

# Multi-Resolution Analysis Wavelet PI Stator Resistance Estimator for Direct Torque Induction Motor Drive

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*Abstract:* - To improve the overall dynamic performance of induction motor in direct torque control (DTC), a novel method of stator resistance estimation based on multi-resolution analysis wavelet PI controller is presented. This estimation method is anchored in an on-line stator resistance correction regarding the variation of the stator current estimation error. The main purpose is to adjust precisely the stator resistance value relatively to the evolution of the stator current estimation error gradient to avoid the drive instability and ensure the tracking of the actual value of the stator resistance. The multi-resolution wavelet controller process the error input with the gains depending on the level of decomposition employed. In order to limit the number of gains, this paper analyzes multi-resolution wavelet controller with a single gain constant. A separate fractional order integrator unit which enhances the controller performance with additional flexibility of tuning and also offers better steady state performance of the motor is introduced. The simulation results show that the proposed method can reduce the torque ripple and current ripple, superior to track the actual value of the stator resistance for different operating conditions.

*Key-Words:* - Direct Torque Control, multi-resolution wavelet analysis, PI Controller, Stator Resistance Estimator.

## 1 Introduction

Due to its simple structure, good dynamic performance, robustness and ability to achieve fast response of flux and torque, the direct torque control (DTC) strategy has attracted more and more interest in recent years [1] and it has been widely used to overcome the problems of variable switching frequency and high torque ripples at low speeds [2-5].

However, the stator resistance change can significantly degrade the performance of a direct torque controlled induction motor since the stator resistance is additionally required for stator flux and torque estimation in the basic configuration of DTC. In fact, one of the main problems of the DTC of induction motor drives is the variation of the stator resistance which is affected mainly by the change in motor temperature [1]. This variation which is usually in the range of 0.75-1.7 times its nominal value [6], deteriorates the performance of the drive by introducing errors in the estimated flux linkage's magnitude and its position and hence in the electromagnetic torque [6]. At low speed, this effect is important for a given load torque. And if the

value of the stator resistance used in the DTC controller is less than the actual value, the developed flux and torque will be decreased. Moreover, using greater value of the stator resistance in controller than its real value may lead to instability [1].

Elsewhere, an accurate value of the stator resistance is of crucial importance for correct operation of a sensorless drive in the low speed region, since any mismatch between the actual value and the value used within the speed estimator may lead not only to a substantial speed estimation error but to instability as well [3, 7]. As a consequence, numerous online schemes for stator resistance estimation have been proposed in the recent past years.

An adaptive stator resistance compensation scheme applied to eliminate the stator resistance parameter sensitivity using only the existing stator current feedback has been presented [6]. A procedure for finding the stator current phasor command from the torque and the stator flux linkage commands is derived to realize the adaptation







decomposed in low frequency signal  $e_1(t)$  with gain  $K_1$ , and high frequency signals  $e_2(t) - e_N(t)$  with gain  $K_2 - K_N$ , respectively. For appropriate controller performance the controller gains  $K_1 - K_N$ , are to be tuned properly. The number of controller gains depends on the level of decomposition. Also the multi resolution analysis requires high and low pass filters to be cascaded, depending on the decomposition levels greater computational burden and execution time would be imposed.

$$u(t) = K_1 e_1(t) + K_2 e_2(t) + K_3 e_3(t) + \dots + K_N e_N(t) \quad (11)$$

A multi-resolution wavelet controller requiring three controller gains for a proportional plus integral plus derivative (PID) controller and two for PI controller. The discrete wavelet decomposition has the form of transformation using quadrature mirror filters by which a signal sequence  $x(k)$  is decomposed into  $n$  scales and the results of the decomposition operation is stored in the variable  $w_i$  shown in Eq.(12), where matrices  $G$  and  $H$  are the low and high pass filter, and signal sequence  $x$  is decomposed in  $n$  scale [29].

