Design of Fuzzy Based Iterative Learning Controllers for Induction Motor Drives

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Abstract – This paper investigates the feasibility and performance of applying fuzzy based iterative learning control algorithms in special control applications of induction motors. Based on different motor operating conditions, two control schemes are studied, i.e., proportional plus various iterative learning control algorithms (P+ILC) and proportional-integral plus various iterative learning control algorithms (PI+ILC) with the aid of on-line parameters tuning using a fuzzy controller. The performances of the proposed control schemes are compared with the conventional P- and PI-type controllers in terms of speed tracking errors and robustness when a periodic disturbance is encountered. In hardware implementations, several complex computational and signal processing tasks are accomplished using the TI DSP2812 chip. The simulation tasks and hardware implementation of controllers with various test examples are carried out via a personal computer, DSP and the VisSim software environment. Both simulation and experimental results are presented to show the performance of the proposed control scheme.

Index Terms-- iterative learning control, fuzzy algorithms, induction motors.

I. INTRODUCTION

The induction motors having a number of intrinsic advantages, e.g., rugged, reliable, low cost and simple hardware structure have been widely used in various industrial driving systems. From the mathematical point of view, the induction motor with the stator and rotor energy loops is a highly nonlinear and coupled system. In the past, it was not an easy task to achieve high-level servo control using AC induction motors; therefore, its applications were limited to simple driving operations. In recent years, the fast development in power semiconductors, DSP chips and high-performance microprocessors has made the possibility of using the induction motors in designing advanced driving and control applications. Basically, with the use of vector control technologies, the design of high-performance servo control system on AC induction motors can be achieved as easy as that on DC motors [1-4].

Although there are many studies regarding the design of servo control systems using AC induction motors reported in the open literature, new control means to improve the overall control performance are still call for investigations, especially when special or difficult operating conditions are met. Periodic operating signals are frequently encountered in industrial applications such as rotational machinery and robot controls. There are many industrial control applications, which require compensating periodic signals, e.g., either tracking periodic reference or rejecting periodic disturbances. Good examples of periodic reference signal tracking include, for example, servo control systems [5-6], where high precision tracking performance for a periodic reference is required, control of robot manipulators, where tracking the desired periodic trajectory is required [7-8]. In normal application cases, the most widely used speed controller is the conventional PID controller due to its simplicity from both design and parameter tuning points of view. However, a conventional PID type controller can not provide a high performance in control especially when the control task is tracking a periodic signal with periodic disturbances. To solve the above mentioned problem, this paper presents the analysis and design of novel speed control schemes using the iterative learning control (ILC) and the fuzzy theory [9-14] for the AC induction motor drives.

The original idea about ILC was proposed in 1978 [15-18]. The fundamental concept of ILC is to learn by the experiences of control actions so that the control systems can be self-adjusted. Because there are many restrictions in the application of ILC, it was not widely applied. As addressed previously in the abstract, in the aspect of developing new controllers, this paper investigates two control schemes for the AC induction motors: (1) proportion (P) controller combined with various ILC and (2) PI or PD controller combined with various ILC. In both control schemes a fuzzy controller is used to tune the ILC parameters on-line. In the hardware implementations, the DSP (TI2812) is used as the kernel of controlling induction motor so that the complexity of interface circuit can be reduced. A set of comprehensive simulation tasks and hardware verifications of controllers with various test examples are carried out via a personal computer, DSP and the VisSim software environment. Both simulation and experimental results are presented to show the performance of the proposed control scheme.

II. MODELLING AND CONTROLLER DESIGN

A. The Dynamic Model of Induction Motors

The basic concept in the field oriented vector control (FOVC) of AC induction motors is to make use of two components, magnetic current and torque current, to achieve
the desired control objectives. The main control idea of FOVC is to use the technique of coordinate conversion to convert the three-phase, time-varying AC variables in synchronous rotating coordinate to the equivalent two-phase d-q axes DC values. This follows that through the control of the value of slip the vector of rotor flux can be fixed on the d-axis. Then the torque of motor can be controlled by adjusting the magnitude of q-axis current. In this way, the AC induction motor can be controlled easily just like the control of the DC motor. The dynamic equation of AC induction motor can be written as bellow, in which the stator currents (iₐ and iₜₚ) and the rotor flux (λₐ, λₚ) are set as state parameters under the d-q axes:

