

Fuzzy Logic Control for Motor Flux Reduction during Steady states and for Flux Recovery in Transient states of Indirect-FOC AC Drives

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Abstract – The aim of this paper is to present a new fuzzy control scheme for real time drive efficiency improvement by the adaptive flux reduction at light loads during steady states and by the optimum flux recovery during transient states. The optimum flux recovery instead of the rated flux does not sacrifice the drive dynamic response since the torque capacity remains the same and accelerates the search convergence in steady states. The control scheme is cooperated with an Indirect-Field-Oriented-Control (IFOC) motor drive. The design of the new fuzzy control scheme is focused to recognize the motor state operation in order to control under the corresponding circumstances. The proposed fuzzy control scheme includes three main units: one Fuzzy-Logic-Search Controller FLSC1, one Fuzzy-Logic-Controller FLC2 and a State detector unit. The State detector unit decides which of the FLSC1 or FLC2 controllers is used, in accordance to the operation circumstances. The fuzzy controllers utilize the stator flux-producing current component into d-q reference frame (stator current direct axis i_{sd}) as control variable, in order to estimate the next optimal change of Δi_{sd} . The drive efficiency improvement and the drive dynamic response is currently validated in laboratory using an experimental array of a 3-phase 1 Hp induction motor drive. The control scheme is implemented using the platform eZdsp from Digital Spectrum based on the fixed point 32 bit DSP TMS320F2812 from TI.

Index Terms—Efficiency, FOC, Flux control, Fuzzy logic controller, Indirect FOC, Loss Minimization, Motor control, Search controller, steady state, transient state.

I. INTRODUCTION

Loss minimization of the motor drive's controllable losses (magnetic energy of the motor and the power dissipated by the stator and rotor resistances) is important because the energy saving achieves economic account, imposes the motor to operate at lower temperatures resulting in a longer life span and meets the environmental pollution prevention standards. In many industrial drive applications the motor does not operate at the nominal point since the load may change. Motor efficiency is maximal only when the drive operates at its nominal operating point. Below this point (light load conditions), the excessively stored energy in the coil inductances unnecessary decreases the motor efficiency due to the unbalanced copper and iron motor losses. The drive efficiency during light load operation can be improved by the optimum air-gap flux level adjustment in accordance with the torque and speed demand

of the motor drive. Minimizing the controllable losses has two important effects: one is to minimize the magnetic energy that corresponds to maximizing the power factor, and the other is to minimize the coil losses that increase motor efficiency. The problems that arise at light load operation are how to achieve the minimum time response (i.e., a minimum speed drop) if a sudden load change takes place and how to minimize the duration of an acceleration transient after step speed command increase [1]. To implement the above flux reduction, the motor should be fed through an inverter with an electronic control system which uses optimization algorithms.

In 1999 [2], in 2000 [3] and in 2009 [4] report the main approaches for loss minimization control. In [2], an extensive overview with over 100 references specifies that the loss minimization algorithms can be classified into three different types: The first is called “loss model controller” (LMC), the second type is named “search controller” (SC), and the third one uses “look up tables”. The SC idea is to decrease the motor flux as a function of the power consumption, until a minimum loss point is found. The SC is only effective during steady state operation under constant speed and constant torque conditions, because only in steady state the input power is a flux depended convex function. When a transient change is occurred the search process stops and rated flux is established. This solution is recommended by the majority of the researchers, as proved by the bibliography.

The latest investigations in SCs use Fuzzy or neuro-fuzzy algorithms in the optimization algorithm, instead the traditional search algorithms such as: Rosenbrock method, Fibonacci, Golden section, Gradient, Proportional method. The use of fuzzy logic in SCs (FLSCs) the recent years indicates by experience that these controllers can perform high performance in motor drives applications, that they provide high degree of accuracy without the need of detailed mathematical models, that they can be cost effectively implemented and that they allow rapid implementation of complex fuzzy logic controllers (FLCs) into low-cost modern digital signal processors (DSPs) [5].

A Loss minimization controller can be cooperated with an adjustable speed motor drive in various ways, depending on how the motor drive application is speed controlled. The different speed control implementations include scalar voltage or scalar current technique (V/Hz control), field oriented current control (FOC), which is also known as vector control technique and direct torque control (DTC). The FOC technique gets over the limitations of V/Hz technique by decoupling the torque and magnetizing flux, i.e. at low speeds the magnetization can be maintained at the proper level, and the torque can be controlled to adjust the speed. In comparison with the FOC and V/Hz speed control techniques, the DTC technique has good dynamic performance but shows quite poor performance in steady-

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state due to high level of torque and flux ripples. The FOC is an attractive control method but it has a serious drawback: it relies heavily on precise knowledge of the motor parameters. The rotor time constant is particularly difficult to measure precisely, and it varies with temperature.

The FOC control variants are established as the most popular used in high performance industrial applications. The goal of FOC is to maintain the amplitude of the rotor flux linkage Ψ_r at a fixed value, except for field-weakening operation or flux optimization, and only modify a torque-producing current component in order to control the torque of the ac motor [6]. FOC control operates by measuring and adjusting the stator currents in order to keep the angle between the stator flux and rotor flux as close to 90° as possible. Instead of attempting to control the three phases that power the stator independently, FOC maps them as a single space vector and runs that quantity through several mathematical transforms (Park, Clarke and inverse Park transform). These real time mathematical transformations must be carried out very quickly by high performance processing capability of computer engines (e.g. modern DSPs, FPGAs). The FOC speed control technique, in a sense, imitates the DC motor's operation because its goal is to be able to separately control the torque producing and magnetizing flux components. The knowing of motor parameters, especially rotor time constant, is very important in order to achieve the FOC control.

