Online ISSN 1848-3380, Print ISSN 0005-1144
ATKAFF 57(3), 714–723(2016)

Erdal Kilic, Hasan Riza Ozcalik, Saban Yilmaz

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

DOI 10.7305/automatika.2017.02.1330
UDK [681.513.66-531.6:621.313.333.044]:004.032.26

Original scientific paper

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.

Učinkovito upravljanje brzinom induktivnog motora korištenjem metode adaptivnog upravljanja s referentnim modelom zasnovane na RBF-u. Ovaj rad prikazuje adaptivni regulator s referentnim modelom zasnovan na neuronskoj mreži za induktivne motore. Ponašanje tradicionalnih regulatora s povratnom vezom pokazalo se nedovoljno dobrom za upravljanje brzinom induktivnih motora zbog nelineatnosti strukture sustava, promjene okolišnih uvjeta, i efekta ulaznih poremećaja. Uspješno upravljanje brzinom induktivnog motora zahtjeva nealinearne upravljačke sustave. S druge strane, posljednjih godina pokazano je kako su upravljačke metode zasnovane na umjetnoj inteligenciji bitno uspješnije u primjenama upravljanja nelinearnim sustavima. U ovome radu razvijen je inteligentni regulator za upravljanje brzinom induktivnog motora s kombinacijom radijalne neuronske mreže (RBF) i strategije adaptivnog regulatora s referentnim modelom (MRAC). RBF je realiziran kako bi adaptivno kompenzirao nepoznatu nelinearnost u sustavu upravljanja. Tehnika indirektnog vektorskog upravljanja (IFOC) i metoda prostorno vektorske širinsko impulsne modulacije koje su široko korištene za induktivne motore visokih performansi preferirani su kao metode u ovome radu. Kako bi se prikazala pouzdanost tehnike upravljanja, predloženi adaptivni regulator ispitan je u različitih uvjetima rada i uspoređeno je vladanje s obzirom na konvencionalni PI regulator. Rezultati pokazuju kako predloženi regulator očito pokazuje bolje vladanje od konvencionalnih linearnih regulatora.

Ključne riječi: Induktivni motor, neuronska mreža, adaptivno upravljanje s referentnim modelom, vektorsko upravljanje.

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 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]:

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

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

$$\frac{d\psi_{rd}}{dt} = \frac{R_r L_m}{L_r} i_{sd} - \frac{R_r}{L_r}\psi_{rd} + (\omega_s - \omega_r)\psi_{rq} \quad (3)$$

$$\frac{d\psi_{rq}}{dt} = \frac{R_r L_m}{L_r} i_{sq} - \frac{R_r}{L_r}\psi_{rq} - (\omega_s - \omega_r)\psi_{rd} \quad (4)$$

$$\frac{d\omega_r}{dt} = \frac{3}{2}\frac{pL_m}{JL_r}(i_{sq}\psi_{rd} - \psi_{rq} i_{sd}) - \frac{B}{J}\omega_r - \frac{T_L}{J} \quad (5)$$

where $R_E = R_s + \frac{R_r' L_m^2}{L_r^{2'}}$ is equivalent resistance, $\sigma = 1 - \frac{L_m^2}{L_s L_r^{2'}}$ is leakage coefficient, $\omega_m = \frac{\omega_r}{p}$ is mechanical speed. ω_s and ω_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 ψ_{rq} are *d-q* axes stator currents and rotor fluxes respectively; R_s 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 ψ_{rq} and ω_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:

$$T_e = \frac{3}{4}\frac{pL_m}{L_r}(i_{sq}\psi_{rd} - \psi_{rq} i_{sd}) \quad (6)$$

The motor slip frequency can be calculated as:

$$\omega_{sl} = \omega_s - \omega_r = \frac{L_r}{R_r}\frac{i_{sq}^*}{i_{sd}^*} \quad (7)$$

Rotor electrical position is given by:

$$\theta_s = \int \omega_s.dt = \int (\omega_r + \omega_{sl}) = \theta_r + \theta_{sl} \quad (8)$$

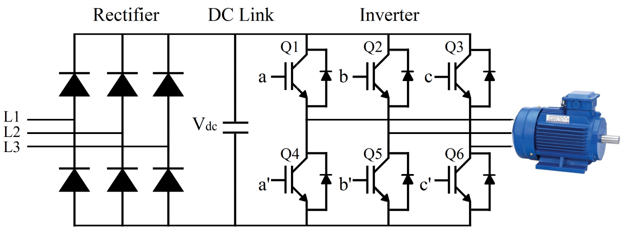


Fig. 1: *Three phase voltage source inverter.*

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_{a0}, V_{b0}, V_{c0}), the vector components $(V_\alpha V_\beta)$ in this frame are found by the Clarke transform [29-32].