$$w_i = (Gx, GHx, GH^2x, \dots, GH^{n-1}x, H^n x) \quad (12)$$

The decomposition expressed in Eq.(12) can be implemented using a recursive algorithm and with  $n$  scale discrete wavelet transform the input signal into  $n$  parts, each one representing a parameter of the dynamics of the signal [29]. The speed error signal is sampled and the sampled data is fed to an  $1 \times N$  array. For every new sample the data position is shifted from the  $N^{\text{th}}$  position towards the  $0^{\text{th}}$  position, with the oldest data being discarded and the latest data being in the  $N^{\text{th}}$  position. As per the mother wavelet, Haar wavelet, the matrices  $G$  and  $H$  are given by Eqs.(13-14). Application of a three level decomposition wavelet transform for the error input sequence results in Eq.(15) [29], where,  $H^3x$  and  $GH^2x$  are as given in Eqs.(16-17), respectively, with  $f(k)$  representing the low harmonic component of the input error and  $g(x)$  expressing the higher harmonic component of the input error.

$$G = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \end{bmatrix} \quad (13)$$

$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -1 \end{bmatrix} \quad (14)$$

$$w_i = (Gx, GHx, GH^2x, H^3x) \quad (15)$$

$$f(k) = H^3x(k) = x_0(k) + x_1(k) + \dots + x_{N-1}(k) \quad (16)$$

$$g(k) = GH^2x(k) = x_0(k) + x_1(k) + \dots + x_{(N/2-1)}(k) - \dots - x_{N-1}(k) \quad (17)$$

$$f(k) = H^3x(k) = f(k-1) - x_0(k) + x_{in}(k) \quad (18)$$

$$g(k) = GH^2x(k) = g(k) - x_0(k) - x_{in}(k) + 2x_{(N/2)}(k) \quad (19)$$

An integrator term is added to eliminate the steady state error. The resulting multi-resolution PID controller is described in Eq. (18) [29], where  $U(k)$  is the controller output at the  $k^{\text{th}}$  sampling instant, and  $K_p, K_i, K_d$  are the proportional, integral and differential gains, respectively. The integral term  $I(k)$  is defined in Eq. (19), where  $T_s$  is the sampling time.

$$U(k) = K_p f(k) + K_d g(k) + K_i I(k) \quad (20)$$

$$I(k) = I(k-1) + T_s x_{in}(k) \quad (21)$$

In motor drive systems, the motor winding inductance persevere the damping requirements, leaving the derivative controller redundant. Also, the derivative controller acts as an amplifier for the noise signals and may lead to increase in noise and ripples in the controller output. The PI controller satisfies the needs of many controllers used in a motor drive system and it is usually implemented in practice significantly. The multi-resolution wavelet controller defined in Eq. (22), where the PI controller operation is obtained by neglecting the high frequency term which further simplifies the computations

$$U(k) = K_p f(k) + K_i I(k) \quad (22)$$

A significant advantage of the proposed controller over the wavelet controller proposed in [28-29] is the reduction in the computational burden and consequently the execution time. This merit is acquired as only two equations need to be solved for the determination of the high and low frequency components of the input discrete signal. This results in the elimination of the need of the low and high pass filtering at each level of decomposition. The low computational burden and execution time facilitate the further use of higher sampling and carrier frequency which leads to the reduction in harmonic losses

Fig. 3 shows the block diagram of a multi-resolution wavelet PI controller. The commanded and the actual value are compared and the resulting error  $x_{in}$  is fed to the 2- dimensional array. The necessary elements of the array are retrieved for the high and low frequency component computations. The low and high frequency component of the input error signal are represented by  $f(k)$  and  $g(k)$ , respectively. These signals as per their gains are scaled and fed to the summer block. One more input to the summer block is the scaled integral of the error input. The output of the summer block represents the multi-resolution wavelet controller output. With the absence of the scaled high frequency signal, the summer output would represent the multi-resolution PI controller output.