Literature distinguishes two types of FOC technique, the Direct- and the Indirect-FOC control (IFOC). In the case of the Direct FOC control the rotor flux is directly estimated using the measurements of the terminal voltages and currents. In the case of the IFOC control the slip is estimated using the motor model in FOC condition and the rotor flux angle is recalculated from the integration of estimated slip and measured rotor speeds. In case of induction machines, the indirect method is based on reconstruction (estimation) approaches employing terminal quantities such as voltage and currents in a motor model to calculate the flux position. IFOC does not have inherent low-speed problems and is therefore preferred in most applications.

Back in 2000, Z. Zhu, Y. Chen, D. Howe [7], optimized the flux during steady states and improved the transient dynamic performance by reducing the time step when searching for the optimal magnetizing current (using vector control based on optimal current profiles).

In 1996-97 and 2006, M. Cipolla [8], J. Moreno, J. Paracaula [9], and E. Sergaki, G. Stavrakakis [10] respectively, introduced efficiency optimization during transient states using fuzzy controllers in order to recover the motor flux. In [8-10] the dynamic speed response is deteriorated more or less due the delay to recover the wanting flux.

In 2005 Liao, J.C. Yeh, S.N. Hwang, J.C. Huang, T.M., [11], improve the motor efficiency by reduced flux during steady and transient states, without scarifying the motor dynamic response.

In 2006 C.M. Vege, J.R Arribas and D. Ramirez [12] propose the application of Pontryagin's maximum principle in order to improve the efficiency of Induction motors during transient states.

In 2008, our previous work [13] proposes a fast efficiency control scheme suitable for various types of motors, which combines the fast operation characteristic of an LMC during transient states and the precise advantage of a Fuzzy Logic

SCs (FLSCs) system. In 2009, our work [14] improves the Hybrid Efficiency Control system proposed from [13], during transient and steady states. For many industrial control applications the efficiency improvement during transient motor operation (torque or speed transitions) is very important because they represent an important part of the total motor operation. In cases such as cranes, elevators, electric vehicles, the energy losses minimization during transient states can be of extreme importance. In our present work, is proposed a fuzzy real time control scheme which reduces motor flux levels during steady operation, while during transitions the flux is recovered to an optimum value (lower or equal than the rated), in order to optimize the power input consumption, to accelerate the search process during steady states, and to maintain the drive dynamic response on acceleration and deceleration mode. For low load torque operation the air-gap flux is reduced in constant torque operation and for high speed operation in the constant power region. The proposed fuzzy based control scheme is incorporated into an adjustable speed drive (ASD) which utilizes Indirect FOC control. The design of the parameters of the new fuzzy control scheme is focused on the concept to recognize the motor state operation (steady or transient) and to adjust the motor flux under the corresponding circumstances. The flux is reduced during steady operation depending of the minimization of the power losses measurement and is increased during transient operations depending on the measurements of speed and load torque.

II. FUZZY LOGIC OPTIMUM FLUX ADJUSTMENT

The proposed fuzzy control scheme utilizes the flux-producing current component into d-q reference frame (stator current direct axis i_{sd}) as a control variable, in order to estimate the optimal rate of Δi_{sd}^* . This approximate optimal solution implies time-varying rotor flux norm operation as reference input into a IFOC drive, in opposition to the classical IFOC that operates with constant rotor flux norm.

During transient states operation the flux is recovered in a value lower or equal to the rated value. In each sample period, after the value of power losses P_L and the value of torque reference T_{em}^* are calculated by PI controllers, the appropriate fuzzy controller is used to determine the optimum field current step change Δi_{ds} . After that the vector controller generates the terminal voltage, using the space vector modulation, and the switching signals are produced to control the inverter. The structure of the proposed fuzzy control system is shown in Fig. 1. It combines three units: the "FLSC1", the "FLC2" and the "State detection" unit.

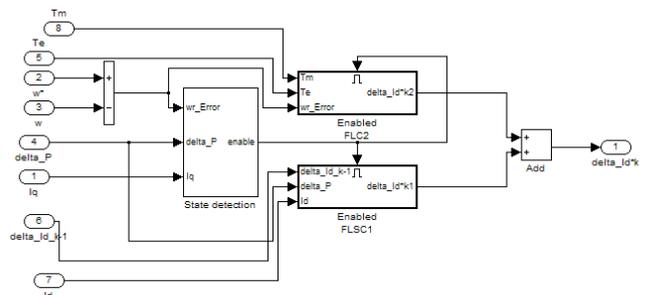


Fig. 1. Simulink model of the fuzzy control system included in Fig. 2.

The "State detection" block recognizes the motor state operation (steady or transient) and by the current values decides which of the "FLSC1" or "FLC2" blocks will be

used, by using the following conditions

If $|\Delta\omega[k]| \leq \alpha$ and $|\Delta P_L[k]| \leq \beta$ then steady state

If $|\Delta\omega[k]| > \alpha$ or $|\Delta P_L[k]| > \beta$ then transient state

If $|i_{qs}[k]| \leq \gamma$ then is under light load condition

where α, β, γ are the thresholds of speed error, of power loss variation and of the torque producing current component.

As shown in Fig. 2, the Simulink block labeled as “delta_Id Fuzzy Calculation” includes the fuzzy system of the Fig. 1. The fuzzy controllers have one linguistic control (output) variable, the step change of the flux (d- axis) current component of the stator current. The fuzzy rules are based of seven linguistic values presented in Tables I and II.