$$\overrightarrow{V_{ref}} = \overrightarrow{V_\alpha} + j\overrightarrow{V_\beta} = \frac{2}{3}\left(V_{a0}.\overrightarrow{a}^{0} + V_{b0}.\overrightarrow{a}^{1} + V_{c0}.\overrightarrow{a}^{2}\right) \quad (9)$$

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_{ref}, voltage vector is obtained with two null vectors and six active vectors that can be calculated as:

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

Any reference vector V_{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:

$$\begin{bmatrix} T_k \\ T_{k+1} \end{bmatrix} = \quad (11)$$

$$\frac{\sqrt{3}T_s}{2V_{dc}} \begin{bmatrix} \sin\frac{k\pi}{3} & -\cos\frac{k\pi}{3} \\ -\sin(k-1)\frac{\pi}{3} & \cos(k-1)\frac{\pi}{3} \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix}$$

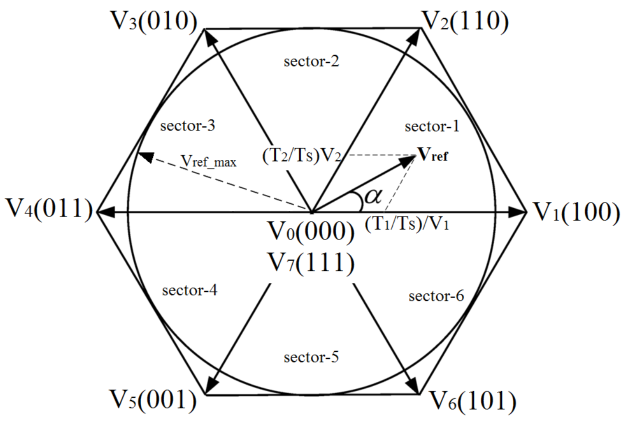


Fig. 2: *Space vector diagram.*

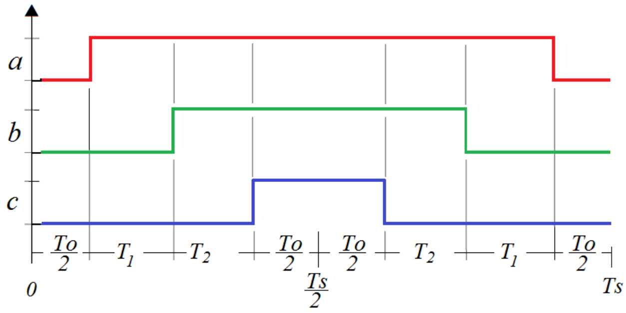


Fig. 3: *SVPWM switching sequence.*

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

$$\frac{T_S}{2} = T_0 + T_k + T_{k+1} \Rightarrow T_0 = \frac{T_S}{2} - T_k + T_{k+1} \quad (12)$$

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

$$V_{ref} = \frac{T_k}{T}V_k + \frac{T_{k+1}}{T}V_{k+1} \quad (13)$$

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 DESING 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-

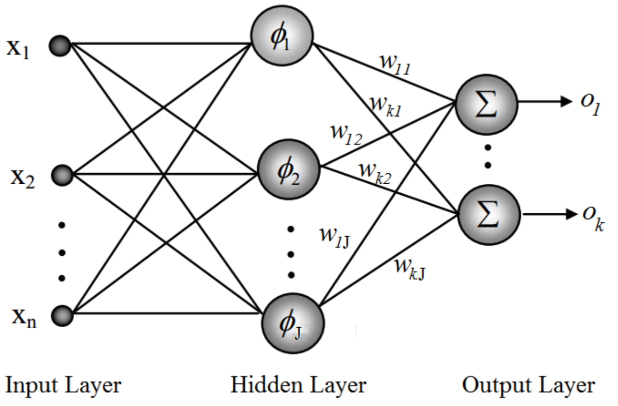


Fig. 4: *Structure of RBF network.*

termining of adaptive parameters that are network center (*cj*), width of basis function (σ_j) and output layer weights (w_{kj}). c_j and σ_j must be chosen according to the scope of the input value [33-36]. The back-propagation algorithm is used to update parameters of RBF. The output of each hidden unit can be calculated as:

$$\varphi_j(x) = \exp\left[\frac{-\left\|x - c_j\right\|^2}{\sigma_j^2}\right] \qquad (14)$$

where ϕ_j denotes the output of the j_{th} node in hidden layer, x is the input vector, $||x - c_j||$ is Euclidian distance function, c_j is center of the j_{th} gaussian function, σ_j is the width of the gaussian function of the j_{th} node and J denotes the number of hidden layer nodes. The transformation to hidden layer to output layer is a linear and it can be computed as following:

$$o_k = \sum_{j=1}^{J} w_{kj}\varphi_j(x) \qquad (15)$$

where w_{kj} is weights of the RBF network and Φ_j is the radial basis function.

MRAC method has been used to design an adaptive controller. In MRAC scheme, the actual plant output is forced to asymptotically track the reference model output by adjusting controller parameters.