To incorporate the merits of fractional order controller, multi-resolution wavelet PI speed controller with fractional order integrator, as defined in Eq. (23), has been proposed. The factorial order integrator term  $I_{fo}(s)$  is defined in Eq. (24), where  $s$  is the Laplace operator and  $0 < \delta < 1$  [25].

$$U(s) = K_p f(s) + K_i I_{fo}(s) \quad (23)$$

$$I_{fo}(s) = s^{-\delta} x_{in}(s) \quad (24)$$

#### 4 Multi-Resolution Wavelet Analysis PI Stator Resistance Estimator

The proposed multi-resolution wavelet analysis PI estimator, which is designed to estimate the actual value of the stator resistance for different load torque and speed operating conditions, is shown in Fig. 4. The inputs of the wavelet network are the current error and the change in the current error, denoted by and, respectively. They are defined as

$$e(k) = \Delta I_s(k) = I_s^*(k) - I_s(k) \quad (25)$$

$$\Delta e(k) = e(k) - e(k-1) \quad (26)$$

$$I_s(k) = \sqrt{I_{s\alpha}^2(k) + I_{s\beta}^2(k)} \quad (27)$$

$$R_s(k) = R_s(k-1) + \Delta R_s(k-1) \quad (28)$$

where  $I_s^*(k)$  is the stator command current and  $I_s(k)$  is the actual current. The change in error is needed since the stator current magnitude changes nonlinearly as the stator resistance changes. The command current is determined using simulations and its value depends implicitly on the electromagnetic torque, the stator flux, and rotor speed commands, calculated using the conventional DTC. The relationship of  $I_s^*(k)$  as a function of the stator flux, electromagnetic torque, and rotor speed commands can additionally be determined using a nonlinear function identification or a look-up table build upon experimental data. The output of the wavelet network gives the change in stator resistance  $\Delta R_s(k)$  which is added to the previous value  $R_s(k-1)$  to give an estimate for the actual value of the stator resistance  $R_s(k)$ , as it is shown in Fig. 4.

#### 5 Results

The proposed system has been simulated by using MATLAB-SIMULINK package. To validate the performance of the multi-resolution analysis wavelet PI stator resistance estimator for a DTC of induction motor, the drive system has to be tested with and without stator resistance estimator. In Table 2, the induction motor parameters and the

multi-resolution wavelet PI controller gains are given.

Table 2. Induction motor parameters and multi-resolution wavelet PI controller gains.

Motor Parameter	Value
Power	2.2 kW
Voltage, $V$	240V
Frequency, $f$	50 Hz
Number of poles, $p$	4 poles
Stator resistance, $R_s$	3.8 $\Omega$
Rotor resistance, $R_r$	1.92 $\Omega$
Stator self inductance, $L_s$	0.254 H
Rotor self inductance, $L_r$	0.254 H
Mutual inductance, $L_m$	0.228 H
Rotor inertia, $J$	0.0272 kg.m <sup>2</sup>
Viscous friction coefficient, $B$	0.0742 N.m/rad/s
$R_s$ controller gain $K_p$	1.56
$R_s$ controller integral gain $K_i$	0.872

#### 5.1 DTC for Induction Motor without Resistance Estimator

Instability in the DTC drive is occurred if the controller set stator resistance is greater than its actual value in the induction motor drive system [31]. Fig. 5(a) shows simulation results for a ramp stator resistance decrease from the nominal value (3.8  $\Omega$ ) at 0.3 s. The drive system becomes unstable. This can as be explained as follows:

- 1- As the motor resistance decreases in the machine, the stator current increases for the same applied voltages. This leads to an increase of the stator flux and electromagnetic torque.
- 2- The controller has an opposite effect so that the increased currents, which are inputs to the system, cause increased stator resistance voltage drops in the calculator resulting in lower flux linkages and electromagnetic torque estimation. They are compared with their command values giving larger torque and flux linkages errors resulting in commanding larger voltages and hence larger currents leading to a run off condition as shown in Fig. 5(b-e)
- 3- In fact, from Fig. 5(f), it can be noticed that the stator resistance error causes improper flux estimation making the DTC perform poorly and leads to drive instability.

