Speed Load Control of Induction Motor Using Immune Algorithm and Fuzzy Phase Plane Controller

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***Abstract*—This paper proposes a speed load control of induction motor using immune algorithm (IA) and fuzzy phase plane controller. Fuzzy membership functions, phase plane theory and the IA are employed to design the proposed controller (FPPC) for controlling the speed of an induction motor with loading, based on the desired specifications. The proposed FPPC has merits of rapid response, simply designed fuzzy logic control and an explicitly designed phase plane theory. Simulations and experimental results reveal that the proposed FPPC is superior in optimal speed and load control to conventional PI controller.**

***Index Terms*—Fuzzy phase plane, immune algorithm, speed load control.**

I. Introduction

Conventional proportional integral (PI) dynamic controls for speed and the load have drawbacks [1]. Although fuzzy logic is commonly applied to the field oriented control of induction motors, the fuzzification, defuzzification, and decision procedures that establish a knowledge base are more complicated, difficult and time-consuming. Moreover, although some studies [2]-[6] have been performed in this area, most, if not all, are based on conventional trial-and-error techniques. However, optimal performance may not be achieved. The phase plane technique [7]-[9] is now widely used to enhance the control performance in the transient and steady states. This paper describes a new method for advancing the indirect oriented field control (IFOC) [3], [4] technique for controlling the speed load of an induction motor. The proposed controller (FPPC) speeds up the response because the defuzzification procedure and the fuzzy rules derived from expert experiences (knowledge bases) are no longer required. The block diagram of the proposed controller design has shown in Fig. 1 for controlling speed load of an induction motor.

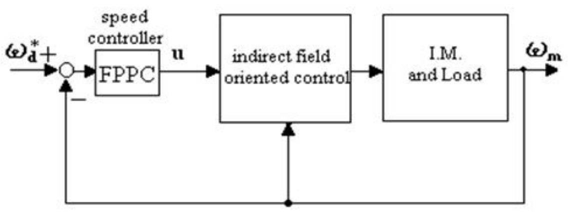

Fig. 1. The block diagram for controlling the induction motor speed.

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IA [10] is inspired by immunology, immune function and principles observed in nature. IA is a very intricate biological system which accounts for resistance of a living body against harmful foreign entities. It is now interest of many researchers and has been successfully used in various areas of research [10]-[12].

Fuzzy membership functions, phase plane theory and the IA are used to design the proposed controller (FPPC) for the IFOC of an induction motor, based on the desired specifications. The proposed FPPC has rapid response, simply designed fuzzy logic control and an explicitly designed phase plane theory. The simulated and experimental results indicate that the proposed FPPC outperforms the conventional PI controllers in the optimal speed control and loading controls.

II. System Formulation

By assuming a linear magnetic circuit and neglecting the iron losses, the dynamic equations for an induction motor can be expressed in a d^e-q^e rotating two-axis coordinate frame [13] as,

$$p\begin{bmatrix} i_{qs}^e \\ i_{ds}^e \\ \Phi_{dr}^e \end{bmatrix} = \begin{bmatrix} \frac{-R_s}{L_\sigma} & 0 & 0 \\ 0 & \frac{-R_s}{L_\sigma} - \frac{L_m^2 R_r}{L_\sigma L_r^2} & \frac{L_m R_r}{L_\sigma L_r^2} \\ 0 & \frac{L_m R_r}{L_r} & \frac{-R_r}{L_r} \end{bmatrix} \begin{bmatrix} i_{qs}^e \\ i_{ds}^e \\ \Phi_{dr}^e \end{bmatrix} + \frac{1}{L_\sigma}\begin{bmatrix} \upsilon_{qs}^{e^*} \\ \upsilon_{ds}^{e^*} \\ 0 \end{bmatrix} \tag{1}$$

where

$$\upsilon_{qs}^{e^*} = \upsilon_{qs}^e - \omega_e L_\sigma i_{ds}^e - \left(L_m / L_r\right)\omega_e \Phi_{dr}^e \tag{2}$$