The proposed adaptive controller structure consists of two main component parts, a reference model and a RBF neural network. RBF neural network based proposed controller produces controller signal to compensate nonlinearity of plant and following the reference model output. The reference model is very stable linear filter which is supplying set values to be imitated by induction motor. The nonlinear part of the controller has been implemented by RBF network [8, 37]. The reference model and machine

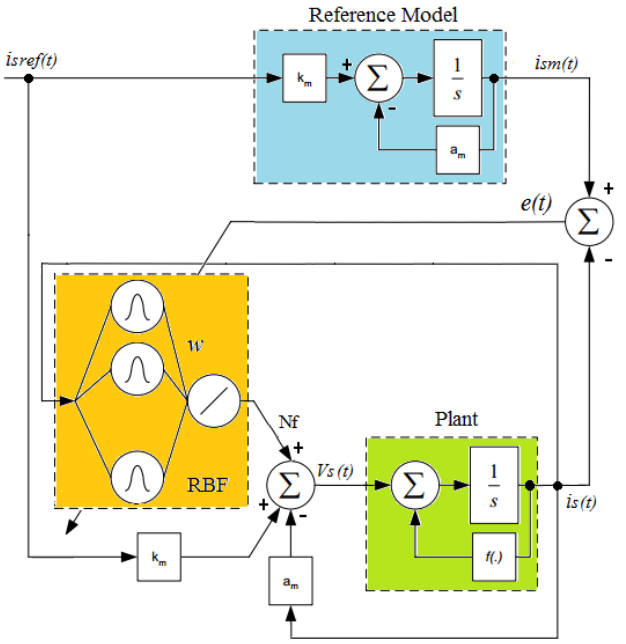


Fig. 5: *RBF based MRAC system structure.*

can be represented by the following differential equation:

$$\overset{\bullet}{i}_{sdq}(t) + f\left[i_{sdq}(t)\right] = V_{sdq}(t) \qquad t \geq 0 \qquad (16)$$

$$\overset{\bullet}{i}_{sdqm}(t) + a_m i_{sdqm}(t) = k_m i_{sdqref}(t) \qquad t \geq 0 \qquad (17)$$

where $V_{sdq}(t)$ ($V_{sq}(t)$ and $V_{sd}(t)$) is output of current controller, $i_{sdq}(t)$ ($i_{sq}(t)$ and $i_{sd}(t)$) is current of induction motor and $f(.)$ is unknown static nonlinear function which is continuously differentiable and Lipschitz; k_m and a_m real positive coefficients which are tuned appropriately in the preparation of control software. The main objective the control is to obtain desired control inputs, $V_{sq}(t)$ and $V_{sd}(t)$ by updating the network parameters. Diagram of the control system which obtained using this structure is presented in Fig. 5.

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:

$$V_{sq}(t) = -a_{mq} i_{sq}(t) + k_{mq} i_{sqref}(t) + N_f\left[i_{sq}(t), w(t)\right] \qquad (18)$$

$$V_{sd}(t) = -a_{md} i_{sd}(t) + k_{md} i_{sdref}(t) + N_f\left[i_{sd}(t), w(t)\right] \qquad (19)$$

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

$$N_f\left[i_{sdq}(t), w(t)\right] = \sum_{j=1}^{J} w_j(t) \exp\left[\frac{\left\|i_{sdq}(t) - c_j\right\|^2}{2\sigma^2}\right] \qquad (20)$$

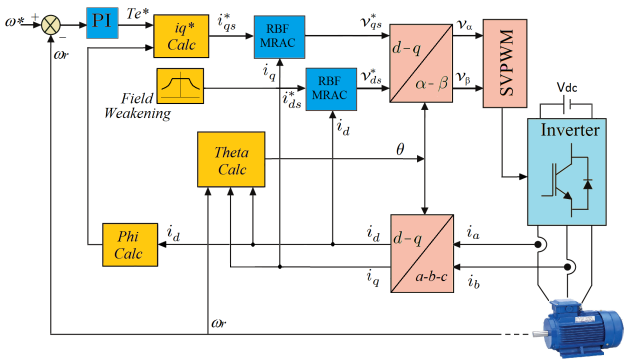


Fig. 6: *Simulation block diagram.*

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

$$\left[\dot{i}_{sdq}(t) - \dot{i}_{sdqm}(t)\right] + a_m\left[i_{sdq}(t) - i_{sdqm}(t)\right] \\ = N_f\left[i_{sdq}(t), w(t)\right] - f\left[i_{sdq}(t)\right] \tag{21}$$

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.

$$e(t) = i_{sdq}(t) - i_{sdqm}(t) \tag{22}$$

$$\dot{e}(t) + a_m e(t) \approx 0 \tag{23}$$

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.

$$w_{kj}(t+1) = w_{kj}(t) + \eta e(t)\varphi_j \tag{24}$$

$$c_j(t+1) = c_j(t) + \eta e(t)\varphi_j w_j \frac{(x - c_j)}{\sigma^2} \tag{25}$$

$$\sigma_j(t+1) = \sigma_j(t) + \eta e(t)\varphi_j w_j \frac{\|x - c_j\|}{\sigma^3} \tag{26}$$

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.