\[
\begin{bmatrix}
\dot{i}_a \\
\dot{i}_q \\
\dot{\lambda}_a \\
\end{bmatrix} =
\begin{bmatrix}
-\frac{R_s}{L_s} & \frac{L_m}{L_s} & 0 & \omega - \omega_0 \\
-\frac{R_s}{L_s} & \frac{L_m}{L_s} & 0 & \omega - \omega_0 \\
\frac{L_m}{L_s} & \frac{L_m}{L_s} & -\frac{R_s}{L_s} & \omega - \omega_0 \\
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_q \\
\lambda_a \\
\end{bmatrix}
+ \frac{1}{L_s}
\begin{bmatrix}
\sigma \\
\sigma \\
\sigma \\
\end{bmatrix}
\]  
(1)

where,

- \( \omega \): synchronous angular velocity
- \( \sigma = 1 - \frac{L_m^2}{L_s L_r} \): coefficient of the leakage flux 
- \( \lambda_{ad}, \lambda_{qd} \): rotor flux under d-axis and q-axis
- \( R_s, R_r \): rotor resistance and stator resistance
- \( L_s, L_r \): rotor inductance and stator inductance 
- \( L_m \): mutual inductance between rotor and stator
- \( \rho \): differential operator
- \( \omega_0 \): angular velocity of rotor

Assuming that under steady-state, i.e. the changes of \( \lambda_{ad} \) and \( \lambda_{qd} \) are zero, the following equations can be derived from (1):

\[
0 = \frac{L_m}{L_r} R_i \dot{i}_a - R_r \lambda_{ad} + (\omega - \omega_0) \lambda_{qd} 
\]  
(2)

\[
0 = \frac{L_m}{L_r} R_i \dot{i}_q - (\omega - \omega_0) \lambda_{ad} - R_r \lambda_{qd} 
\]  
(3)

By (2) and (3), the rotor flux under d-axis and q-axis can be calculated:

\[
\lambda_{ad} = \frac{L_m R_i^2 \dot{i}_a - (\omega - \omega_0) R_i L_m L_r i_{a}}{(\omega - \omega_0)^2 L_r^2 + R_r^2} \]  
(4)

\[
\lambda_{qd} = \frac{L_m R_i^2 \dot{i}_q - (\omega - \omega_0) R_i L_m L_r i_{q}}{(\omega - \omega_0)^2 L_r^2 + R_r^2} \]  
(5)

Given the slip \( \omega_s \) as:

\[
\omega_s = \omega_1 - \omega = \frac{R_i}{L_r} i_{a} = \frac{R_i R_s}{L_r} \lambda_{ad} 
\]  
(6)

The electromagnetic torque can be calculated from (5) and (6) as:

\[
T_e = \frac{3}{2} P \frac{L_m}{L_r} \lambda_{ad} i_{a} 
\]  
(7)

(7) can be further simplified into (8).

\[
T_e = \frac{3}{2} P \frac{L_m}{L_r} \lambda_{ad} i_{a} 
\]  
(8)

Based on the vector control theory, if both the slip velocity \( \omega_s \) and the rotor flux \( \lambda_{ad} \) fixed on the d-axis can be kept as constant, the electromagnetic torque of the induction motor can be controlled by the magnitude of q-axis stator current component.

Fig. 1 is the general vector control structure of AC induction motor.

\[
\text{Fig. 1. Vector control structure of an AC induction motor.}
\]

B. Iterative Learning Control

- The Restrictions in Applying ILC

ILC produces the required current control input based on the previous control experience. The whole learning structure is constructed and performed on the continuously adjusting loops. The present adjustment is based on the error of previous control result. In practical applications, ILC has the following restrictions:

(1): The system will be stopped at a limited time, \( T, T > 0 \).

(2): The dynamics of system should be in consistent in every repeated operation.

(3): The initial state \( x_i(0) \) of every repeated operation is equal to the expected ideal initial state, \( x_{i0} \), i.e., \( x_i(0) = x_{i0}, i = 0,1,2,... \). The \( i \) is the number of times of repeated learning operation.

(4): The system can be repeated and the ideal output, \( y_i(t) \), is only caused by the input, \( u_i(t) \).

(5): The present learning output, \( e_i(t) = y_i(t) - y_{i}(t) \), can be applied in the next times’ input \( u_{i+1}(t) \).

(6): The system must be able to get the ideal output at \( t \in [0,T] \).