$$\upsilon_{ds}^{e^*} = \upsilon_{ds}^e + \omega_e L_\sigma i_{qs}^e \tag{3}$$

R_s, R_r = stator resistance and rotor resistance referred to the Stator

$\upsilon_{ds}^e, \upsilon_{qs}^e$ $= d^e$ and q^e axis stator voltages

i_{ds}^e, i_{qs}^e $= d^e$ and q^e axis stator currents

Φ_{dr}^e, Φ_{qr}^e $= d^e$ and q^e axis rotor flux linkages

$L\sigma$ = Ls –Lm2 /Lr , total leakage inductance

Lm, Lr = mutual inductance and rotor inductance referred to the stator

T_e = electromagnetic torque

ωe = synchronous rotating frame angular speed

ωm = rotor mechanical speed (rad/s)

p = differential operator ($p \equiv d/dt$)

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By applying (1) and letting Φ_{dr}^{e} be a constant, Φ_{dr}^{e} can be expressed in terms of i_{ds}^{e} as,

$$\Phi_{dr}^{e}=\frac{i_{ds}^{e}L_m}{1+\frac{L_r}{R_r}s} \tag{4}$$

Once the d^e-axis position is determined, the magnetizing current component, or equivalently, the d^e-axis current component can be easily determined:

$$i_{ds}^{e}\cong\frac{\Phi_{dr}^{e}}{L_m^{*}} \tag{5}$$

where L_m^{*} is the unsaturated nominal mutual inductance. After decoupling, the stator current command ($i_{qs}^{e^*}$) can be controlled by motor torque generation. Two command values (ω_{sl}^{*} and $i_{qs}^{e^*}$) are obtained from the vector controllers. The slip command (ω_{sl}^{*}) satisfies,

$$\omega_{sl}^{*}=\frac{R_r^{*}L_m^{*}i_{qs}^{e^*}}{L_r\Phi_{dr}^{e^*}} \tag{6}$$

where R_r^{*} represents the nominal rotor resistance. Substituting (6) into (1) enables the stator current command ($i_{qs}^{e^*}$) to be written as,

$$i_{qs}^{e^*}=\frac{4}{3P}\frac{L_r}{L_m^{*}}\frac{T_e^{*}}{\Phi_{dr}^{e^*}} \tag{7}$$

The torque current command ($i_{qs}^{e^*}$) is generated primarily from the output of the proposed FPPC.

III. The Design of Controllers

A. The Proposed Controller (FPPC)

The output signal $u(t)$ of the proposed FPPC shown in Fig. 1 is given by,

$$u(t)=U(n)\ \text{, for }\ ndT<t<(n+1)dT \tag{8}$$

where dT indicates the sampling period and n is an integer. The value of $U(n)$ is determined using the following steps.

Step 1. Sample the error (E) and compute the scaled variation of error (dE_{scale}) by,

$$dE(n)=E(n)-E(n-1) \tag{9}$$

$$dE_{scale}(n)=k_o\times dE(n) \tag{10}$$

where $dE(n)$ is the variation of error at n^{th} sampling time; dE_{scale} is the scaled dE and k_o is the scaling factor.

Step 2. Compute $\theta(n)$ and $R_i(n)$, which are shown in Fig. 2.

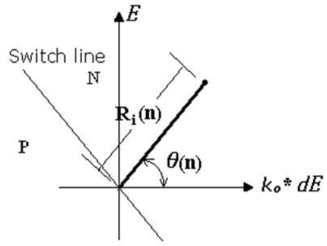

Fig. 2. Induction motor condition on the phase plane.