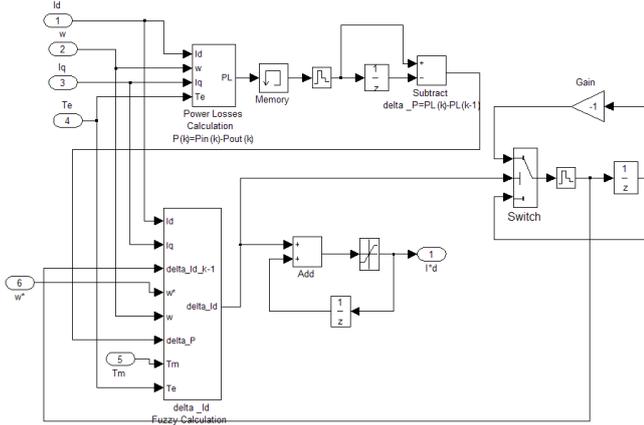


Fig. 2. The Simulink model of the fuzzy-logic control system, includes a unit for the power loss calculation labeled as “Power Losses Calculation $P(k)=P_{in}(k)-P_{out}(k)$ ” and the fuzzy system labeled as “delta_id Fuzzy Calculation”. The above model is included in the block labeled as “I*d(k) Fuzzy Calculation” in Fig. 3.

A. Fuzzy Logic Search Controller for Optimum Flux Reduction during Steady state

The fuzzy block “FLSC1” shown in Fig. 1, is used during steady state operation, using the sign and the step of power losses decrement $\Delta P_L[k]$ and the last change of the flux producing current component $\Delta i_{sd}[k-1]$ as state variables.

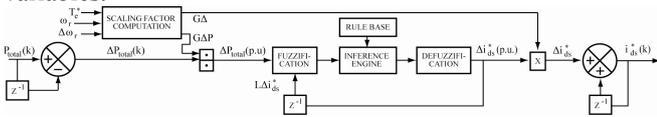


Fig. 3. The fuzzy search controller FLSC1 adjusts i_{sd}^* during steady states.

The “FLSC1” utilizes the adaptive step changes of flux-producing current component into d-q reference frame (stator current direct axis i_{sd}) Δi_{sd}^* as a control variable, in order to estimate the optimal field current i_{sd}^* .

$$\Delta P_L[k] = P_L[k] - P_L[k-1] \quad (1)$$

$$\text{sign}(\Delta P_L[k]) = \begin{cases} -1 & \Delta P_L[k] \leq 0 \\ 1 & \Delta P_L[k] \geq 0 \end{cases} \quad (2)$$

The power losses ΔP_L are estimated by a PI controller while flux is tuning as the difference between the input and output power

$$P_L[k] = P_{in}[k] - P_{out}[k] \quad (3)$$

$$P_{out}[k] = \omega[k] T_{em}^*[k] \quad (4)$$

$$P_{in}[k] = V_{DC} I_{DC}[k] \quad (5)$$

where the V_{DC} and I_{DC} are the feedback signals of DC-link voltage and current, the ω is the mechanical speed. The current I_{DC} can be direct measured in the DC-link. The Speed ω can be measured or estimated.

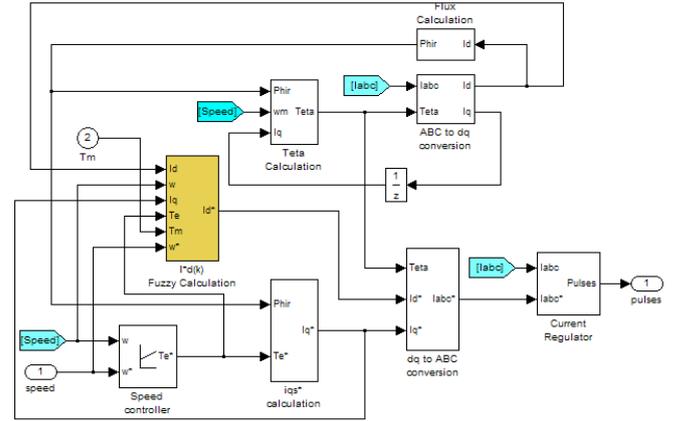


Fig. 4. The Simulink model of the fuzzy-logic control scheme, labeled as “I*d(k) Fuzzy Calculation”, is incorporated into an IFOC speed control drive. The following steps are applied:

- Measure the motor quantities (phase voltages/currents, speed and load torque)
- Calculate required power to produce load torque
- Compare input power to previous input power
- Transform them to the 2-phase system (α, β) using a Clarke transformation
- Calculate the rotor flux space vector magnitude and position angle
- Transform stator currents to the d-q coordinate system using a Park transformation
- The change rate of the stator current flux- (i_{sd}) producing component is estimated from the fuzzy system
- The output stator volt is calculated by the decoupling block
- An inverse Park transformation transforms the stator volt back from the d-q coordinate syst. to the 2-phase system fixed with the stator
- Using the space vector modulation, the output 3-phase voltage is generated.

The universe of discourse for the ΔP_L state variable and the control variable Δi_{sd}^* is scaled and limited into the range $[-1, 1]$ and is divided into seven overlapping fuzzy sets. The universe of discourse for the $\Delta i_{sd}[k-1]$ state variable is scaled and limited into the range $[-1, 1]$ and is divided into two overlapping fuzzy sets. The grade of membership distribution is described in Table I.