According to the above restrictions, the ILC control law
can be found as following:

\[ u_{r+1}(t) = f(u_r(t), e_r(t)) \quad \text{and} \quad \lim_{t \to \infty} \|e_r(t)\| = 0. \]

Before the structure of ILC is addressed, the output value of the main controller, \( u_k^p \), should be firstly assumed. In this control case, the \( u_k^p \) is transferred to ILC and then the ILC can calculate its \( u_k^{(1)} \). Adding up \( u_k^{(1)} \) and \( u_k^p \) the control signal, \( u_k(t) \), can be calculated. The mathematic model of P-type ILC can be expressed as follows:

\[ u_k^p = \beta \cdot e_k(t) \quad (9) \]
\[ u_k^p(t) = u_k^{(1)}(t) + L \cdot u_k^p(t) \quad k > 0 \quad (10) \]
\[ u_k(t) = u_k^p(t) + u_k^{(1)}(t) \quad (11) \]

where, \( \beta \) is the main controller; \( L \) is the gain; \( k \) is the number of iterations, \( e_k(t) = y_d(t) - y_k(t) \). Here, if (12) is used to replace (10) the controller of PD-type ILC can be obtained. Similarly, the PI-type ILC can be readily constructed by modify the last term of (12).

\[ u_k^p(t) = u_k^{(1)}(t) + (L_p u_k^p(t) + L_d \frac{du_k^p}{dt}) \quad (12) \]

Again, \( L_p, L_d \) are gains and \( k \) is the number of iterative operations.

- **T-S Fuzzy Systems**

For a T-S fuzzy system with two inputs and a single output, the fuzzy rules are given by (13). To address the inference system of a T-S fuzzy model, Fig. 2 illustrates the result of fuzzy inference as given in (14).

\[ R_1: \text{if } x \text{ is } A_1 \text{ and } y \text{ is } B_1 \text{ then } z = f_1 = p_1 x + q_1 y + r_1 \]
\[ R_2: \text{if } x \text{ is } A_2 \text{ and } y \text{ is } B_2 \text{ then } z = f_2 = p_2 x + q_2 y + r_2 \quad (13) \]
\[ \bar{f} = \frac{w_1 f_1 + w_2 f_2}{w_1 + w_2} = \frac{w_1}{w_1 + w_2} f_1 + \frac{w_2}{w_1 + w_2} f_2 \quad (14) \]

Where \( \bar{w}_1 = \frac{w_1}{w_1 + w_2} \) and \( \bar{w}_2 = \frac{w_2}{w_1 + w_2} \), \( w_i \) can be the lower one or the product of \( A_i \) and \( B_i \) as expressed in (15).

\[ w_i = \min \left( A_i (x), B_i (y) \right) \quad (15) \]
\[ w_i = A_i (x) \times B_i (y) \quad (16) \]

- **T-S Fuzzy System Design on PSO**

Fuzzy controllers belong to the field of intelligent control which are based on soft computing algorithms. The main advantage of using fuzzy controllers in various industrial applications is that the experts’ experiences and other heuristic methods can be applied to obtain a satisfactory performance without the detailed mathematical model of the controlled plant. In this study, the PSO is used to determine the consequent membership functions of the fuzzy controller, while the corresponding antecedent membership functions are assigned to suit the controlled parameters of the systems. In this design case, the rules are to be designed by the PSO algorithm.

![Fig. 2. A two-input first-order Sugeno fuzzy with two rules](image)

1) Design of antecedent membership functions

In this control case, the fuzzy controller has two inputs, \( e \) and \( de \), and one output. The membership functions of both fuzzy inputs are illustrated in Fig. 3. The ranges of inputs are defined at \([-0.3, 0.3]\). Here, two types of membership functions, trapezoidal and triangular types are used. The input, \( e \), has seven membership functions. The membership functions of far left and right are assigned with trapezoidal types, or alternatively with trapezoidal types. The input, \( de \), is designed with five membership functions. All the membership functions for \( de \) are triangular types. The equations describing the trapezoidal and triangular types are respectively shown in (17) and (18).

\[ f(x; l, u, r) = \begin{cases} 0, & x \leq l \\ \frac{x-l}{u-l}, & l \leq x \leq u \\ \frac{r-x}{r-l}, & u \leq x \leq r \\ 0, & r \leq x \end{cases} \quad (17) \]
2) Design of rules
To decide the rules without depending on expert' experiences, all of the rules are given their own consequence membership functions as shown in Table I.