Consequently, the motor stator resistance adaptation is essential to overcome instability and to guarantee a linear torque amplifier in the direct torque controlled drive.

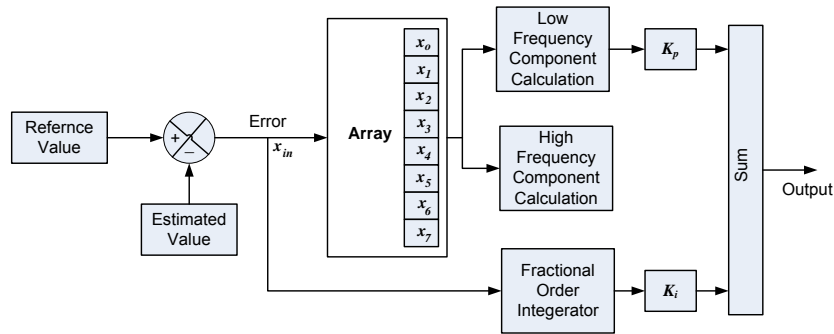


Fig. 3. Block diagram of multi-resolution wavelet PI controller and fractional order integrator.

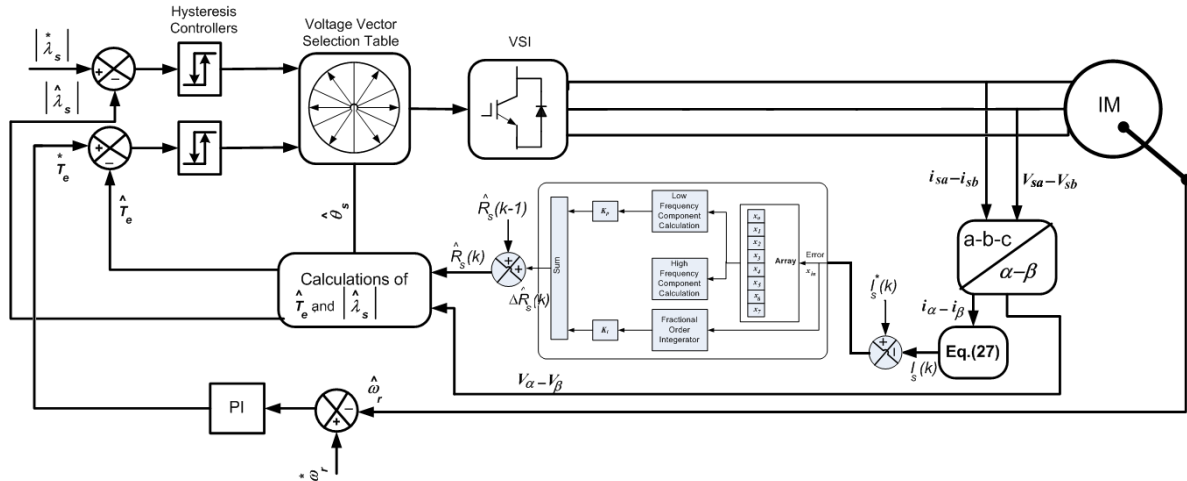


Fig. 4. Overall block diagram for DTC with the proposed stator resistance estimator.