The adjustable gains, power gain $G\Delta P$ and the current gain $G\Delta$ are calculated by the scaling computation block, and convert the state and control variables, respectively, to per unit values, such that a single fuzzy rule base can be used for any torque and speed condition. The state gain $G\Delta P$ is calculated as a function of motor speed ω as G. Sousa and B. Bose [15]

$$G\Delta P = b_1 \omega + b_2 \quad (6)$$

The power variation is scaled by a power gain as follows

$$\Delta P_L[k] = \Delta P_L[k] / G\Delta P \quad (7)$$

The control gain $G\Delta$ is calculated from the motor speed ω and the estimated i_{sq} and i_{sd} [11]

$$G\Delta = c_1 |i_{sd}^* - i_{sq}^*| - c_2 T_{em}^* + c_3 \quad (8)$$

$$\Delta i_{sd}^*[k] = \Delta i_{sd}^*[k] G\Delta \quad (9)$$

where the b_1, b_2, c_1, c_2, c_3 are designed by simulation study in advance.

TABLE I

REASONING RULE TABLE – BASE OF FLSC1

$\Delta P_L[k] \setminus \Delta i_{sd}^*[k-1]$	-1.00	1.00
-1.00	NB	PB
-0.50	NM	PM
-0.30	NS	PS
0.00	Z	Z

0.30	PS	NS
0.50	PS	NS
1.00	PM	NM

The fuzzy values of the control variable Δi_{sd}^* are: NB=-1.00, NM=-0.70, NS=-0.40, Z=0.00, PS=0.40, PM=0.70, PB=1.00.

B. Fuzzy Logic Controller for Optimum Flux Recovery during Transient State

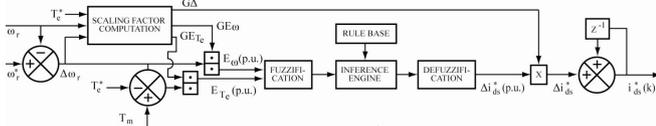


Fig. 5. The fuzzy controller FLC2 adjusts i_{sd}^* during transient states.

The fuzzy block ‘‘FLC2’’ is shown in Fig. 1. The universe of discourse of each of the state variables of the FLC2 is scaled and limited into the range $[-1, 2.1]$ and is divided into seven overlapping fuzzy sets. The grade of membership distribution is described in Table II.

TABLE II
REASONING RULE TABLE – BASE OF FLC2

E_d/E_T	-0.85	-0.60	-0.30	0.00	0.75	1.45	2.10
-0.85	L	XXL	XXXL	XXXXL	XXXXL	XXXXL	XXXXL
-0.60	S	L	XXL	XXXL	XXXXL	XXXXL	XXXXL
-0.30	XS	L	XL	XXL	XXXL	XXXXL	XXXXL
0.00	XS	L	XL	XXL	XXL	XXXL	XXXXL
0.75	XXS	S	M	L	XL	XXL	XXXXL
1.45	XXS	S	S	M	L	XXL	XXXXL
2.10	XXS	XS	XS	M	L	XXL	XXXXL

The fuzzy numbers of the linguistic control variable Δi_{sd}^* are: XXL=0.97, XL=0.87, L=0.64, M=0.55, S=0.45, XS=0.38, XXS=0.29.

The FLC2 is used during transient states, using the difference between the estimated motor torque and the measured load torque as first state variable,

$$\text{Torque_Error} = T_{em}^* - T_m \quad (10)$$

The estimated torque T_{em}^* is estimated from a PI controller from the reference between the speed ω^* and the feedback motor speed ω . The T_m is measured by a torque meter on the motor shaft. The difference between the reference speed and the measured speed is the second state variable

$$\text{Speed_Error} = \omega^* - \omega_m \quad (11)$$

C. The Proposed Fuzzy control System into an IFOC drive

The classical IFOC operates with constant reference stator flux norm. In IFOC control of induction motor drives, the stator phasor currents i_s of the induction motor are transformed into the stator reference frame α, β as components $i_{s\alpha}$ and $i_{s\beta}$, are calculated with a Clarke transformation. Because the stator reference frame is rotating at a rate equal to the angular frequency of the phase currents, the components $i_{s\alpha}$ and $i_{s\beta}$ depend on time and speed, so they are not suitable for the control process, so sequentially they are transformed via Park transformation, from the stator reference frame to the d-q reference frame rotating at the same speed as the angular frequency of the phase currents. The i_{sd} and i_{sq} components do not depend on time and speed. The component i_{sd} is called the direct axis current component (the flux-producing component) and i_{sq} is called the quadrature axis current component (the torque-producing component). By utilizing transformation to the d-q

coordinate system, whose direct axis d- is aligned with the rotor flux space vector ϕ_r and the q- axis is perpendicular to the rotor flux, means that the q-axis component of the rotor flux space vector is always zero. The stator voltage components u_{sd} and u_{sq} cannot be considered as decoupled control variables for the rotor flux and electromagnetic torque. The direct axis component u_{sd} also depends on i_{sd} and the quadrature axis component u_{sq} also depends on i_{sq} . Considering the rotor-voltage equation of the squirrel cage machine in a reference frame which is fixed to the rotor flux [16], the Eq. (13) is exported.

$$\phi_{qr} = 0 \Rightarrow \frac{d}{dt} \phi_{qr} = 0 \text{ and } \phi_{dr} = \phi_r = L_m i_{ds} \quad (12)$$

$$\frac{d}{dt} \phi_{dr} + \frac{1}{\tau_r} \phi_{dr} - L_m \frac{1}{\tau_r} i_{ds} = 0 \quad (13)$$

where ϕ_{dr} , ϕ_{qr} are the flux- and torque- producing components of the rotor flux ϕ_r , $\tau_r = L_r/R_r$ is the motor time constant, L_m is the magnetizing inductance.

