Efficient speed control of induction motor using RBF based model reference adaptive control method

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This paper proposes a model reference adaptive speed controller based on artificial neural network for induction motor drives. The performance of traditional feedback controllers has been insufficient in speed control of induction motors due to nonlinear structure of the system, changing environmental conditions, and disturbance input effects. A successful speed control of induction motor requires a nonlinear control system. On the other hand, in recent years, it has been demonstrated that artificial intelligence based control methods were much more successful in the nonlinear system control applications. In this work, it has been developed an intelligent controller for induction motor speed control with combination of radial basis function type neural network (RBF) and model reference adaptive control (MRAC) strategy. RBF is utilized to adaptively compensate the unknown nonlinearity in the control system. The indirect field-oriented control (IFOC) technique and space vector pulse width modulation (SVPWM) methods which are widespread used in high performance induction motor drives has been preferred for drive method. In order to demonstrate the reliability of the control technique, the proposed adaptive controller has been tested under different operating conditions and compared performance of conventional PI controller. The results show that the proposed controller has got a clear superiority to the conventional linear controllers.

Key words: Induction motor, neural network, model reference adaptive control, vector control.

1 INTRODUCTION

Three phase induction motors have been widely used in industrial applications, due to its low maintenance, high robustness, simple structure and high efficiency [1-2]. The speed control of induction motor is more important to achieve maximum torque and efficiency. Many researchers have focused on developing algorithms for effective control of high performance induction motor drives. In the recent studies, it has been seen that neural network based control method is used to increasing the performance of induction motor drives [3-9].

For electrical drives good dynamic performance is mandatory so as to respond to the changes in command speed and torques [10]. Vector controlled drives provide...
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excellent dynamic performance of the induction motor and offers good satisfactory steady state as well as transient response and it works like a separately excited DC motor. This method uses the dynamic mathematical model of induction motor and allows independent control of flux and torque [11-15]. IFOC technique is widely used in induction motor drive system to obtain high performances in terms of torque and speed [4, 16-17].

MRAC has been widely used for control of complex nonlinear systems. In this method, the controller is designed to perform plant output converges to reference model output based on the assumption that plant can be linearized. MRAC is a direct adaptive strategy with some adjustable controller parameters and an adjusting mechanism to adjust them. The performance of MRAC algorithm depends on the choice of a suitable reference model and the derivation of an appropriate learning mechanism [18-20].

In recent years artificial neural networks (ANN) have gained a wide attention in control applications. It is the ability of the artificial neural networks to model nonlinear systems that can be the most readily exploited in the synthesis of non-linear controllers [21]. The learning and adapting capability of neural networks makes them ideal for control purposes. An ANN can be successfully applied even if the motor which is to be controlled and the load parameters are unknown [22]. RBF is powerful computational tools that have been used extensively in the areas of pattern recognition, systems modeling and identification [23]. RBF has shown its potential for online identification and control, and hence arouses much research interest. The nonlinear part of the controller, which compensates the plant nonlinearity, is implemented by an RBF network [24].

In this study, RBF based MRAC approach has been developed to increase the performance and efficiency of induction motor drive. The performances of proposed and PI controllers have been analyzed under different operating conditions for the induction motor drive system which has been implemented via MATLAB software. In order to determine the success of the proposed controller, the results are compared by performance of conventional PI controller. The results demonstrated that the control performance of RBF based MRAC scheme is better than the performance of PI controller.

2 DYNAMIC MODEL OF INDUCTION MOTOR

The \( d-q \) transformation is a mathematical transformation that is used to simplify the analysis of three phase circuit. A dynamic \( d-q \) model of the induction motor to be controlled must be known in order to understand, analyze and design vector controlled drives. It has been found that the dynamic model equations developed on a rotating reference frame is easier to describe the characteristics of induction motors. The mathematical model of induction motor can be expressed in the \( d-q \) synchronously rotating frame by the following nonlinear equations [25-28]:

\[
\frac{di_{sd}}{dt} = \frac{1}{\sigma L_s} \left[ -R_E i_{sd} + \sigma L_s \omega_s i_{sq} + \frac{L_m R_r}{L_r^2} \psi_{rd} + \omega_r \frac{L_m}{L_r} \psi_{rq} + V_{sd} \right]
\]

\[
\frac{di_{sq}}{dt} = \frac{1}{\sigma L_s} \left[ -R_E i_{sq} - \sigma L_s \omega_s i_{sd} + \frac{L_m R_r}{L_r^2} \psi_{rd} - \omega_r \frac{L_m}{L_r} \psi_{rq} + V_{sq} \right]
\]