Step 3. Define the membership function, which contains sigmoid functions that determine the angle-direction gain is presented. The bell-shaped membership function of $P(\theta)$, which has a positive gain, is illustrated as,

$$P(\theta)=\frac{1}{1+e^{-e_i(\theta-\alpha)}}-\frac{1}{1+e^{-e_i[\theta-(\alpha+180)]}} \tag{11}$$
$$\alpha-90\le\theta\le(\alpha-90)+360$$

Fig. 3 shows the corresponding waveform to (11). This figure presents $N(\theta)$, which is the negation of $P(\theta)$, is equal to 1-$P(\theta)$. If the $\theta<\alpha$ - 90 condition occurs, θ plus 360 results (11). We set e_i and α to 100.0 and 135^o respectively, and expect to obtain a rapid response and simplified design.

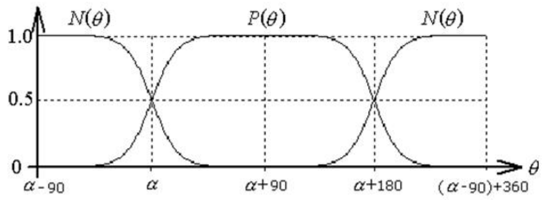

Fig. 3. The bell-shaped membership function for angle-direction gain distribution.

Step 4. Determine the radius-direction gain function $G(R_i(n))$, and is defined in (12). Where the f_i is an adjustable centripetal gain; $R_i(n)$ is the length between the dynamic and original points , ($R_i(n)=|(k_0*dE_i(n), E_i(n))|$).

$$G(R_i(n))=\frac{2}{1+e^{-f_iR_i(n)}}-1 \tag{12}$$

Step 5. Compute the output of the proposed controller ($U(n)$), represented as,

$$U(n)=\{G(R_i(n))\cdot[2P(\theta(n))-1]\}\cdot U_{MAX} \tag{13}$$

where U_{MAX} is the maximum output of $U(n)$ for a practical hardware system.

Step 6. Increase n by 1, and repeat steps 1 to 5.

Some parameters regarding the proposed controller must be optimized to improve the performance of the proposed FPPC. Equation (14) defines the index for optimizing the aforementioned parameters. The performance index is defined as the sum of absolute errors with constraints (SAEC).

$$\min \text{SAEC} = \min J = \sum_{n=1}^{M} |error(n)| + \sum_{n=1}^{M}\sum_{k=1}^{L} \lambda_k g_k \tag{14}$$

where M denotes the total number of data sampled. λ_k is the penalty factor associated with the constraint g_k, and L is the total number of constraints.

B. The Field-Weaken Control, the Flux Controller and Two Current Controllers

The conventional PI controller has been extensively used for controlling the speed of induction motor drives. The major feature of the PI controller is its capability to maintain a zero steady state error within a step change. The controller has the merits of simplicity and stability. However, a PI controller has some disadvantages, such as undesirable speed overshoot and oscillation, a sluggish response to a sudden change in load torque, a long settling time, and sensitivity to controller gains k_P and k_i. Hence, the proposed FPPC is used as the primary controller, which can overcome the disadvantages in the PI controller. Three PI controllers are employed as subordinate controllers [14] in the IFOC drive system design, including the flux controller and two current controllers of i_{qs} and i_{ds}.

The determination of $\Phi_{dr}^{e^*}$ requires fairly complicated computations because the solution of $\Phi_{dr}^{e^*}$ is based on an eighth-order polynomial equation [15]. Let T_e^* = 0; then $\Phi_{dr}^{e^*}$ can be approximated by,

$$\Phi_{dr}^{e*} \approx \frac{L_m V_s^{\max}}{L_s \omega_r} \tag{15}$$

where V_s^{max} and ω_r are the maximum stator voltage and the electrical angular speed, respectively. To keep $i_{ds}^{e^*}$ constant, the flux controller uses the PI control expressed as,

$$i_{ds}^{e*} = \left(k_{pf} + \frac{k_{if}}{s}\right)\left(\Phi_{dr}^{e*} - \Phi_{dr}^{e}\right) \tag{16}$$

To eliminate variant values $\upsilon_{qs}^{e^*}$ and $\upsilon_{ds}^{e^*}$ in (2) and (3), two PI controllers are used in the current decoupling controllers of the d^e and q^e axes, defined as (17) and (18).