Equation (12) straightly relates the required d-axis component of the stator current, i_{ds} , to achieve a given rotor flux magnitude demand ϕ_{dr}^* .

In Fig. 3 is shown our proposed IFOC scheme. Two of the main units of the classical IFOC are replaced by our proposed fuzzy control system. The replaced units are: the unit which estimates the motor’s rotor flux, ϕ_r , based on motor model and the unit which uses the rotor flux reference, ϕ_r^* , to compute the stator current direct component i_{ds}^* required to produce the rotor flux in the motor.

The proposed control system is assumed to operate under a uniform sample rate. In each sample period, the error between the measured speed ω_m and the feedback motor speed is estimated by a PI controller that generates the estimated torque T_{em}^* . After the generation of the reference torque, and the calculation of the motor power losses the suitable fuzzy logic controller is chosen to determine the reference field current i_{ds}^* . The IFOC controller generates the terminal voltage, using the space vector modulation. The switching signals are produced to control the inverter.

III. SIMULATION AND EXPERIMENTAL RESULTS

The complete drive control system is discrete, is developed in Simulink model which is converted in C via Code Composer Studio (CCS), in order to be implemented using the platform eZdsp from Digital Spectrum based on the fixed point 32 bit DSP TMS320F2812 from TI. Due to limitations in the memory size (when Matlab is linked with CCS in the simulator mode), only 32 Kbyte data can be processed. The inverter DMC1500 is interfaced with the eZdsp. The fuzzy system is activated every 0.5 s. The tested motor is a 1Hp, 3x380 V, rated speed 1390 rpm. The motor drive is tested by simulations and experiments in order: (i) to validate the efficiency improvement of the proposed control method and (ii) to compare the response with a sudden load step for different methods (the proposed method with and without transient optimum flux recovery).

The following operations are tested: (i) The motor speed at $t=0$ s changes from 0 to 1(pu), under a constant load torque 0.1(pu). (ii) At $t=20$ s, is applied a torque step change from 0.1 to 0.7pu. (iii) At $t=40$ s is applied a step torque decrease from 0.7 to 0.1(pu).

A. Simulation Results

The simulations are executed in CCS environment, for C “floating-point”, and the TMS320F2812 eZdsp as computing engine. The appropriate coefficients b_1, b_2, c_1, c_2, c_3 , for the Eqs. (7), (9) are defined from simulation studies off-line [15], and are mapped in the memory. The simulation results are shown in Figs. 6, 7.

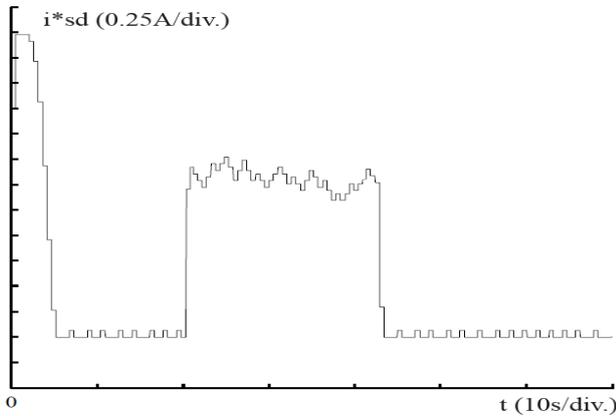


Fig. 6. Simulation result of the proposed control system of an 1Hp, 1390 rpm, 5.152 Nm, 3-phase motor. Field-producing component of the stator current under constant nominal speed 1pu and suddenly step load from 0.1 pu (0.088 Nm) to 0.7 pu (6.159 Nm).

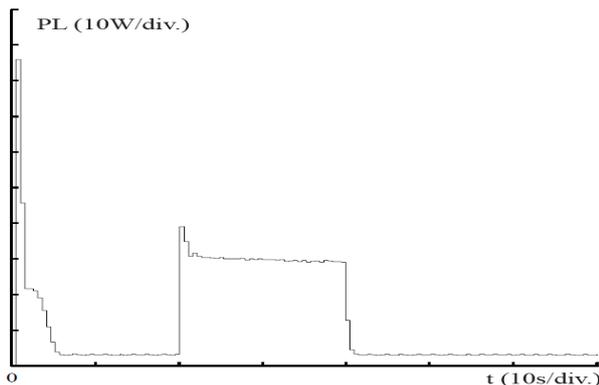


Fig. 7. Simulation result of the proposed control system. Power losses under constant nominal speed 1 (p.u) and suddenly step load from 0.1 (pu) to 0.7 (pu).

B. Experimental Results

For the experimental implementation, the necessary scale gains for the two fuzzy controllers, are experimentally derived, based on the patented method of Sergaki Eleftheria [17], upon the initialization of the device, by using a power meter (power analyzer) and a torque meter. This is achieved by firing up one fuzzy controller after another following the steps as explained below:

A power meter is connected to the input of the dc link power converter or to the input terminals of the motor. A torque meter is connected to the shaft of the motor.

A. The motor is set initially to operate into steady-state operation with pre-determined values for the load torque and the shaft speed, based on the type of application, i.e. load torque 0.02 p.u. and speed 0.5 p.u. In this pre-determined operation mode, the necessary scaling gains of the FLSC1 which controls the steady-state operation, are regulated manually with the method of trial-and-error, from the CCS “watch window” with continuous refresh feature, so that the power meter determines the minimum of electric power.