\[
\frac{d\psi_{rd}}{dt} = \frac{R_r L_m}{L_r^2} i_{sd} - \frac{R_r}{L_r} \psi_{rd} + \omega_s (\omega_r - \omega_r) \psi_{rq}
\]

\[
\frac{d\psi_{rq}}{dt} = \frac{R_r L_m}{L_r^2} i_{sq} - \frac{R_r}{L_r} \psi_{rq} - \omega_s (\omega_r - \omega_r) \psi_{rd}
\]

\[
\frac{d\omega_r}{dt} = \frac{3 \rho L_m}{2 J L_r} \left( i_{sq} \psi_{rd} - \psi_{rq} i_{sd} \right) - \frac{B}{J} \omega_r - \frac{T_L}{J}
\]

where \( R_E = R_s + \frac{\rho^2 L_r^2}{L_m^2} \) is equivalent resistance, \( \sigma = 1 - \frac{L_r^2}{L_m L_r^2} \) is leakage coefficient, \( \omega_m = \frac{p}{p} \) is mechanical speed. \( \omega_s \) and \( \omega_r \) are synchronous angular speed, rotor angular speed respectively; \( V_{sd} \) and \( V_{sq} \) are \( d-q \) axes stator voltages; \( i_{sd}, i_{sq}, \psi_{rd} \) and \( \psi_{rq} \) are \( d-q \) axes stator currents and rotor fluxes respectively; \( R_r \) and \( R_r' \) are stator and rotor resistances respectively; \( L_s \) and \( L_r' \) are stator and rotor main inductances respectively, \( L_m \) is mutual inductance between stator and rotor; \( p \) is number of motor poles; \( J \) is the moment of inertia of the motor and load; \( B \) is viscous friction coefficient of the motor; \( T_L \) is load torque.

The state space model of induction motor is the nonlinear differential equations due to state variables multiplied by angular speed. The state variables are \( i_{sd}, i_{sq}, \psi_{rd} \) and \( \psi_{rq} \) and \( \omega_r \).

To obtain high dynamic performance, the induction motors can be operated as a separately excited DC motor with IFOC technique. It is necessary to take the following dynamic equations into consideration to implement the IFOC technique. The electromagnetic torque is given by:

\[
T_e = \frac{3 p L_m}{4 J L_r} (i_{sq} \psi_{rd} - \psi_{rq} i_{sd})
\]

The motor slip frequency can be calculated as:

\[
\omega_{sl} = \omega_s - \omega_r = \frac{L_s}{R_r} \frac{i_{sq}}{i_{sd}}
\]

Rotor electrical position is given by:

\[
\theta_s = \int \omega_s dt = \int (\omega_r + \omega_{sl}) dt = \theta_r + \theta_{sl}
\]
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3 SPACE VECTOR PULSE WIDTH MODULATION

SVPWM method is an advanced, computation-intensive PWM method and possibly the best PWM techniques for three phase voltage source inverter in applications such as control of induction motors and permanent magnet synchronous motors. Due to its superior performance characteristics, it has been to find a common application in recent years. This technique can be easily implemented into modern DSP based control systems.

The three phase output voltage is represented by a reference voltage vector which rotates at an angular speed of \( \omega = 2\pi f \). SVPWM is based on the fact that there are only two independent variables in three-phase voltage system. Given three output voltages of inverter \((V_a, V_b, V_c)\), the vector components \((V_\alpha, V_\beta)\) in this frame are found by the Clarke transform [29-32].

\[
\overrightarrow{V}_{\text{ref}} = \overrightarrow{V}_\alpha + j \overrightarrow{V}_\beta = \frac{2}{3} \left( V_{a0} \cdot e^{j\frac{\pi}{3}} + V_{b0} \cdot e^{j\frac{2\pi}{3}} + V_{c0} \cdot e^{j\frac{4\pi}{3}} \right) \tag{9}
\]

where \( \overrightarrow{a} = e^{j\frac{2\pi}{3}} \). The voltage source inverter enables to realize eight switching combinations. The circuit model of a three-leg voltage source PWM inverter is shown in Fig. 1. \(Q_1\) to \(Q_6\) are six power switches that shape output, which are controlled by the switching variables \(a-a', b-b', c-c'\). \(V_{\text{ref}}\), voltage vector is obtained with two null vectors and six active vectors that can be calculated as:

\[
V_{k} = \frac{2}{3} V_{dc} e^{j(k-1)\frac{\pi}{3}} \quad k = 1, 2, 3, 4, 5, 6 \tag{10}
\]

Any reference vector \(V_{\text{ref}}\) can be approximated by having the inverter in switching states \(V_k \) and \(V_{k+1}\) for \(T_k\) and \(T_{k+1}\) duration of time respectively. The space vector diagram is divided into six equal sectors denoted as 1, 2, 3, 4, 5, 6 in Fig. 2.