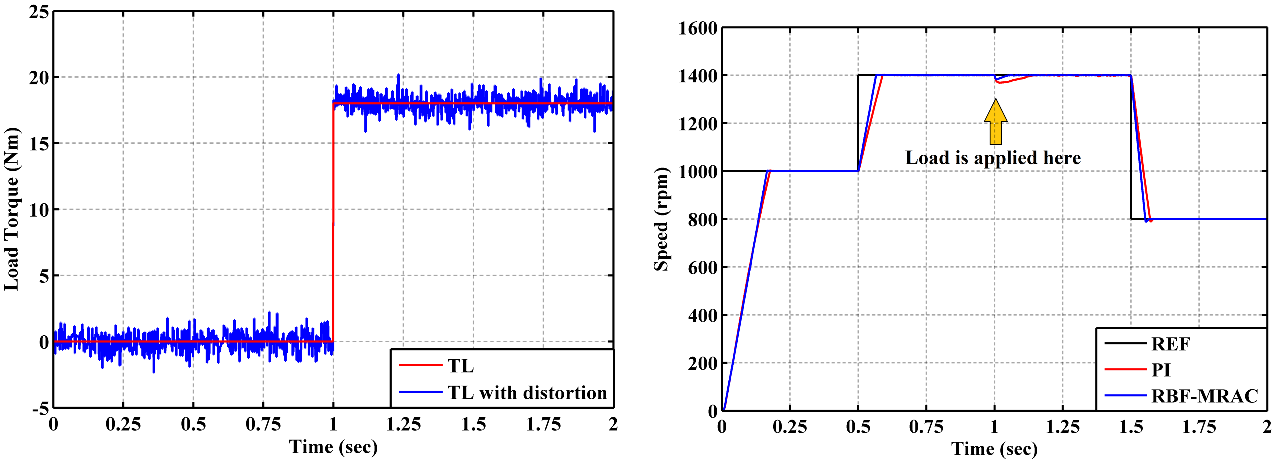
Simulation case 2: The induction motor is started up with a constant load of 10 Nm. The reference speed is set to 1000 rpm for forward and −1000 rpm for reverse direction. The speed reversal command is applied at $t = 1.0$ sec. The response of drive system is shown in Fig.8.

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.