3) Design of consequence membership functions
As can be seen in Table I, every rule has its own membership function. In this study, the PSO algorithm is used to search the membership functions. Equation (19) presents the parameters to be decided by PSO. For zero-order equations, \( MFi = ri \) where \( i = 1, 2, 3...35 \).

\[
p = [r_1, r_2, r_3, ..., r_{35}]^{T}
\]  

(19)

In some control cases, the consequence membership functions have symmetry property. One can take advantage of this characteristic to reduce the number of parameters searched by PSO and to reduce the computation time. The arrangement is briefly expressed in (20).

\[
MF_i = -MF_{36-i}, i = 1, 2, 3...17
\]

(20)

### Table 1: Fuzzy Rules Table
<table>
<thead>
<tr>
<th>Vref</th>
<th>e</th>
<th>mf1</th>
<th>mf2</th>
<th>mf3</th>
<th>mf4</th>
<th>mf5</th>
<th>mf6</th>
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<td>MF10</td>
<td>MF15</td>
<td>MF20</td>
<td>MF25</td>
<td>MF30</td>
<td>MF35</td>
</tr>
</tbody>
</table>

\[ MF_{i} = -MF_{36-i}, i = 1, 2, 3...17 \]

\[ MF_{18} = 0 \]

\[
p = [r_1, r_2, r_3, ..., r_{17}]^{T}
\]

(20)

The Concept of Controller Design
Fig 3. shows the main control structure proposed in this paper which composes the P or PI controller and ILC. Because the proposed control system is designed to counteract the periodic disturbances by continuously adjusting the ILC’s output, the fuzzy block is used to tune the gain of ILC on-line so that the convergent velocity can be speeded up. The fuzzy can be used to tune the gain of ILC if the switch, SW, shown in Fig. 3 is closed.

### III. Simulation and Experimental Results
The hardware implementation of the proposed control structure for the AC induction motor is shown in Fig. 4. In simulation studies, the personal computer and VisSim software are used; while in the experimental tests, the JTAG interface is utilized to communicate the controlled induction parameters and control commands with the DSP.

A. Simulation Results
To verify the feasibility and correctness of the proposed controller, the fuzzy and the related ILC controllers are modeled in Visual C++ languages and induction motor is modeled in VisSim environment for simulative and experimental studies. In the cases of simulations, the P or PD controllers are attempted to work with ILC and the fuzzy function is used to tune the gain of ILC on-line.

**Simulated case 1:**
In this simulation case, four control structures, i.e., control structure 1 (conventional PI controller), control structure 2 (conventional P controller + P_ILC), control structure 3 (conventional P controller + PD_ILC) and control structure 4 (conventional P controller + P_ILC + fuzzy) are tested to compare their performances. The command and parameters of the controller are given as follows: periodic step-type speed command tracking \( n = 600 \text{rpm} \), \( TL = 0.5 \text{n-m} \), \( kp = 0.01 \). A periodic disturbance, \( TL = 0.2 \text{n-m} \), is added to the motor at every half of the speed command cycle. Some typical simulated results of case 1 and 4 are respectively presented in Fig. 5 and 6. As one can see from the presented results, the case 4 with the gain of ILC on-line tuned by using fuzzy controller has much better anti-disturbance effects. The results are achieved within only 5 periods. It is also found that a higher convergent velocity can be obtained by the P type ILC.

**Simulated case 2:**
In this simulation case, two control structures, i.e., control structure 1 (conventional PI controller) and control structure 2 (conventional PI controller + PI_ILC+Fuzzy) are tested to compare their performances. The command and parameters of the controllers are given as follows: the speed tracking command is sine wave with \( n = 600 \text{rpm} \), \( TL = 0.5 \text{n-m} \), \( kp = 3 \) and \( ki = 0.001 \). As can be seen from Fig. 7 and 8 with the proposed controller, the tracking error can be reduced to zero within only three cycles.
Experimental Results
To further confirm the feasibility and effectiveness of the proposed ILC schemes presented in the previous sections, the hardware implementations and tests of the controllers based on DSP are presented in this subsection. Experimental case 1 uses the same condition as that of simulation case 1. The related measured results concerning control structure 1 and 4 (presented in the simulation studies) are respectively presented in Fig. 9 and 10. The experimental study of case 2 uses the same conditions as that of the simulation case 2. Fig. 11 and 12 respectively present the measured control results.

In these figures, the ratio of measured parameters are 1V : 25V for the measured voltage : actual voltage and 1V : 0.5A for the measured voltage : actual current.
IV. CONCLUSION

In this paper, a number of ILC control structures applied to the design of advanced induction motor drives, especially when the periodic disturbances are taking into account are investigated. The design methods and performance of the proposed control schemes have been verified with simulation and experimental tests. Of the feasible control structures, the integration of ILC and the conventional P-type or PI-type controller and on-line tuned by fuzzy control algorithms can efficiently suppressed the periodic disturbances and the lagging phenomenon in sine wave speed tracking.

REFERENCES