B. After a certain amount of time, as soon as the

temperature balance of the motor is restored, the motor is set into transient state operation, by varying the values of load torque in selected steps (i.e. from 0.2 to 0.4 p.u.), keeping the motor speed constant (i.e. 0.5 p.u.). In this pre-determined operation mode, the necessary scaling gains of the FLC2 which controls the transient state operation, are regulated with the method of trial-and-error, so that the torque meter determines the minimum torque variation.

C. After a certain amount of time, as soon as the temperature balance of the motor is restored, the motor is set into transient state operation, by varying the values of motor speed in selected steps (i.e. from 0.5 to 1.0 p.u.), keeping the load torque constant (i.e. 0.2 p.u.). In this pre-determined operation mode, the necessary scaling gains of the FLC2 are regulated with the method of trial-and-error.

D. All the above mentioned experimental adjustments of steps A. B. C. are repeated, after a certain amount of time, as soon as the temperature balance of the motor is restored, in order to calculate the optimum values of the necessary scaling gains of the fuzzy logic controllers by the software-based statistical data manipulation (i.e. the average) of the experimental values measured during this experimental adjustment repeat step.

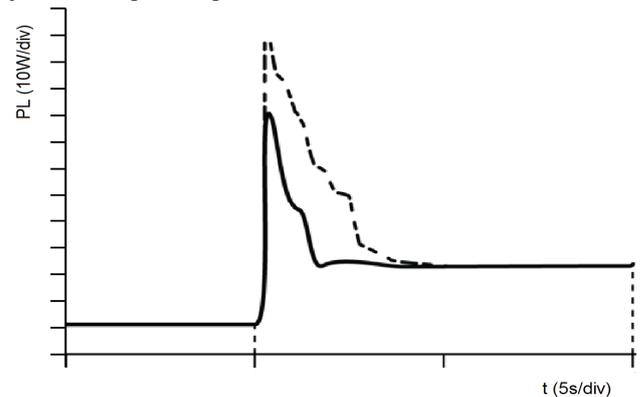


Fig. 8. Experimental results of the proposed control system validate the efficiency improvement. Power losses under constant nominal speed 1 (p.u) and suddenly step load from 0.1 (pu) to 0.7 (pu). Dot-line: At transition time the FLC2 is not activated, the stator current is recovered to its nominal value. Solid-line: At transition time the FLC2 is activated, the stator current is recovered to an optimal value lower to its nominal.

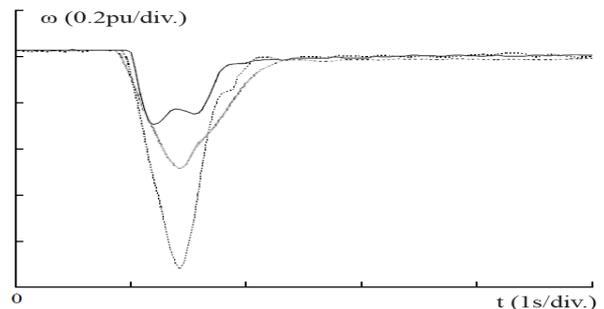


Fig. 9. Experimental result of the proposed control system. The motor speed response under constant nominal speed 1 (p.u) and suddenly step load from 0.1 (pu) to 0.7 (pu). The gray line presents the proposed control with rated flux recovery in transient state. The longer (dot line) presents the proposed control with optimum flux recovery in transient state. The solid line presents the proposed system without efficiency optimization (operation under rated flux).

The transient efficiency improvement is evident in Fig. 8 where the proposed control system is tested with and without efficiency improvement. At transient position, the power losses peak is 90 W (instead of 40 W in simulation results) lower. At steady state, the control converges to 35 W instead of 32 W in simulation results).

In Fig. 9 is shown the speed response at 1 (pu) under step torque application during the interval of the proposed control scheme (with transient optimum flux recovery) in comparison with the case without transient optimization (with transient rated flux recovery) and the case without efficiency improvement (rated flux). The Fig. 9 shows that the overshoot of speed response without efficiency improvement is better (lower and shorter convergence). The speed overshoot of the proposed method with flux optimum recovery in transient state is shorter and bigger than the case of efficiency improvement without flux control in transient state. The speed overshoot with the optimum flux recovery in transient state increases 40% approximately comparing to that with rated flux transient operation, since has better convergence. Due to the shorter convergence of a transient duration, the proposed control system achieves more input energy saving compared with the rated flux recovery.

IV. CONCLUSIONS

The test results validate that the proposed control system improves the motor at light loads. At transition operation points, the stator current recovery to an optimal value lower instead to its nominal, improves the motor efficiency during transient states and accelerates the algorithm convergence in steady states. Moreover, the drive has better dynamic behavior in a high range of speed when suddenly torque load is applied.

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VI. BIOGRAPHIES

Eleftheria Sergaki leaves and works in Chania, in the island of Crete, Greece. She studied Physics in Aristotle University of Thessaloniki, Greece. She received her Postgraduate degree and the Ph.D. degree from the Technical Univ. of Crete/Greece, Electrical and Computer Engineering Department. Since 1990, she has been with the Department of Science, teaching Physics experiments for the graduate level students and designing new experimental arrays. Her current research interests include the loss minimization in variable speed drives and control optimization.

