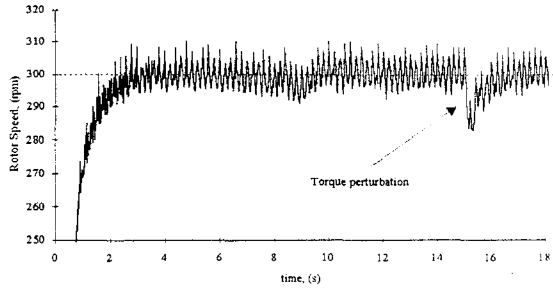

Fig. 8. Speed evolution with a torque perturbation using reduced flux in the transition.

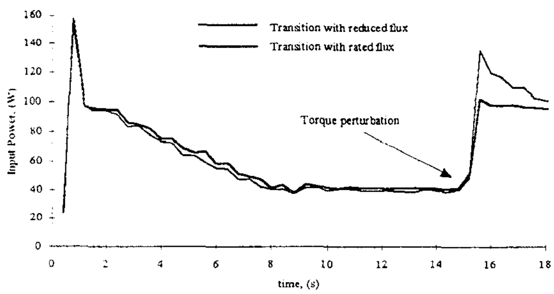

Fig. 9. Comparison of consumed power with rated and reduced flux during the torque transition.

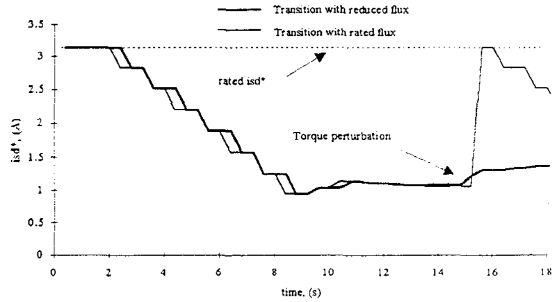

Fig. 10. Reference flux currents for the torque transition (Figs. 7, 8, 9).

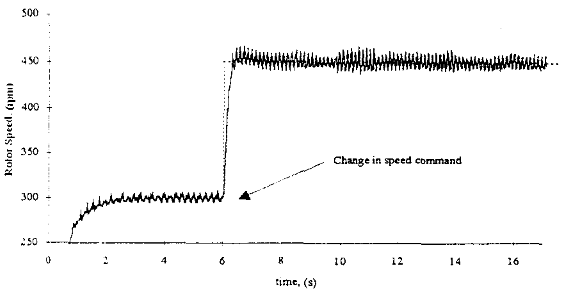

Fig. 11. Speed evolution with transition at rated flux.

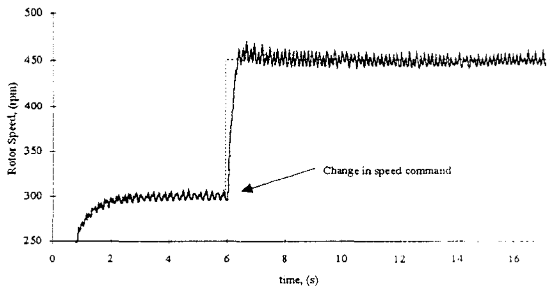

Fig. 12. Speed evolution with transition at reduced flux.

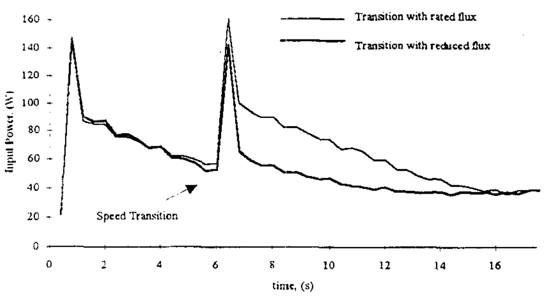

Fig. 13. Comparison of consumed power for the speed transition with rated and reduced flux.

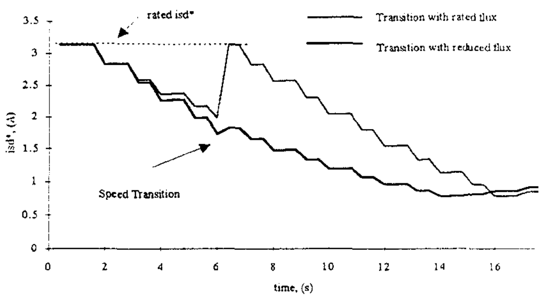

Fig. 14. Reference flux current i_{sd}^{*} for the speed transition (Figs. 11, 12, 13).

6. Conclusions

In this work, advantages of using fuzzy logic in efficiency optimization for induction motor drives have been described.

A fuzzy logic based search controller improves the speed of convergence and reduces oscillations around the optimum flux using a simple rule table. However, the controller requires adjustable speed and torque gains, which depend on the motor power.

A new fuzzy logic based controller, actuating as a supervisor has been proposed to optimize efficiency during transients. Two different rule tables have been designed for torque transitions and for reference speed changes.

Experimental results of the proposed controllers with a 1.5 kW induction motor drive demonstrate the validity of the described methods.

Present research is focused on how to design an autonomous efficiency controller, using the energy consumed in a mechanical cycle to adjust the controller gains, in order to get the optimum response from the point of view of efficiency. And important open question is how to quantify the benefits of the proposed solution for all operation points of the machine. And obviously, the compromise between efficiency optimization and a good dynamic response always depends on the kind of application.

Acknowledgments

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