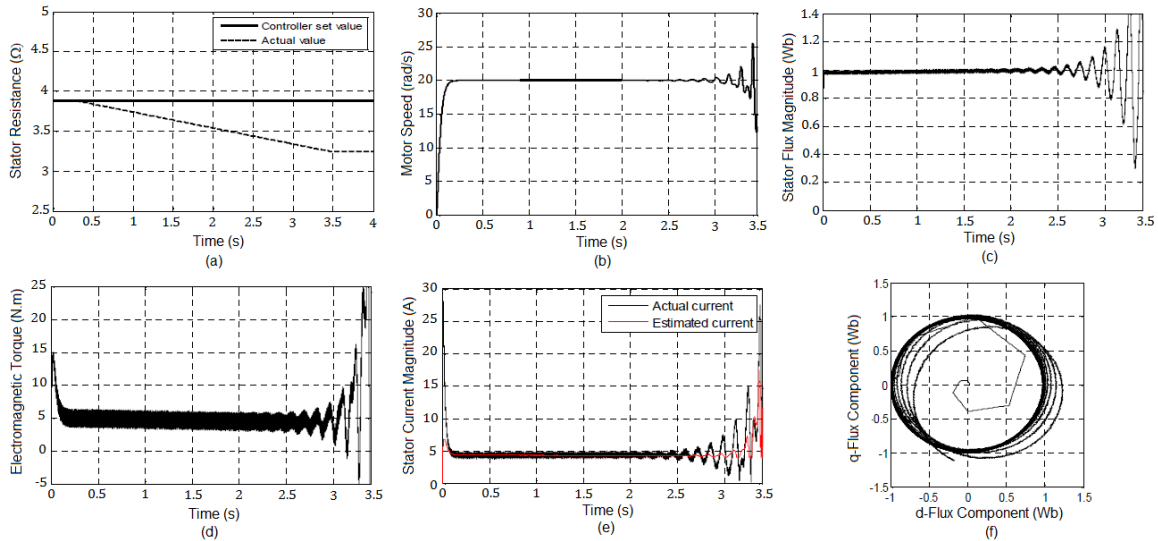


Fig. 5. Simulation results for a ramp stator resistance decrease without using resistance estimator.

### 5.2 DTC for IM with Multi-Resolution Wavelet PI Resistance Estimator

The proposed multi-resolution wavelet PI stator resistance estimator for the DTC IM drive has been implemented using MATLAB-SIMULINK package. Fig. 6 shows how the proposed PI estimator and its percentage of error. The estimated value of the

stator resistance is precisely follows the actual value of the stator resistance. The multi-resolution wavelet PI response has the following parameters: 1- rise time is 0.21s, 2- percentage overshoot is 4.2%, and 3- steady state error is 0%.

To investigate the performance of the proposed PI stator resistance estimator, the stator resistance was changed as shown in Fig. 6(a). In this case the

actual resistance variation has a step change profile. Initially, the stator resistance is stepped up from its nominal value of  $3.8 \Omega$  to  $5.7 \Omega$  (150% of its nominal value) at  $t=2s$ . It is kept constant to 4 seconds, then it is stepped down from  $5.7 \Omega$  to  $2.3\Omega$  (60% of its nominal value) at  $t=6s$ . Fig. 6(a) shows that the estimated stator resistance has tracked its actual value in both dynamic and steady-state cases.

Moreover, the motor speed, the electromagnetic torque, the stator current, the stator flux linkages

and its trajectory, shown in Fig. 6(b-f) respectively, are tracking their references very closely in the steady state. Attention to the waveforms of the flux and the torque that show that the DTC system in this case has a good performance in terms of robustness against large variations of the stator resistance. It can be seen obviously by comparing Fig. (5) by Fig. (7) that; in the steady state, the proposed method can reduce the torque ripple, current ripple, and the flux vector trajectory moves in a circle track perfectly.

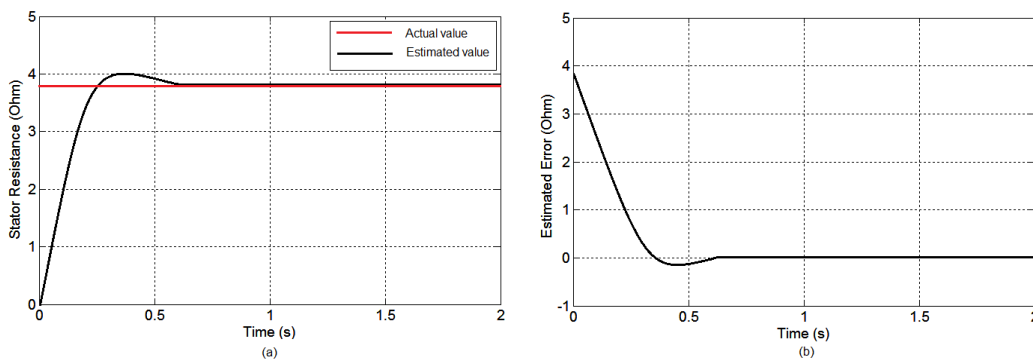


Fig. 6. Stator resistance estimation results with PI; (a) Estimated resistance, and (b) Estimation error.

