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A Fuzzy Logic Controller with Tuning Output Scaling Factor for Induction Motor Control Taking Core Loss into Account

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Abstract: This paper presents a design of a fuzzy logic controller (FLC) with tuning output scaling factor for speed control of indirect field oriented induction motor (IM) taking core loss into account. The variation of output scaling factor of FLC depends on the normalized output of FLC. Firstly the speed control of IM taking core loss into account is presented by using FLC with fixed scaling factors (FLC-FSF). Secondly the speed controller based on suggested FLC with tuning output scaling factor (FLC-TOSF) is proposed. The performance of the proposed FLC-TOSF for speed control of IM are investigated and compared to those obtained using FLC-FSF at different operating conditions and variation of parameters. A comparison of simulation results shows that the convergence of actual speed to reference speed is faster by using the proposed FLC-TOSF.

Keywords: *Core loss, field oriented induction motor, fuzzy logic controller, fuzzy logic controller with tuning output scaling factor*.

1. Introduction

The field oriented control (FOC) [1] of induction motor (IM) used in industrial and process applications for high dynamics performances based on conventional PI controller [2]. Fuzzy logic control (FLC) is used in order to overcome the problems of conventional PI controller based FOC of IM [3 - 6]. But the FOC has been developed by neglecting core loss [1-6]. The decoupling control of rotor flux and torque has been implemented by decomposing the stator currents components [7]. The effects of core loss in AC drive have been investigated and it has been clarified that some compensation is required for FOC to overcome the perturbations of core loss [8]. The flux controlling stator current components and electromagnetic torque control stator current components are interfered with each other due to the effects of core loss. The effects of core loss in IM have been investigated and an indirect FOC (IFOC) in terms of magnetizing current components has been proposed in [9]. But the proposed IFOC is valid only for steady state condition.

Based on the proposed IFOC in [9], the conventional PI controller has been proposed in [10] for both transient and steady state operations of an IM taking core loss into account. The gains of PI controller have been changed when the load torque changed [10] by which it has proven that the proposed PI controller is not robust under the variation of load torque. Consequently, fuzzy logic based high performance control of IM taking core loss into account has been proposed in [11]. It is assumed that the FLC is a best controller in terms of dynamics response and best disturbance rejection [12, 13].

The FLC has been designed where the scaling factors, membership function of the linguistic variable and the rules are kept constant. But these parameters can be altered on-line in order to improve and to modify the controller performance [14, 15].

In this paper, we suggested a novel design of a FLC with tuning the output scaling factor (FLC-TOSF) by the normalized output of FLC-FSF for speed control of IM taking core loss into account. The improvements and the effectiveness of the proposed FLC-TOSF are verified by using simulation. The faster convergence of actual speed to the reference speed is achieved around the operating rated conditions and under the variations of load torque and parameters of IM. The special merits of this controller is that it does not require the knowledge of a mathematical model of the plant for the variation of output scaling factor and it can be easily implemented.

2. MODEL OF IM TAKING CORE LOSS INTO ACCOUNT

The equivalent circuit of an IM taking core loss into account in a synchronously rotating reference frame is shown in **Fig. 1** [9]. The voltage and flux linkage can be expressed by the following equations.

$$\boldsymbol{v}_1 = R_1\boldsymbol{i}_1 + d\boldsymbol{\Phi}_1/dt + j\omega_e\boldsymbol{\Phi}_1 \quad (1)$$

$$0 = R_2\boldsymbol{i}_2 + d\boldsymbol{\Phi}_2/dt + j\omega_s\boldsymbol{\Phi}_2 \quad (2)$$

$$R_c\boldsymbol{i}_c = d\boldsymbol{\Phi}_m/dt + j\omega_e\boldsymbol{\Phi}_m \quad (3)$$

$$\boldsymbol{\Phi}_1 = L_1\boldsymbol{i}_1 + \boldsymbol{\Phi}_m;\ \boldsymbol{\Phi}_2 = L_2\boldsymbol{i}_2 + \boldsymbol{\Phi}_m;\ \boldsymbol{\Phi}_m = L_m\boldsymbol{i}_m \quad (4)$$