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Fuzzy Logic Control for Motor Flux Reduction during Steady states and for Flux Recovery in Transient states of Indirect-FOC AC Drives

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ABSTRACT

This paper presents a new fuzzy control scheme for real time drive efficiency improvement by the adaptive flux reduction at light loads during steady states and by the optimum flux recovery during transient states. The optimum flux recovery instead of the rated flux does not sacrifice the drive dynamic response since the torque capacity remains the same and accelerates the search convergence in steady states. The control scheme is combined with an Indirect-Field-Oriented-Control (IFOC) motor drive. The design of the new fuzzy control scheme is focused to recognize the motor state operation in order to control under the corresponding circumstances.

The proposed fuzzy control scheme includes three main units: one Fuzzy-Logic-Search Controller FLSC1, one Fuzzy-Logic-Controller FLC2 and a State detector unit. The State detector unit decides which of the FLSC1 or FLC2 controllers is used, in accordance to the operation circumstances. The fuzzy controllers utilize the stator flux-producing current component into d-q reference frame (stator current direct axis i_{sd}) as control variable, in order to estimate the next optimal change of Δi_{sd} .

The drive efficiency improvement and the drive dynamic response is currently validated in laboratory using an experimental array of a 3-phase 1 Hp induction motor drive. The control scheme is implemented using the platform eZdsp from Digital Spectrum based on the fixed point 32 bit DSP TMS320F2812 from TI.

I. FUZZY LOGIC OPTIMUM FLUX ADJUSTMENT

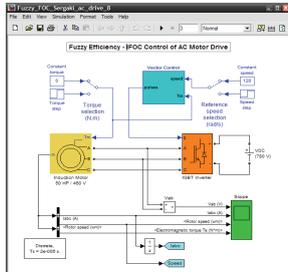


Fig.1: The proposed control system in Simulink blocks.

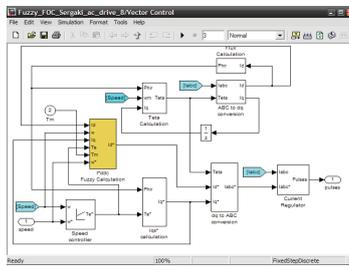


Fig.2: The Simulink model of the fuzzy-logic control scheme, labeled as "F^d(k) Fuzzy Calculation", is incorporated into an IFOC speed control drive.

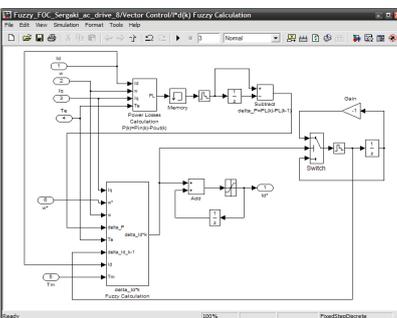


Fig.3: The Simulink model of the fuzzy-logic efficiency control system, includes a unit for the power loss calculation labeled as "Power Losses Calculation P(k)=Pin(k)-Pout(k)" and the fuzzy system labeled as "delta_id Fuzzy Calculation". The above model is included in the block labeled as "F^d(k) Fuzzy Calculation" in Fig. 2.

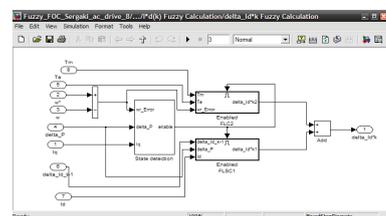


Fig.4: The Simulink model of the fuzzy efficiency control system includes the fuzzy controllers FLSC1, FLC2, and the State detection unit. The State detector unit decides the activation of the fuzzy blocks FLSC1 and FLC2.

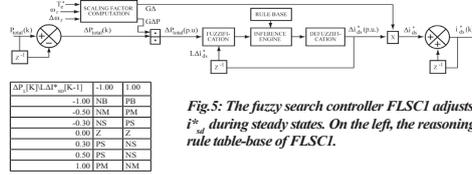


Fig.5: The fuzzy search controller FLSC1 adjusts i_{sd}^* during steady states. On the left, the reasoning rule table-base of FLSC1.

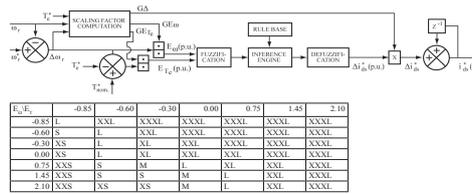


Fig.6: The fuzzy controller FLC2 adjusts i_{sd}^* during transient states. Below, the reasoning rule table-base of FLC2.

II. SIMULATION RESULTS

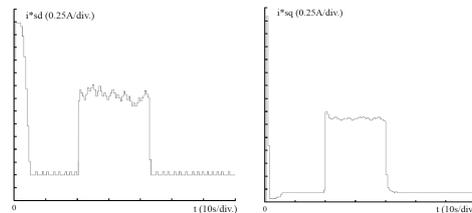


Fig.7: Simulation results of the proposed control system for an 1Hp, 1390 rpm, 5.152 Nm, 3-phase motor IFOC drive. The field-producing component of the stator current (i_{sd}^*) and the torque-producing component of the stator current (i_{sq}^*) under constant nominal speed 1pu and suddenly step load from 0.1 pu (0.088 Nm) to 0.7 pu (6.159 Nm).

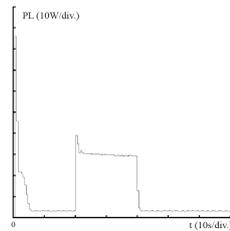


Fig.8: Left, simulation result of the proposed control system. Power losses minimization process under constant nominal speed 1 (pu) and suddenly step load from 0.1 (pu) to 0.7 (pu).