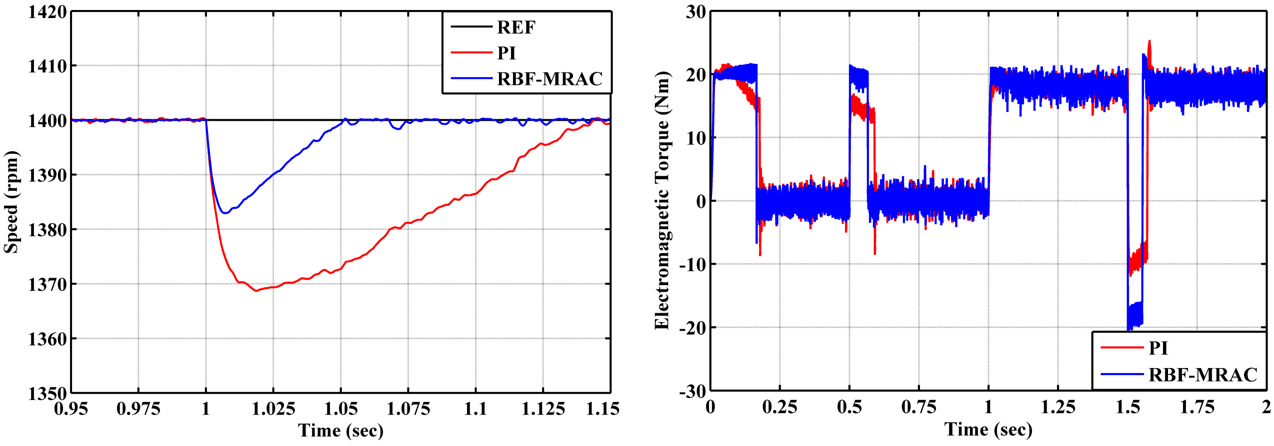
6 CONCLUSION

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



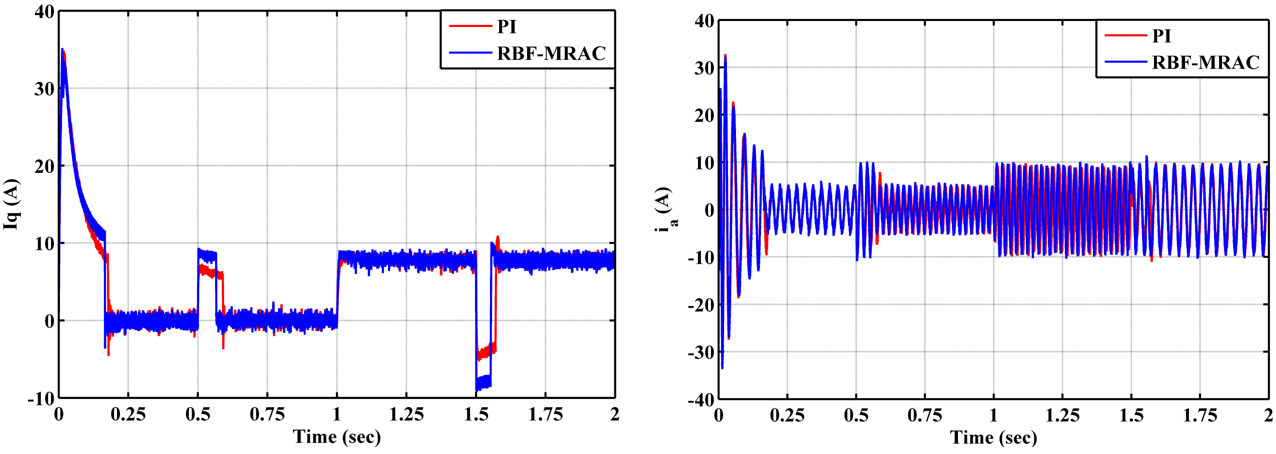
(a) *Load of torque*

(b) *Speed response*



(c) *Speed response at sudden load*

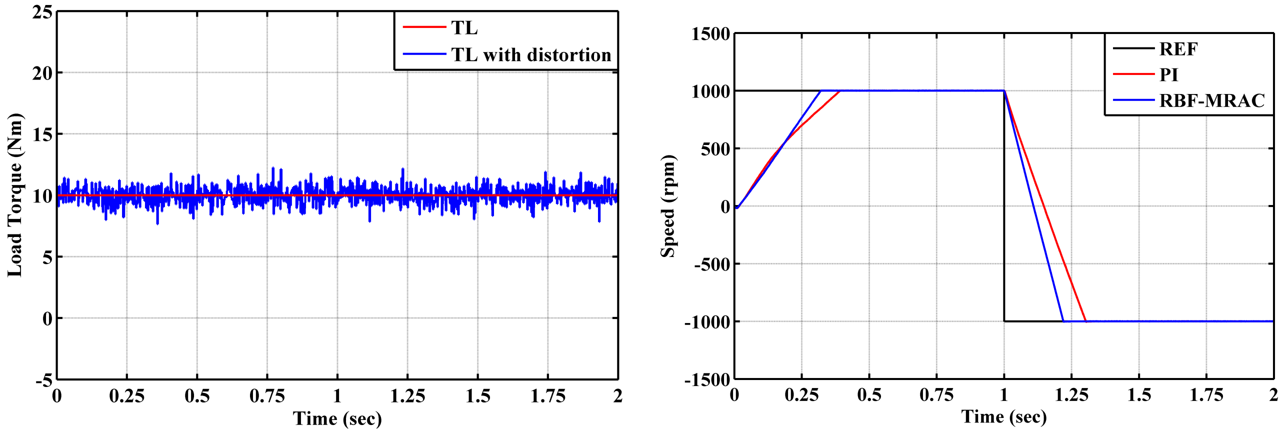
(d) *Torque response*



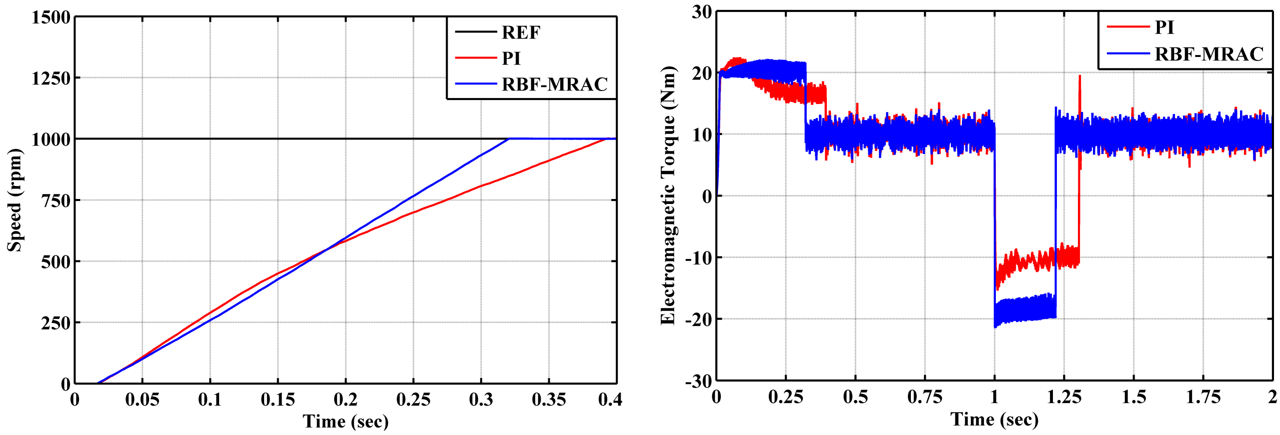
(e) *The quadrature current* (I_q)