The mechanical modelling part of IM is given by

$$d\omega_m/dt = -(D/J)\,\omega_m + (P_n/J)(T_e - T_L) \quad (5)$$

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with

$$T_e = P_n(L_m/L_2)(i_{mq}\Phi_{2d} - i_{md}\Phi_{2q}) \quad (6)$$

where, symbols R_1, R_2, R_m indicate stator, rotor and core loss resistances. L_1, L_2, L_m indicate stator and rotor leakage and mutual inductances. P_n indicates number of pole pair. ω_e, ω_m, ω_s indicate synchronous, rotor and slip speeds. $\boldsymbol{v}_1$indicates stator voltage vector. $\boldsymbol{i}_1$, $\boldsymbol{i}_2$,$\boldsymbol{i}_m$, $\boldsymbol{i}_i$ indicate stator, rotor, magnetizing and core loss current vectors. $\boldsymbol{\Phi}_1$, $\boldsymbol{\Phi}_2$, $\boldsymbol{\Phi}_g$ indicate stator, rotor and air gap flux vectors. T_e, T_L indicate electrical and load torques. J, D indicate total inertia and damping factor. Suffix d and q indicate direct axis and quadrature axis components.

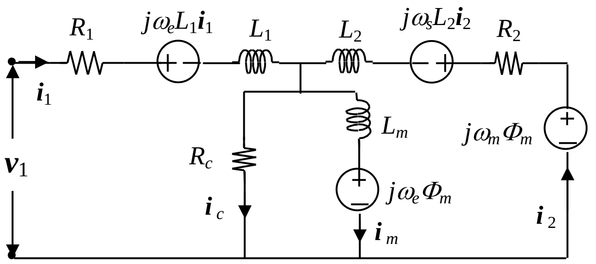


Fig. 1. Equivalent circuit of IM taking core loss into account.

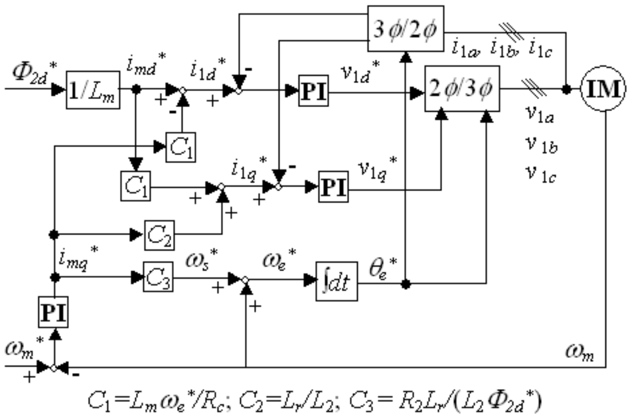


Fig. 2. Control structure of IM taking core loss into account based on PI controller

According to the IFOC theory [9], the rotor flux and electromagnetic torque are decomposed into i_{md} and i_{mq} components. Consequently, the constraint of IFOC can be written by the following expression.

$$\Phi_{2d} = \text{Constant}; \; \Phi_{2q} = 0 \quad (7)$$

Hence, the rotor flux and electromagnetic torque are decoupled from each other, and can be separately controlled as desired. Then the behaviour of IM can be described by the following simplified model equations [9]:

$$\Phi_{2d} = L_m i_{md} \quad (8)$$

$$T_e = Pn(L_m/L_2)i_{mq}\Phi_{2d} \quad (9)$$

$$\omega_s = (R_2L_m/L_2)(i_{mq}/\Phi_{2d}) \quad (10)$$

According to the theory of IFOC, the whole control system structure based on PI controller is shown in **Fig. 2** [10]. There are three PI controllers are used one for speed control and the others for stator currents control. Due to the drawbacks of conventional PI controller, a FLC was proposed for replacing PI speed controller.