$$\upsilon_{qs}^{e^*} = \left(k_{pc1} + \frac{k_{ic1}}{s}\right)\left(i_{qs}^{e*} - i_{qs}^{e}\right) \tag{17}$$

$$\upsilon_{ds}^{e^*} = \left(k_{pc2} + \frac{k_{ic2}}{s}\right)\left(i_{ds}^{e*} - i_{ds}^{e}\right) \tag{18}$$

Thus, the two decoupled stator voltages can be rewritten as,

$$\upsilon_{qs}^{decouple} = \upsilon_{qs}^{e} = \omega_e L_\sigma i_{ds}^{e} + \left(L_m / L_r\right)\omega_e \Phi_{dr}^{e} \tag{19}$$

$$\upsilon_{ds}^{decouple} = \upsilon_{ds}^{e} = -\omega_e L_\sigma i_{qs}^{e} \tag{20}$$

$$U(n) = \left(\frac{2}{1+e^{-f_i R_i(n)}} - 1\right) \cdot \left[\left(\frac{2}{1+e^{-100.0(\theta-135^\circ)}} - \frac{2}{1+e^{-100.0(\theta-315^\circ)}}\right) - 1\right] \cdot U_{MAX} \tag{21}$$

The parameters of the flux controller and the two current controllers (*k_{pf}, k_{if}, k_{pc1}, k_{ic1}, k_{pc2}* and *k_{ic2}*) slightly influence the performance of motor controls because the principal controller (FPPC) performs most of this work.

IV. The Optimal Algorithm

In IA [12], mimics these biological principles of clone generation, proliferation and maturation. The main steps of IA based on clonal selection principle are activation of antibodies, proliferation and differentiation on the encounter of cells with antigens, maturation by carrying out affinity maturation process, eliminating old antibodies to maintain the diversity of antibodies and to avoid premature convergence, selection of those antibodies whose affinities with the antigen are greater. In order to emulate IA in optimization, the antibodies and affinity are taken as the feasible solutions and the objective function respectively.

V. Results of the Simulations and Experiments

A. Setups of the Proposed Controller

The proposed controller (FPPC) was implemented using fuzzy membership functions, the phase plane theory and the IA. Fig. 1 shows the block diagram for controlling the speed of an induction motor using the IFOC. The proposed FPPC has one output ($U(n)$, the torque T_e^*) and two input state variables (the state *E(n)* and the variation of the error state *dE (n)*). Substituting (11) and (12) into (13) yields the output $U(n)$ shown as (21).

In (21), f_i is an adjustable parameter related to G (R_i (*n*)), and the scaling factor k_o of (10) is an adjustable parameter on the phase plane. For optimal control, the parameters f_i and k_o must be optimized. The maximum output U_{MAX} was set to 3 for the practical hardware system. Matlab /Simulink software was employed on a P-IV 2.0GHz CPU to perform the simulations and experiments. The sampling interval was chosen as 0.1ms. Table I lists the parameters for the induction motor.

TABLE I: The Parameters of the Induction Motor

R_s = 2.85Ω，L_s = 0.19667H
R_r = 2.34Ω，L_r = 0.19667H
L_m = 0.1886H
J_m = 0.002 kg m^2
B_m = 0.003 N m/rad/s
4-pole， 220V Δ-connected，1 hp

B. Optimal Parameters of the Proposed Controller

In practice, the desired performance of a control system is specified in terms of time-domain quantities. An induction motor drive must usually meet the following specifications [5], [14], [16];

1) Delay time (t_d), $t_d \leq 0.15$s. 2) Rise time (t_r), $t_r \leq 0.1$s. 3) Settling time (t_s), $t_s \leq 0.2$s. 4) Maximum step response overshoot (m_p), $m_p \leq 0.3$%. 5) Step response steady state error (e_{ss}), $e_{ss} \simeq 0$.