(f) *The stator current* (i_a)

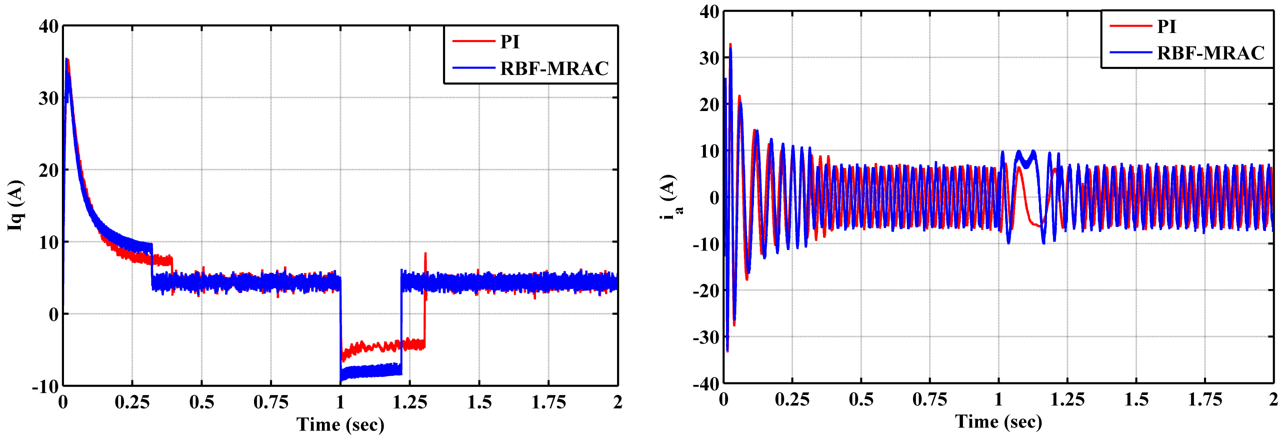
Fig. 7: *Simulation results during step change in speed command and sudden load*



(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)

Fig. 8: *Simulation results during reversal command speed under constant load*

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

$P = 3\,\mathrm{kW}$	$R_s = 1,45\,\omega$	$n = 1430\,\mathrm{d/d}$
$U = 380\,\mathrm{V}$	$R'_r = 1,93\,\omega$	$J = 0,03\,\mathrm{kg.m2}$
$I = 6,7\,\mathrm{A}$	$L_s = 0,2\,\mathrm{H}$	$L_m = 0,1878\,\mathrm{H}$
$M = 19\,\mathrm{Nm}$	$L'_r = 0,2\,\mathrm{H}$	$B = 0,03\,\mathrm{Nm.s/rad}$

REFERENCES

[1] Blaschke, F., “The Principle of Field-Orientation as applied to the New Transvector Closed-Loop Control System for Rotating-Field Machines”, Siemens Review 34, 217-220, 1972.

[2] T.F. Chan, K. Shi, Applied Intelligent Control of Induction Motor Drives, IEEE Willey Press, First edition, 2011.

[3] Reddy, M.H.V., Jegathesan, V., “Open Loop V/f Control of Induction Motor Based on Hybrid PWM with Reduced Torque Ripple”, Emerging Trends in Electrical and Computer Technology (ICETECT), 2011 International Conference on, 23-24 March 2011, pp.331-336.

[4] A. Mechernene, M. Zerikat, S. Chekroun, “Adaptive Speed Observer using Artificial Neural Network for Sensorless Vector Control fof Induction Motor Drive”, Automatika Journal of Control, Measurement, Electronics, Computing and Communications, Vol.53, No.3, 2012.

[5] A. Mishra, P. Choudhary, “Artificial Neural Network Based Controller for Speed Control of an Induction Motor using Indirect Vector Control Method”, International Journal of Power Electronics and Drive System (IJPEDS), Vol.2, No.4, December 2012, pp.402-408.

[6] P.M. Menghal, A.J. Laxmi, N. Mukhesh, “Dynamic Simulation of Induction Motor Drive using Neuro Controller” Int. J. on Recent Trends in Engineering and Technology, Vol. 10, No. 2, Jan 2014.

[7] E. Kilic, H.R. Ozcalik, S. Yilmaz, S. Sit, “A Comparative Analysis of FLC and ANFIS Controller for Vector Controlled Induction Motor Drive”, IEEE International Conference on ACEMP-OPTIM-ELECTROMOTION 2015, Side, Turkey, 2015, pp.102-106.