III. EXPERIMENTAL RESULTS

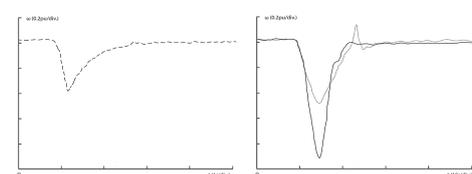


Fig.9: Experimental result of the proposed control system. The motor speed response under constant nominal speed 1 (pu) and suddenly step load from 0.1 (pu) to 0.7 (pu). The dashed line presents motor control without efficiency optimization (operation under rated flux).

Fig.10: Experimental result of the proposed control system. The motor speed response under constant nominal speed 1 (pu) and suddenly step load from 0.1 (pu) to 0.7 (pu). The dot line presents the motor control with rated flux recovery in transient state. The solid line presents the proposed control with optimum flux recovery in transient state.

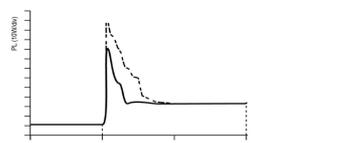


Fig.11: Experimental results of the proposed control system for a 3-phase induction motor validate the efficiency improvement. Power losses under constant nominal speed 1 (pu) and suddenly step load from 0.1 (pu) to 0.7 (pu). Dot-line: At transition time the FLC2 is not activated, the stator current is recovered to its nominal value. Solid-line: At transition time the FLC2 is activated, the stator current is recovered to an optimal value lower to its nominal.

THE PATENT

Sergaki Eleftheria, Patent No. 1006612, INT.CL HO2P 21/08, "FUZZY LOGIC SEARCH EFFICIENCY CONTROLLER FOR ELECTRICAL DRIVES"

For the experimental implementation, the necessary scale gains for the two fuzzy controllers, are experimentally derived, based on the patented method of Sergaki Eleftheria, upon the initialization of the device, by using a power meter (power analyzer) and a torque meter. This is achieved by firing up one fuzzy controller after another following the steps as explained below:

A power meter is connected to the input of the dc link power converter or to the input terminals of the motor. A torque meter is connected to the shaft of the motor.

- The motor is set initially to operate into steady-state operation with pre-determined values for the load torque and the shaft speed, based on the type of application, i.e. load torque 0.02 pu and speed 0.5 pu. In this pre-determined operation mode, the necessary scaling gains of the FLSC1 which controls the steady-state operation, are regulated manually with the method of trial-and-error, from the CCS "watch window" with continuous refresh feature, so that the power meter determines the minimum of electric power.
- After a certain amount of time, as soon as the temperature balance of the motor is restored, the motor is set into transient state operation, by varying the values of load torque in selected steps (i.e. from 0.2 to 0.4 pu), keeping the motor speed constant (i.e. 0.5 pu). In this pre-determined operation mode, the necessary scaling gains of the FLC2 which controls the transient state operation, are regulated with the method of trial-and-error, so that the torque meter determines the minimum torque variation.
- After a certain amount of time, as soon as the temperature balance of the motor is restored, the motor is set into transient state operation, by varying the values of motor speed in selected steps (i.e. from 0.5 to 1.0 pu), keeping the load torque constant (i.e. 0.2 pu). In this pre-determined operation mode, the necessary scaling gains of the FLC2 are regulated with the method of trial-and-error.
- All the above mentioned experimental adjustments of steps A, B and C. are repeated, after a certain amount of time, as soon as the temperature balance of the motor is restored, in order to calculate the optimum values of the necessary scaling gains of the fuzzy logic controllers by the software-based statistical data manipulation (i.e. the average) of the experimental values measured during this experimental adjustment repeat step.

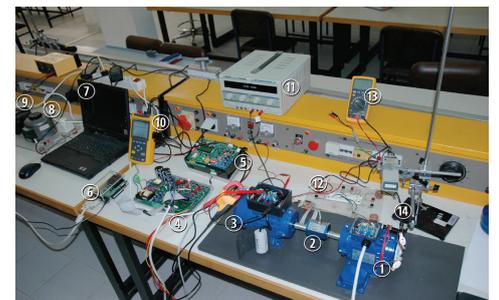


Fig.12: The experimental setup (1) test motor, (2) torque meter, (3) load motor, (4) DMC 1500 inverter from Digital Spectrum, (6) eZdsp F2812 controller, (10) power analyzer, (14) tachometer.

The transient efficiency improvement is evident in Fig. 11 where the proposed control system is tested with and without efficiency improvement. At transient position, the power losses peak is 90 W (instead of 40 W in simulation results) lower. At steady state, the control converges to 35 W instead of 32 W in simulation results.

In Fig. 10 is shown the speed response at 1 (pu) under step torque application during the interval of the proposed control scheme (transient optimum flux recovery) in comparison with the case without transient optimization (transient rated flux recovery). The case without efficiency improvement (rated flux), is shown in Fig. 9. Fig. 9 & 10 show that the overshoot of speed response without efficiency improvement is better (lower and shorter convergence). The speed overshoot of the proposed method with flux optimum recovery in transient state is shorter and bigger than the case of efficiency improvement without flux control in transient state. The speed overshoot with the optimum flux recovery in transient state increases 40% approximately comparing to that with rated flux transient operation, since has better convergence. Due to the shorter convergence of a transient duration, the proposed control system achieves more input energy saving compared with the rated flux recovery.

IV. CONCLUSIONS

The test results validate that the proposed control system improves the motor at light loads. At transition operation points, the stator current recovery to an optimal value lower instead of its nominal, improves the motor efficiency during transient states and accelerates the algorithm convergence in steady states. Moreover, the drive has better dynamic behavior in a high range of speed when suddenly torque load is applied.