3. DESIGN OF A FLC WITH TUNING OUTPUT SCALING FACTOR FOR IM SPEED CONTROL

The discrete time form of PI speed controller (see Fig. 2) can be written by the following equation.

$$\Delta i_{mq}^*(k) = K_p\Delta e(k) + K_iT_se(k) \quad (11)$$

where, $e(k) = \omega_m^*(k) - \omega_m(k)$;

$\Delta e(k) = e(k+1) - e(k)$;

$\Delta i_{mq}^*(k) = i_{mq}^*(k+1) - i_{mq}^*(k)$, superscript "*"indicates the desired or reference value. K_p and K_i indicate proportional and integral constant. k and T_s indicate sampling instant and sampling time.

Control structure of a standard FLC is shown inn **Fig. 3**. The structure of a standard FLC can be seen as a traditional PI controller, so the design of FLC is explained in the following:

3.1. Fuzzification

Like a PI controller, the speed error $e(k)$ and its variation $\Delta e(k)$ are considered as input linguistic variables and the change of magnetizing q-axis current $\Delta i_{mq}^*(k)$ is considered as the output linguistic variable. For convenience, the inputs and output of the FLC are scaled with three different coefficients K_e, $K_{\Delta e}$ and K_i (see Fig. 3). These scaling factors play an important role for FLC in order to achieve a good behaviour in both transient and steady state conditions. These scaling factors can be constants or variable.

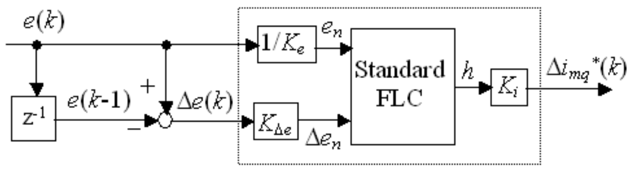


Fig. 3 Control structure of a standard FLC.

In this work, seven membership functions with overlap, of triangular shape are used for each input and output variable. The membership functions of linguistic variable are shown in **Fig. 4**. The linguistic variables are represented by NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Big). The grade of input membership functions can be obtained as follows.

$$\mu(x) = [w - 2|x - m|]/w \quad (12)$$

where, $\mu(x)$ is the value of grade of membership, w is the width and m is the coordinate of the point at which the grade of membership is 1, x is the value of the input variable.

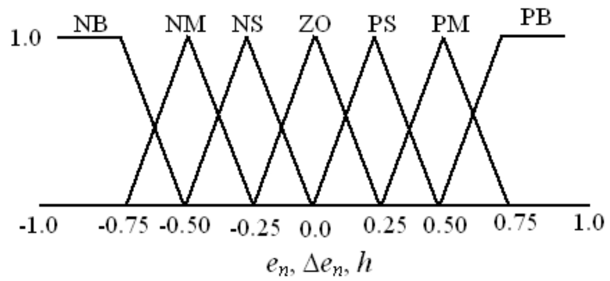


Fig. 4 Membership functions of input and output of FLC.

3.2. Rule Base

By using the scaling factors of input variables are normalized within the range –1 to 1 and then the range of output variable of FLC is also within –1 to 1. Here, we defined e_n,Δe_n and h as normalized speed error, change of speed error and change of magnetizing q-axis current (see Fig 3). The fuzzy mapping of the input variables to the output is represented by fuzzy IF-THEN rules of the following form:

IF < e_n is ZO> and <Δe_n is NB> THEN <h is NM>

IF < e_n is NB> and <Δe_n is PB> THEN <h is ZO>

Since the number of membership function for each input is seven, there are total 49 rules to achieve desired speed trajectory. The entire rule base is given in **Table 1**.