[8] H.R. Ozcalik, C. Yıldız, M. Danaci, Z. Koca,“RBF Based Induction Motor Control with a Good Nonlinearity Compensation”, Lecture Notes in Computer Science, 4507: 878-886, 2007.

[9] M. Sekkeli, C. Yıldız, H.R. Ozcalik, “Fuzzy Logic Based Intelligent Speed Control of Induction Motor Using Experimental Approach” International Symposium on Innovaitons in Intelligent Systems and Applications, Trabzon/Turkey, 2009 INISTA, pp.151-154.

[10] P. Tripura, Y.S.K. Babu, “Fuzzy Logic Speed Control of Three Phase Induction Motor Drive” World Academy of Science, Engineering and Technology 60 2011.

[11] F. Lima, W. Kaiser, I.N. Silva, A. Oliveira, “Open-Loop Neuro-fuzzy Speed Estimator Applied to Vector and Scalar Induction Motor Drives”, Applied Soft Computing Vol. 21, August 2014, pp.469-480.

[12] T. Ramesh, A.K. Panda, S.S. Kumar, “Type-2 Fuzzy Logic Control Based MRAS Speed Estimator for Speed Sensorless Direct Torque and Flux Control of an Induction Motor Drive”, ISA Transactions, April 2015.

[13] A. Mahesh, B. Singh, “Vector Control of Induction Motor Using ANN and Particle Swarm Optimization”, International Journal of Emerging Technology and Advanced Engineering, ISSN 2250-2459, Volume 2, Issue 9, September 2012.

[14] J.A. Santisteban, R.M. Stephan, “Vector Control Methods for Induction Machines: An Overview”, IEEE Transactions on Education, Vol.44, No.2, May 2001.

[15] H. Acikgoz, O.F. Kececioglu, A. Gani, M. Sekkeli, “Speed Control of Direct Torque Controlled Induction Motor By using PI, Anti-Windup PI And Fuzzy Logic Controller” Intelligent Systems and Applications in Engineering (IJISAE) Vol.2 No.3, 2014, pp.58-63.

[16] T.V. Mumcu, I. Aliskan, K. Gulez, G. Tuna, “Reducing Moment and Current Fluctuations of Induction Motor System of Electrical Vehicles by using Adaptive Field Oriented Control”, ELEKTRONIKA IR ELEKTROTECHNIKA, ISSN 1392-1215, Vol.19, No.2, 2013.

[17] W. Cheng Pu, Y. Chang Luo, P. Yan Chu, “Sensorless Stator Field-Oriented Controlled IM Drive at Low Speed with Rr Estimator”, Hindawi Publishing Corporation Mathematical Problems in Engineering Volume 2014, Article ID 676202, 13 pages.

[18] P. Jain, M.J. Nigam, “Design of a Model Reference Adaptive Controller Using Modified MIT Rule for a Second Order System”, Advance in Electronic and Electric Engineering, ISSN 2231-1297, Volume 3, Number 4 (2013), pp. 477-484.

[19] R. Prakash, R. Anita, “Modeling and Simulation of Fuzzy Logic Controller-Based Model Reference Adaptive Controller”, International Journal of Innovative Computing, Information and Control, Vol.8, Number 4, April 2012.

[20] K. Al-Aubidy, M. Ali, "A Hierarchical Neuro-Fuzzy MRAC of a Robot in Flexible Manufacturing Environment", The International Arab Journal of Information Technology, Vol.1, No.2, July 2004.

[21] J. Zilkova, J. Timko, P. Girovsky, "Nonlinear System Control Using Neural Networks", Acta Ploytechnica Hungarica, Vol.3, No.4, 2006.

[22] P. Brandstetter, P. Bilek, "Applications of Artificial Neural Networks in Control of DC Drive", International Joint Conference CISIS'12-ICEUTE'12-SOCO'12 Special Sessions Advanced in Intelligent Systems and Computing Volume 189, 2013, pp.351-360.

[23] S. Mathew, B.K. Mathew, "Direct Torque Control of Induction Motor Using Fuzzy Logic Controller", International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, Vol. 2, Special Issue 1, December 2013.

[24] M. Zhang, W. Li, M. Liu, "Adaptive PID Control Strategy Based on RBF Neural Network Identification", Neural Networks and Brain, ICNN&B '05, International Conference on (Volume:3), published by IEEE, pp. 1854-1857, 2005.

[25] M. Zerikat, S. Chekroun, A. Mechernene, "Fuzzy-Neural Networks Controller-Based Adaptation Mechanism for MRAS Sensorless Induction Motor Drives", ELECTROMOTION 2009, EPE Chapter "Electric Drives" Joint Symposium, 1-3 July 2009, Lille, France.

[26] A. Amrane, M. Louri, A. Larabi, A. Hamzaoui, "A Fuzzy Model Reference Adaptive System Control for Induction Motor Drives", Proceedings of the 3rd International Conference on Systems and Control, Algiers, Algeria, October 29-31, 2013.