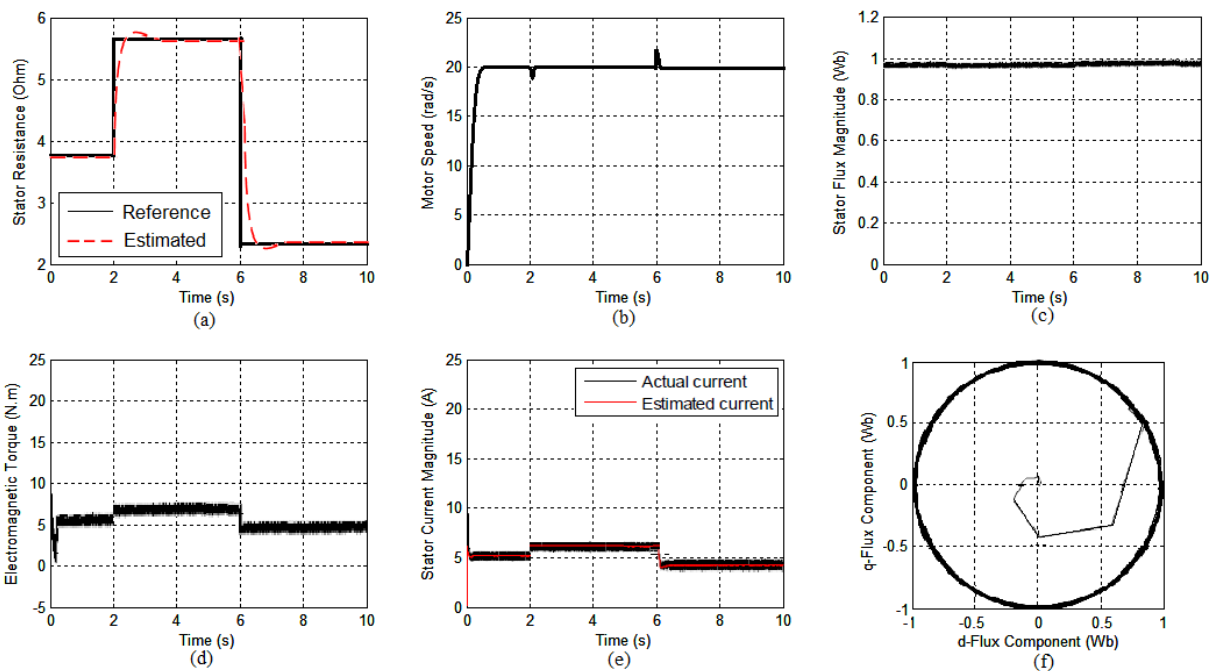


Fig. 7. Simulation results for a step change in stator resistance using multi-resolution wavelet PI resistance estimator.

### 6 Conclusion

The use of wavelet controller separates the high frequency components from the error input and allows the low frequency components to be processed for the determination of the proportional output. The performance of the direct torque

controlled induction motor drive with wavelet stator resistance controller with the integer or fractional order integrator is introduced in this paper. The algorithm implemented for the three level wavelet decomposition is computationally far simpler as compared to the multi-resolution technique with



separate computations for high and low pass filtering at each level of decomposition. Also it is distinguished by less number of tuning constants and less tuning effort as compared to a standard multi-resolution wavelet controller. The simulation results illustrate that the proposed method can decrease the torque ripple and current ripple, superior to follow the actual value of the stator resistance for different operating conditions.