The time interval \(T_k\) and \(T_{k+1}\) can be calculated as:

\[
\begin{bmatrix}
T_k \\
T_{k+1}
\end{bmatrix} = \begin{bmatrix}
\sqrt{3} T_s \\
2 V_{dc}
\end{bmatrix} \begin{bmatrix}
\sin \frac{k\pi}{3} - \cos \frac{k\pi}{3} \\
- \sin((k-1)\frac{\pi}{3}) \cos((k-1)\frac{\pi}{3})
\end{bmatrix} \begin{bmatrix}
V_\alpha \\
V_\beta
\end{bmatrix}
\tag{11}
\]

where \(T_s\) is one sampling interval. The zero period \(T_0\) can be calculated as:

\[
\frac{T_S}{2} = T_0 + T_k + T_{k+1} \Rightarrow T_0 = \frac{T_S}{2} - T_k + T_{k+1} \tag{12}
\]

The rotating reference vector \(V_{\text{ref}}\) with in hexagon is presented by following equation:

\[
V_{\text{ref}} = \frac{T_k}{T} V_k + \frac{T_{k+1}}{T} V_{k+1} \tag{13}
\]

Switching sequence for inverter in the sector-1 is depicted in the Fig. 3. This type of symmetrical pulse pattern produces minimal harmonics in output.

4 DESIGN OF RBF BASED MRAC CONTROLLER

RBF neural network is a kind of neural network that uses radial basis functions as activation function. Because of the good generalization capabilities and a simple network structure, RBF neural network has recently attracted much attention. The RBF neural network has three layers. The input layer consists of the source nodes; the hidden layer is composed of nonlinear units; the output layer is a linear [23-24]. The structure of RBF neural network is shown in Fig. 4. Training of RBF includes process of de-
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The aim of the model reference adaptive system is to design a controller that forces the process to track the model output. To design the controller, the control law can be proposed as in the following form:

\[ V_{sdq}(t) = -a_{mq}i_{sdq}(t) + k_{mq}i_{sdq ref}(t) + N_f [i_{sdq}(t), w(t)] \]  
\[ V_{sd}(t) = -a_{md}i_{sd}(t) + k_{md}i_{sd ref}(t) + N_f [i_{sd}(t), w(t)] \]  

where \( N_f \) is the output of RBF network, \( w \) is weight vector of the RBF neural network [8, 37-39].

\[ N_f [i_{sdq}(t), w(t)] = \sum_{j=1}^{J} w_{jk} \exp \left[ \frac{-∥i_{sdq}(t) - c_j∥^2}{2σ^2} \right] \]  

(20)
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Fig. 6: Simulation block diagram.

(16)-(19) can be considered together re-written as follow:

\[
\begin{align*}
\dot{i}_{sdq}(t) - a_m[i_{sdq}(t) - i_{sdqm}(t)] &= N_f[i_{sdq}(t), w(t)] - f[i_{sdq}(t)] \\
\end{align*}
\]

(21)

When \( N_f \) approaches asymptotically \( f(.) \), the current tracking error \( e(t) \) tends to zero. This is obtained by comparing the reference model output and the plant output for \( d \) and \( q \) axes currents.

\[
\begin{align*}
e(t) &= i_{sdq}(t) - i_{sdqm}(t) \\
\dot{e}(t) + a_m e(t) &\approx 0
\end{align*}
\]

(22)

(23)

The adjustable parameters of RBF network that are weights, network center and width of basis function are online updating by using back-propagation training algorithm and tracking error.

\[
\begin{align*}
w_{kj}(t+1) &= w_{kj}(t) + \eta e(t)\varphi_j \\
c_j(t+1) &= c_j(t) + \eta e(t)\varphi_j w_j \frac{|x - c_j|}{\sigma^2} \\
\sigma_j(t+1) &= \sigma_j(t) + \eta e(t)\varphi_j w_j \frac{|x - c_j|}{\sigma^3}
\end{align*}
\]

(24)

(25)

(26)

where \( \eta \in (0, 1) \) is learning rate.