[27] Y. Zhou, Y. Li, Z. Zheng, "Research of Speed Sensorless Vector Control of an Induction Motor Based on Model Reference Adaptive System", International Conference on Electrical Machines and Systems, ICEMS 2008, 17-20 Oct 2008, pp:1381-1384.

[28] Z. Wei, C.W. Sheng, "Flux Observer for Field Oriented Induction Motor Based on EKF", Software Technology and Engineering (ICSTE), 2010 2nd International Conference on (Volume:2).

[29] R. Arulmozhiyal, K. Baskaran, "Space Vector Pulse Width Modulation Based Speed Control of Induction Motor using Fuzzy PI Controller", International Journal of Computer and Electrical Engineering, Vol. 1, No. 1, April 2009.

[30] P. Tripura, Y.S. Kishore Babu, Y.R. Tagore, "Space Vector Pulse Width Modulation Schemes for Two-Level Voltage Source Inverter", ACEEE Int. J. on Control System and Instrumentation, Vol. 02, No. 03, October 2011.

[31] Analog Devices, "Implementing Space Vector Modulation with ADMC 300" journal from Analog Devices Inc., January 2000.

[32] T. Sutikno, A. Jidin, N.R.N. Idris, "New Approach FPGA-based Implementation of Discontinuous SVPWM", Turk J Elec Eng & Comp Sci, Vol.18, No.4, 2010.

[33] J. Zareen, Z.J. Tamboli, S.R. Khot, "Estimated Analysis of Radial Basis Function Neural Network for Induction Motor Fault Detection", International Journal of Engineering and Advanced Technology (IJEAT), ISSN: 2249 – 8958, Volume-2, Issue-4, April 2013.

[34] S. Haykin, "Neural Networks: A Comprehensive Foundation", 2nd Edition Prentice Hall, Upper Saddle River, New Jersey, USA 1999.

[35] K. Xu, G. Xu, P. Qu, "Study of RBF Neural Network Speed Controller Based on the Fuzzy PI in DTC System", Communications in Information Science and Management Engineering, Nov.2012, Vol.2 Issue 11, pp.21-25.

[36] L. Qin, X. Zhou, P. Cao, "New Control Strategy for PMSM Driven Bucket Wheel Reclaimers using GA-RBF Neural Network and Sliding Mode Control", ELEKTRONIKA IR ELEKTROTECHNIKA, ISSN 1392-1215, Vol.122, No.6, 2012.

[37] D. Patino, D. Liu.,"Neural Network Based Model Reference Adaptive Control System," IEEE Transactions on Systems, Man and Cybernetics, Part B, Vol. 30, No. 1, 2000, pp. 198-204.

[38] I. Pinter,I. Lajtai, "RBF-MRAC Neurocontroller for Industrial Applications", Proceedings of the 7th International Conference on Applied Informatics, Eger, Hungary, January 28–31, 2007, Vol. 1, pp. 247–254.

[39] J. Cheng, J. Yi, D. Zhao, "Neural Network Based Model Reference Adaptive Control for Ship Steering System", International Journal of Information Technology, Vol. 11 No. 6 2005.

Erdal Kilic received the B.Sc. and M.Sc. degrees from the Electrical and Electronics Engineering Faculty, Kahramanmaras Sutcu Imam University, Kahramanmaras, Turkey in 2001 and 2004 respectively. He is currently pursuing the Ph.D. degree in Kahramanmaras Sutcu Imam University. His main field of interest is the induction motor drive control and state variable estimations and microprocessor control of electrical drives.

Hasan Riza Ozcalik was born in Mersin, Turkey in 1950. He received B.Sc., M.Sc. and Ph.D. degrees in Electrical and Eelectronics Engineering from Erciyes University, Turkey in 1982, Uludag University, Turkey in 1987, and Erciyes University, Turkey in 1991. He is currently lecturer in Kahramanmaras Sutcu Imam University, Kahramanmaras, Turkey. His research interests are related with artificial intelligence, fuzzy and neural network based control systems, electrical motor drive systems, solar energy and its usage in electrical energy production.

Saban Yilmaz received the B.Sc. and M.Sc. degrees in Electrical and Electronics Engineering from Istanbul Technical University, Turkey in 1993 and Kahramanmaras Sutcu Imam University, Turkey in 2001. He is currently pursuing the Ph.D. degree in Kahramanmaras Sutcu Imam University. His research interests are related with the solar energy, renewable energy, and automatic control.

Received: 2015-05-13
Accepted: 2016-11-28

AUTHORS' ADDRESSES

Erdal Kilic
Hasan Riza Ozcalik, Ph.D.
Saban Yilmaz
Engineering and Architecture Faculty,
Electrical and Electronics Engineering Department,
Kahramanmaras Sutcu Imam University,
Kahramanmaras, Turkey,
email:
ekilic@ksu.edu.tr,
ozcalik@yahoo.com,
sabanyilmaz1@hotmail.com