The IA was used to find the optimal parameters, f_i and k_o for controlling speed of an induction motor. The fitness function can be calculated using (14). In light of aforementioned specifications, the penalty factors and constraints of (14) are defined as follows;

$$\lambda_k = 10 \quad for \quad k = 1, \cdots 5$$

$$g_1 = \begin{cases} |E(n)|, & if \quad t_d > 0.15s \\ 0, & if \quad t_d \le 0.15s \end{cases}$$

$$g_2 = \begin{cases} |E(n)|, & if \quad t_r > 0.1s \\ 0, & if \quad t_r \le 0.1s \end{cases}$$

$$g_3 = \begin{cases} |E(n)|, & if \quad t_s > 0.2s \\ 0, & if \quad t_s \le 0.2s \end{cases}$$

$$g_4 = \begin{cases} |E(n)|, & if \quad m_p > 0.3\% \\ 0, & if \quad m_p \le 0.3\% \end{cases}$$

$$g_5 = \begin{cases} |E(n)|, & if \quad e_{ss} \ne 0 \\ 0, & if \quad e_{ss} = 0 \end{cases}$$

C. Responses of the Proposed FPPC and Conventional PI Controllers

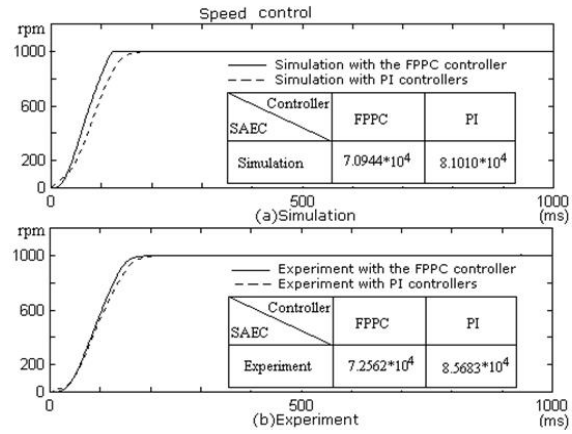

Fig. 4. The optimal speed control responses of the proposed FPPC and conventional PI controllers.

TABLE II: THE OPTIMAL PARAMETERS OF THE PROPOSED FPPC AND CONVENTIONAL PI CONTROLLERS, USING THE IA.

IA	Controller	Optimal parameters	
SPEED CONTROL (ω^*_d =1000 rpm)	FPPC	f_i k_o	30.2618 1.2818
	PI	K_{p2} K_{i2}	45.4267 0.0184

TABLE III: THE CHARACTERISTICS OF THE TRANSIENT AND STEADY STATES FOR THE PROPOSED FPPC AND CONVENTIONAL PI CONTROLLERS

Simulation		t_d (ms)	t_r (ms)	t_s (ms)	m_p (%)	e_{ss} (rpm)
Speed	FPPC	70	109-32=77	120	0.0750	-0.00033
	PI	93	141-47=94	152	0.0246	0.01430

Experiment		t_d (ms)	t_r (ms)	t_s (ms)	m_p (%)	e_{ss} (rpm)
Speed	FPPC	83	130-33=97	140	0.2853	1.0387
	PI	95	153-47=106	166	0.3021	2.0010

The simulated and experimental results for a step command input are given here to demonstrate the effectiveness of the proposed controller (FPPC). The IA was applied ten times, considering the desired specifications. Table II lists the optimal parameters yielding the minimum SAEC using ten runs with the proposed FPPC and conventional PI controllers. Fig. 4 shows the simulated and experimental results using the proposed FPPC and conventional PI controllers to optimally control the speed of an induction motor. Moreover, Table III summarizes the characteristics of the transient and steady states (t_d, t_r, t_s, m_p and e_{ss}), during applications using the proposed FPPC and conventional PI controllers to control the speed of an induction motor. Fig. 4 and Table III indicate that the proposed FPPC not only has a smaller SAEC than the conventional PI controllers in speed control, but also completely satisfies the desired specifications. However, the conventional PI controllers violate most of the desired specifications.