Table 1. Fuzzy rule table

Δi_{mq}^n		Δe_ω^n						
		NB	NM	NS	ZO	PS	PM	PB
e_ω^n	**NB**	NB	NB	NM	NM	NS	NS	ZO
	NM	NB	NM	NM	NS	NS	ZO	PS
	NS	NM	NM	NS	NS	ZO	PS	PS
	ZO	NM	NS	NS	ZO	PS	PS	PM
	PS	NS	NS	ZO	PS	PS	PM	PM
	PM	NS	ZO	PS	PS	PM	PM	PB
	PB	ZO	PS	PS	PM	PM	PB	PB

3.3. Inference and Defuzzification

From the rule base in Table 1, the inference engine provides fuzzy value of h, and then crisp numerical value of Δi_{mq}^* is obtained by using defuzzification procedure. The most popular method on inference and defuzzification is Mamdani's max-min (or sum-product) composition with centre of gravity method. In this work, we used the Mamdani type fuzzy inference and defuzzification method. The centre of gravity method [15] is used for defuzzification to obtain h. The normalized output function is given as

$$h = \sum_{i=1}^{N} \mu_i C_i / \sum_{i=1}^{N} \mu_i \quad (13)$$

where, N is total number rules, μ_i is the membership grade for ith rule and C_i is the coordinate corresponding to the maximum value of the respective consequent membership function [$C_i \in$ {-0.75, -0.5, -0.25, 0.0, 0.25, 0.5, 0.75}]. After finding out h, the actual desired first difference magnetizing current, Δi_{mq}^*, can be found out by product of scaling factor K_i as shown in Fig. 3.

3.4. Proposed Output Scaling Factor Variation

In sub- sections 3.1 to 3.3 described to design a FLC with fixed scaling factors of input and output variables. The FLC-FSF provides good performances at rating operating conditions and for load rejection. We proposed FLC-TOSF where the output factor is tuned in on-line to improve the performance of FLC-FSF in terms of the convergence of actual speed to the reference speed. In the proposed control system, the tuning of output factor does not depend on any mathematical model. The tuning of output factor is changed according to the normalized output of FLC-FSF. Let K_{it} is the modified scaling factor and its can be expressed by the following equation.

$$K_{it} = K_i + (1-h) \quad (14)$$

According to equation (14), the scaling factor K_{it} is used instead of K_i in Fig. 3.

4. SIMULATION RESULTS

In order to verify the performance of the proposed FLC-TOSF for speed control of IM drive, simulations were carried out. The ratings and parameters of the IM model are listed in **Table 2**.

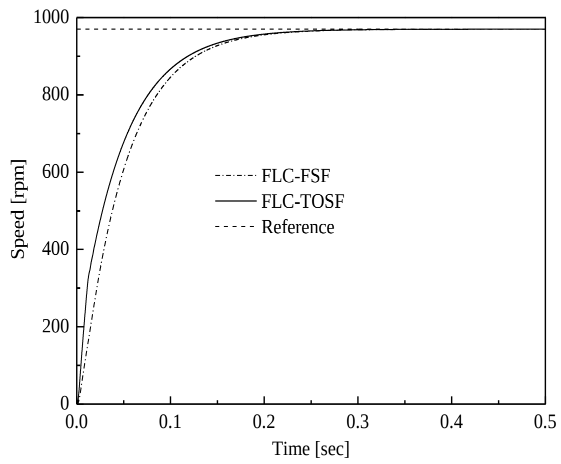
The value of sampling period is chosen 75 μsec. For FLC-FSF, the scaling factors are chosen as K_e = 304.74, $K_{\Delta e}$ = 2.1 rad/sec and K_i = 0.0162. For PI current control, the PI constants are chosen as K_p = 3.0 and K_i = 1500.0. The mentioned scaling factors and PI gains are selected by trial and error method to achieve as good as performance of FLC-FSF and PI controller.