#### References:

- [1] S. Haghbin, M.R. Zolghadri, S. Kaboli, and A. Emadi, Performance of PI Stator Resistance Compensator on DTC of Induction Motor, *IEEE Industrial Electronics Society, The 29th Annual Conference IECON '03*, 2003, pp. 425-430.
- [2] F. Zidani, D. Diallo, M.E.H. Benbouzid, and R. Nait-Said, Direct Torque Control of Induction Motor With Fuzzy Stator Resistance Adaptation, *IEEE Transactions on Energy Conversion*, Vol. 21, No. 2, 2006, pp. 619-621.
- [3] G. Guidi, and H. Umida, A Sensorless Induction Motor Drive For Low Speed Applications Using a Novel Stator Resistance Estimation Method, *IEEE Industry Applications Conference, The 34 IAS Annual Meeting*, 1999, pp. 180-186.
- [4] E.H.E. Bayoumi, An improved approach for position and speed estimation sensorless control for permanent Magnet Synchronous motors, *Electromotion Scientific Journal*, Vol. 14, No.2, 2007, pp.81-90.
- [5] E.H.E. Bayoumi, and H.M. Soliman, A Particle Swarm Optimization-based deadbeat on-line speed control for sensorless induction motor drives, *Electromotion Scientific Journal*, Vol. 15, No.3, 2008, pp. 141-153.
- [6] B.S. Lee, and R. Krishnan, Adaptive Stator Resistance Compensator for High Performance Direct Torque Controlled Induction Motor Drives, *IEEE Industry Applications Conference, 33<sup>th</sup> IAS Annual Meeting*, 1998, pp. 423-430.
- [7] E.H.E. Bayoumi, Sliding Mode Position Control of Synchronous Motor with Parameters and Load Uncertainties, *Electromotion Scientific Journal*, Vol. 17, No. 2, 2010, pp. 99-106.
- [8] R.J. Kerkman, B.J. Seibel, T.M. Owan, and D.W. Schlegel, A new flux and stator resistance identifier for AC Drive systems, *IEEE Transactions on Industry Applications*, Vol. 32, No. 3, 1996, pp. 585-593.
- [9] I. Ha, and S.H. Lee, An online identification method for both stator and rotor resistances of induction motors without rotational transducers, *IEEE Transactions on Industrial Electronics*, Vol.47, No. 1, 2000, pp. 842-853.
- [10] L. Umanand, and S.R. Bhat, Online estimation of stator resistance of an induction motor for speed control applications, *Proc. Inst. Elect. Eng. Elect. Power Application*, Vol. 142, No. 2, 1995, pp. 97-103 .
- [11] L. Liu, S. Shen, S. Liu, Q. Liu, and W. Liao, Stator Resistance Identification of Induction Motor in DTC System Based on Wavelet Network, *Proc. of IEEE the 6th World Congress on Intelligent Control and Automation*, 2006, pp. 6411- 6415.
- [12] R. Marino, S. Peresada, and P. Tomei, On-line stator and rotor resistance estimation for induction motors, *IEEE Transactions on Control System Technology*, Vol. 8, No. 3, 2000, pp. 570- 579.
- [13] G. Guidi, and H. Umida, A novel stator resistance estimation method for speed sensorless induction motor drives, *IEEE Transactions on Industry Applications*, Vol. 36, No. 1, 2000, pp. 1619- 1627.
- [14] A. Monti, F. Pironi, F. Sartogo, and P. Vas, A new state observer for sensorless DTC control, *Proc. Inst. Elect. Eng., Power Electronics and Variable Speed Drives Conference*, 1998, pp. 311-317.
- [15] B. Raison, J. Arza, G. Rostaing, and J.P. Rognon, Comparison of two extended observers for the resistance estimation of an induction machine, *Proc. IEEE Industry Applications Conference*, 2000, pp. 1330-1335.
- [16] M. Tsuji, S. Chen, K. Izumi, and E. Yamada, A sensorless vector control system for induction motors using q-axis flux with stator resistance identification, *IEEE Transactions on Industrial Electronics*, Vol. 48, No. 1, 2001, pp. 185-194.
- [17] K. Shinohara, T. Nagano, and W.Z.W. Mustafa, Online tuning method of stator and rotor resistances in both motoring and regenerating operations for vector controlled induction machines, *Electrical Engineering in Japan Journal*, Vol. 135, No. 1, 2001, pp. 56-64.
- [18] KARANAYIL, B. "Parameter identification for vector controlled induction motor drives using artificial neural networks and fuzzy principles", A PhD thesis, School of Electrical Engineering and Telecommunications, University of New South Wales, 2005.