Fig. 5 shows a three-dimensional plot using ($k_o*dE(n)$, $E(n)$, $U(n)$) as (x, y, z) variables. This figure indicates that the output of the proposed FPPC, ($U(n)$), is a functional designing controller on the phase plane, obtained using (22). The figure also shows that the switch line nearly cuts the phase plane into two semi-planes at 135° . The proposed FPPC accelerates the response because defuzzification and the knowledge base are no longer required. Therefore, the proposed FPPC has the merits of rapid response, simply designed fuzzy logic control and an explicitly designed phase plane theory.

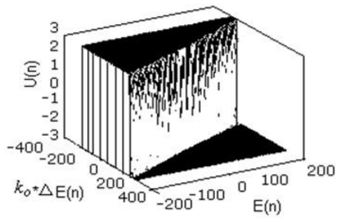

Fig. 5. 3D phase plane diagram of the optimal speed control using the proposed FPPC.

TABLE IV: THREE CASES OF DIFFERENT PARAMETERS FOR THE FLUX CONTROLLER AND TWO CURRENT CONTROLLERS

		Case A	Case B	Case C
Flux Controller Eq. (16)	k_{pf}	20.0	20.0×0.7	20.0×1.3
	k_{if}	351.2	351.2×1.3	351.2×0.7
q^e-Current controller Eq.(17)	k_{pc1}	20.0	20.0×1.3	20.0×0.7
	k_{ic1}	200.0	200.0×.7	200.0×1.3
d^e-Current controller Eq.(18)	k_{pc2}	20.0	20.0×0.7	20.0×1.3
	k_{ic2}	200.0	200.0×1.3	200.0×0.7

D. Parameters of the Three Subordinate Controllers

This paper used (15) to compensate for the field-weaken control of an induction motor, and employed three PI controllers as the subordinate controllers for the IFOC. Table IV lists the computational results from three cases involving different parameters for these PI controllers. This table explains that the flux controller and two current controller parameters (k_{pf}, k_{if}, k_{pc1}, k_{ic1}, k_{pc2} and k_{ic2}) could be roughly chosen, because this task was performed by the proposed FPPC.

E. Responses of the Load Control of the FPPC and PI Controllers

Fig. 6 presents the simulated and experimental speed response results due to a step load torque change, (dT_L=1N • m), using the parameters in Table II to compare the load control responses of the proposed FPPC and conventional PI controllers. The comparisons demonstrate that the proposed FPPC is superior in both its smaller steady state error and quicker response than the conventional PI controllers, in controlling speed loads.

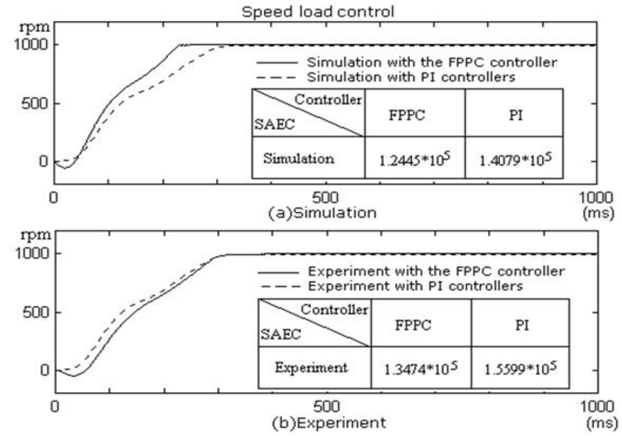

Fig. 6. The speed load control responses of the proposed FPPC and conventional PI controllers.

VI. Conclusions

The proposed controller (FPPC), was presented herein. Fuzzy membership functions, phase plane theory and the IA were employed to design the proposed FPPC to optimally control induction motor speed and load. The contribution of this paper is the methodology of the proposed controller for optimally controlling speed of an induction motor. Simulated and experimental results clearly reveal that the proposed FPPC outperforms conventional PI controllers in optimal speed and load controls.

Acknowledgment

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