Table 2. Ratings and Parameters of IM

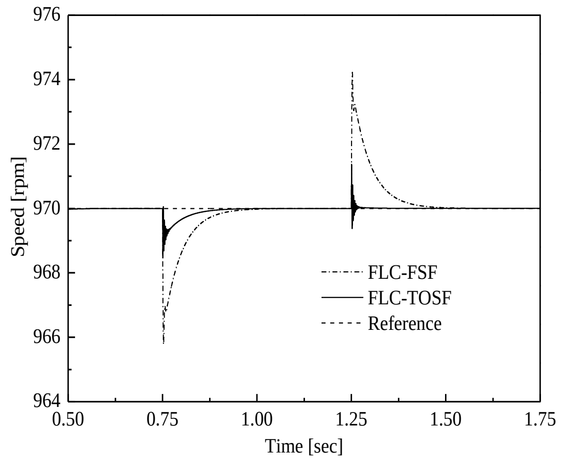
Ratings	**Parameter values**
1.1 kW, 200/√3 voltage/phase, slip=0.03, 6 pole, 50 Hz	R_1 =0.2842 Ω, R_2 =0.2878 Ω, R_c=329.667Ω L_s = 28.3 mH, L_r = 28.8 mH, L_m = 26.8 mH, J = 0.0179 Kg-m^2, D = 0.0

Fig. 5 shows the transient and steady state responses of speed regulation of IM for various operating conditions. Fig. 5 (a) and (b) show the transient responses of speed where speed is changed from 0 r/min to 970 r/min (rated value) at t = 0 sec and the load torque is changed 50% to 100% of its rated value at t = 0.75 sec. The 50% load torque is reduced again at t = 1.25 sec. It is comprehended from Fig. 5 (a) that the convergence of actual speed to the reference speed is faster by using the proposed FLC-TOSF. Fig. 5(b) shows that the transient performance of FLC-FSF is improved by using the proposed FLC-TOSF. Fig. 5 (c) also shows that the transient response of speed regulation can be achieved by using the proposed FLC-TOSF.

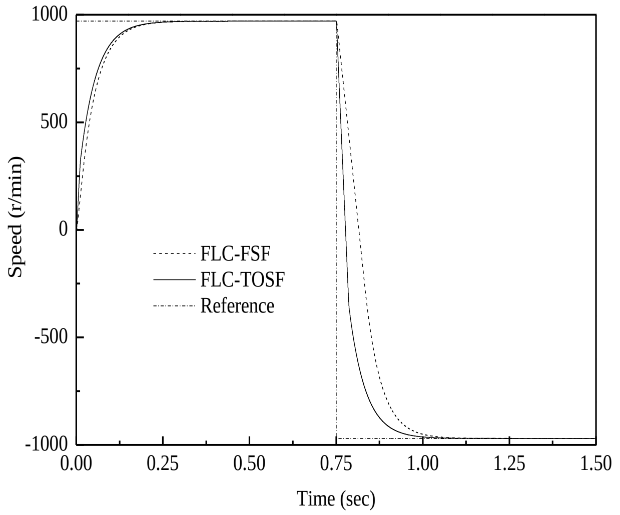
In order to show the robustness of FLC-FSF and FLC-TOSF against parameters variation (R_2 and J), simulation results, are presented as shown in Figs. 6 and 7. It can be seen that non-overshoot speed response is obtained against the large deviations of rotor resistance and inertia by using the FLC-FSF or FLC-TOSF. The transient response of FLC-FSF is also improved by using the proposed FLC-TOSF.



(a) Speed transient from 0 r/min to 970 r/min at 0 sec.

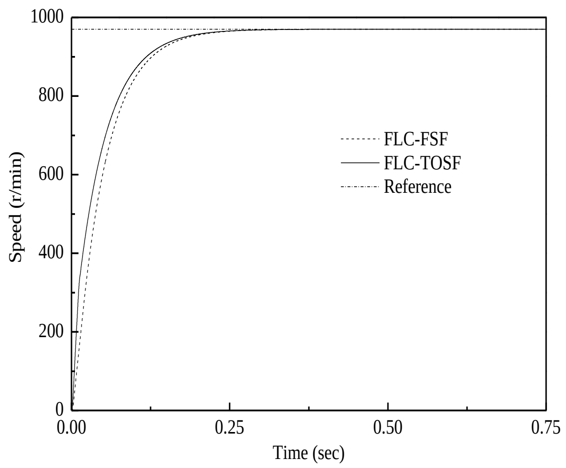


(b) Speed transient response by applying 100% rated torque at 0.75sec and 50% rated torque at 1.25 sec.