- [19] E.H.E. Bayoumi, Parameter Estimation of Cage Induction Motors Using Cooperative Bacteria Foraging Optimization, *Electromotion Scientific Journal*, Vol.17, No.4, 2010, pp.247-260.
- [20] E.H.E. Bayoumi, M. Awadallah, and H.M. Soliman, Deadbeat performance of vector-controlled induction motor drives using particle swarm optimization and adaptive neuro-fuzzy inference systems, *Electromotion Scientific Journal*, Vol.18, no. 4, 2011, pp. 231-242.
- [21] L.A. Cabrera, E. Elbuluk, and I. Husain, Tuning the stator resistance of induction motors using artificial neural network, *IEEE Transactions on Power Electronics*, Vol.12, No. 5, 1997, pp. 779–787.
- [22] M. Awadallah, E.H.E. Bayoumi, and H.M. Soliman, Adaptive deadbeat controllers for BLDC drives using PSO and ANFIS techniques, *Journal of Electrical Engineering*, Vol 60, No. 1, 2009, pp. 3-11.
- [23] J. Campbell, and M. Sumner, Practical sensorless induction motor drive employing an artificial neural network for online parameter adaptation, *Proc. Inst. Elect. Eng., Elect. Power Applications*, Vol. 149, No. 4, 2002, pp. 255–260.
- [24] B.K. BOSE, and N.R. PATEL, Quazi-fuzzy estimation of stator resistance of induction motor, *IEEE Transactions on Power Electronics*, Vol. 13, No. 3, 1998, pp. 401–409.
- [25] S.-J. Steven Tsai, *Power transformer partial discharge (PD) acoustic signal detection using fiber sensors and wavelet analysis, modeling, and simulation*, Master's Thesis, Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Chapter 4, 2002.
- [26] A.S Sant, and K. R.Rajagopal, PM Synchronous Motor Drive with Wavelet Controller and Fractional Order Integrator, *Power Electronics, and Energy Systems (PEDES 2010)*, New Delhi, 2010, pp.1-8.
- [27] L. Liu, S. Shen, S.Liu, Q. Liu, , and W. Liao, Stator resistance identification of induction motor in DTC system based on wavelet network, *Proc. Intelligent Control and Automation*, Dailian, China, 2006, pp.6411-6415.
- [28] S. Parvez and Z. Gao, A wavelet-based multiresolution PID controller, *IEEE Transaction on Industrial Applications.*, Vol. 41, No.2, 2005, pp. 537-543.
- [29] E. Mitronikas and E. Tatakis, Design of a wavelet multiresolution controller for speed control of travelling wave ultrasonic motors, *Proc. 2008 IEEE Power Electronics Specialists Conference*, pp.3937-3942, 2008 .
- [30] M. A. S. K. Khan, and M. A. Rahman, Implementation of a New Wavelet Controller for Interior Permanent Magnet Motor Drives, *Record of the 2007 IEEE Industry Applications Conference, 42<sup>nd</sup> IAS Annual Meeting*, pp.1280 – 1287, 2007.
- [31] Bayoumi, E.H.E. “A novel approach to control an unbalanced three phase induction motor”, *Electromotion Scientific Journal* , Vol 12, No.4, pp.213-222, 2005.