5 SIMULATION RESULTS

The IFOC induction motor drive system is simulated by using MATLAB software. The block diagram of system is shown in Fig. 6. In the PI type control study, all controllers are used as PI type controller. In RBF based MRAC control study, PI type controller was used for speed control loop and RBF based MRAC type controllers were used for current loop.

The output of controllers is limited according to the capacity of the system. In the driving of induction motor, IFOC and SVPWM have been used. For both types of controller, the performance of induction motor drive is presented during starting, step change in speed and load. The results of proposed controllers have been compared with that of PI controllers. During the whole operation, a noise shaped disruptive is added to the load.

In this study, the inverter DC-link voltage is 530 VDC, switching frequency is \( f_s = 5 \) kHz, and simulation sampling time is \( T_s = 0.02 \) msec.

Simulation case 1: The induction motor is started under no-load torque until the 19 Nm sudden load is applied at \( t = 1.0 \) sec. The reference speed is increased from 1000 rpm to 1400 rpm at \( t = 0.5 \) sec and decreased from 1400 rpm to 800 rpm at \( t = 1.5 \) sec. The response of drive system is shown in Fig.7. In the PI-type control study it reached 1000 rpm in 0.17 sec and 1400 rpm in 0.59 sec. In the RBF based MRAC control study it reached 1000 rpm in 0.16 sec and 1400 rpm in 0.56 sec. The reached time of RBF based MRAC controller is shorter than reached time of PI controller for all reference speed. In the PI control study, the speed dips to 1370 rpm and takes 0.15 sec to recover the speed to rated value. In the RBF based MRAC control study the speed dips to 1386 rpm and takes 0.05 sec to recover the speed to rated value.

Fig. 7 shows that RBF based MRAC controller has a shorter rise time, settling time, and recovery time than PI controller. Also proposed controller has the fast torque response and low torque ripple.

Simulation case 2: The induction motor is started up with a constant load of 10 Nm. The reference speed is set to 1000 rpm for forward and \(-1000\) rpm for reverse direction. The speed reversal command is applied at \( t = 1.0 \) sec. The response of drive system is shown in Fig.8.

In PI control, rise time is 0.39 sec for forward direction and 0.3 sec for reverse direction. In RBF based MRAC control, rise time is 0.32 sec for forward direction and 0.22 sec for reverse direction. The percent overshoot and steady-state error is equal to zero for both controllers.

Fig.8 shows that RBF based MRAC controller has a shorter rise time and settling time than PI controller. Also RBF based MRAC controller has the fast torque response and low torque ripple. It can be observed from Fig. 8, when the motor is started, RBF controller has a lower performance than PI controller. Due to adaptive structure of proposed controller it has been increased performance of the induction motor drive system.

6 CONCLUSION

The induction motors are widely used in industrial applications require to be controlled effectively. In this study, high efficient RBF based MRAC algorithm has been developed for vector control of induction motor drive. This
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(a) Load of torque
(b) Speed response
(c) Speed response at sudden load
(d) Torque response
(e) The quadrature current ($I_q$)
(f) The stator current ($i_a$)

Fig. 7: Simulation results during step change in speed command and sudden load
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Fig. 8: Simulation results during reversal command speed under constant load

(a) Load of torque

(b) Speed response

(c) Speed response at rise load

(d) Torque response

(e) The quadrature current ($I_q$)

(f) The stator current ($i_a$)
method has been tested by MATLAB software using dynamic model of the induction motor in $d$-$q$ axis plane under different operations. The RBF based MRAC method has shown better performance response of all conditions when compared with the results obtained using conventional PI type control method. It can be claimed that the proposed controller is highly successful in speed tracking under severe loading conditions and variable speed references. The simulation results show that the RBF based MRAC method is the efficient control method for vector controlled induction motors. The proposed control method can be used in the motor applications when the high dynamic performance, wide speed range and low torque ripple is required.

APPENDIX A MOTOR PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$</td>
<td>3 kW</td>
</tr>
<tr>
<td>$U$</td>
<td>380 V</td>
</tr>
<tr>
<td>$I$</td>
<td>6, 7 A</td>
</tr>
<tr>
<td>$M$</td>
<td>19 Nm</td>
</tr>
<tr>
<td>$R_s$</td>
<td>1.45 $\omega$</td>
</tr>
<tr>
<td>$L_s$</td>
<td>0.2 H</td>
</tr>
<tr>
<td>$L_m$</td>
<td>0.1878 H</td>
</tr>
<tr>
<td>$J$</td>
<td>0.03 kg.m$^2$</td>
</tr>
</tbody>
</table>

REFERENCES

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