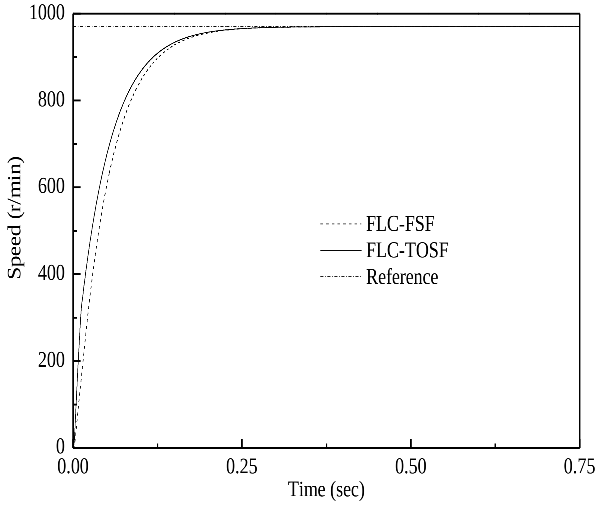


(c) Speed transient from 0 r/min to 970 r/min followed by speed reversion from 970 r/min to –970 r/min at 0.75 sec.

Fig. 5. Simulation results of the speed regulation of IM for both FLC-FSF and FLC-TOSF.

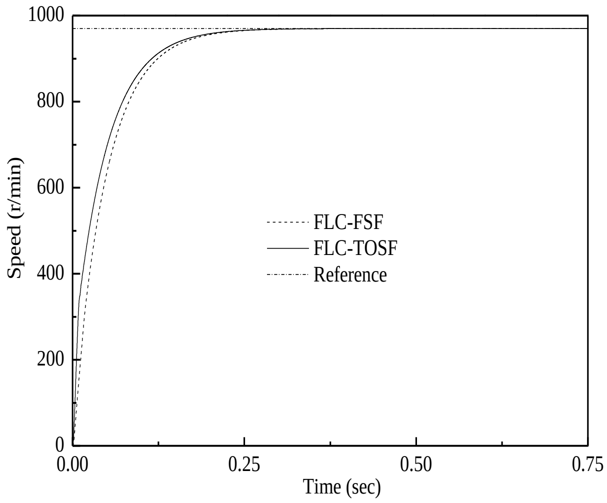


(a) ΔR_2 = +50% of rated R_2

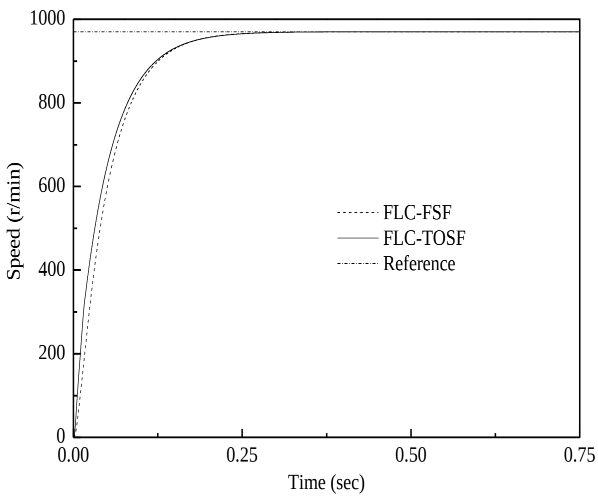


(b) ΔR_2 = -50% of rated R_2

Fig. 6. Simulation results of the speed regulation of IM considering R_2 variation.



(a) ΔJ = -50% of rated J



(b) ΔJ = +100% of rated J

Fig. 7. Simulation results of the speed regulation of IM considering J variation.

5. CONCLUSION

A novel design of a fuzzy logic controller with on-line tuning output scaling factor for the speed control of IM taking core loss into account is fully explained. Moreover, the achievement of the proposed controller for various operating conditions and parameters variation was investigated by simulation study. It has been demonstrate how a simple the transient response can be improved by tuning output scaling factor. It can be concluded that the convergence of actual speed to the reference speed of a FLC with fixed scaling factor can be improved by tuning output scaling factor.

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