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Scalar speed control of induction motors with difference frequency

Fark frekans ile indüksiyon motorun skaler hız denetimi

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Scalar Speed Control of Induction Motors with Difference Frequency

Araştırma Makalesi / Research Article

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ABSTRACT

Speed monitoring of electric motors has attracted the attention of many researchers from past to present. Induction Motor (IM), which is one of the electric motor types, falls behind the nominal speed in different loads. This study was conducted to increase the speed control performance of IM. In the study, speed control of IMs was realized by Difference Frequency (DF). The Scalar Control (SC) method was used in IM speed control. In order to increase the performance of SC, the frequency information received from IM was compared with the reference frequency. The resulting DF was applied to the system input again. For the performance analysis of the study; SC, PI + SC and DF + SC methods were compared. The results obtained from the study simulated in Matlab software show that the proposed method can be used in speed control.

Keywords: Speed control, scalar speed control, IM, frequency, V/f.

Fark Frekans ile İndüksiyon Motorun Skaler Hız Denetimi

ÖZ

Elektrik motorlarının hız denetimi geçmişten günümüze pek çok araştırmacının ilgisini çekmiştir. Elektrik motor çeşitlerinden biri olan Indüksiyon Motor (IM) ya da Asenkron Motor (ASM) farklı yüklerde nominal hızın gerisinde kalmaktadır. Bu çalışmada IM'nin hız denetim başarımını arttırmak amacıyla yapılmıştır. Yapılan çalışmada IM'lerin hız denetimi Fark Frekans (FF) ile gerçekleştirilmiştir. IM hız denetiminde Skaler Denetim (SD) yöntemi kullanılmıştır. SD'nin başarımını arttırmak için IM'den alınan frekans bilgisi referans frekans ile karşılaştırılmıştır. Elde edilen FF tekrar sistem girişine uygulanmıştır. Çalışmanın performans analizi için; SD, PI + SD ve FF + SD yöntemleri karşılaştırılmıştır. Analiz sonuçları tablo ve grafikler ile sunulmuştur. Matlab yazılımında benzetimi gerçekleştirilen çalışmadan elde edilen sonuçlar önerilen yöntemin hız denetiminde kullanılabileceğini göstermektedir.

Anahtar Kelimeler: Hız denetimi, skaler hız denetimi, IM, Frekans, V/f.

1. INTRODUCTION

Induction Motors (IM) are preferred in industrial areas due to advantages such as simple structure, low cost, low maintenance requirements and high efficiency [1] - [5]. This situation reveals the need for use of IMs at different speeds. However, the nonlinear dynamic model, the time varying parameters and external load torque of these motors makes the speed control quite complicated [6] - [9]. In this context, it is expected from the control system that to have proper behavior of location and speed at transient and steady state, to respond well to the variable speed, not to be affected by changes in the disruptive input parameter such as an external force (load torque) [1], [10], [11].

Speed control of IMs is carried out in two distinct ways: scalar and vector [12], [13]. Considering the industrial application; Scalar Control (SC) method is being used because of simple structure, easy application and low cost [14]. SC method is performed by maintaining Voltage / frequency (V / f) rate constant. The goal here is to keep constant the motor torque desired to be operated at different speeds. However, when IMs operated at low speed, torque production is reduced due to the reduction of internal voltage drop and dynamic performance of the motor decreases due to disruptive influences such as external load conditions [15] - [18]. Therefore, SC method is used in conjunction with additional control methods such as Proportional-Integral-Derivative (PID) [19] - [21]. However, parameter sensitivity of the PID controls is fairly weak. If the system controller coefficients are set well, system can be controlled in a good way. However, any changes in system parameters affect the performance of the controller negatively. In this case, the PID control coefficients will need to readjust [19], [22].

In addition to classical methods of control, many methods have been suggested [23] - [25]. These; Kalman filter [26], field orientation [27], [28], position [29], adaptive [30], finite elements [31], finite differences [32], logic [33], state feedback [34], stator voltage [35], observer-based [36], matrix theory [37], shift mode [38],

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digital signal processor [39], sensor-sensor-less [40], robust [41] control, etc.

When the studies in recent years are examined, it is understood that intelligent audit methods Artificial Neural Network (ANN), Fuzzy Logic (FL), Genetic Algorithm (GA) etc. and these methods are used together with classical methods. In addition to the above-mentioned methods, we observed that control methods such as ANN, FL, GA are used [42] - [45]. Referring to the literature, it is observed that intelligent control systems which can be used instead of the PID have been developed [46], [47]. These methods show the desired performance in the nonlinear case in system [48]. Also, the control performance system is less affected from parameter variations [49] - [51].The aim of this study is not to reveal the positive and negative aspects of the known methods, but to reveal a different solution method.

The purpose of this study is to improve the performance of the SC method utilized in speed control of IMs without the need for additional controller. The motor that controls to be carried are required to reach the reference speed at idle and load. Therefore, Difference Frequency (DF) + SC method is recommended in control of IMs.

2. MATERIAL AND METHOD

2.1. Mathematical Expressions of IMs

In terms of ease of simulation biaxial mathematical expressions of IMs are used. These statements are [4], [52], [53];

The stator voltage equations of *dq* axis:

$$\begin{aligned} v_{sd} &= i_{sd} r_s + \frac{d}{dt}\psi_{sd} - w_e \psi_{sq} \\ v_{sq} &= i_{sq} r_s + \frac{d}{dt}\psi_{sq} - w_e \psi_{sd} \end{aligned} \tag{1}$$

Rotor voltage equations of dq axis:

$$\begin{aligned} v_{rd} &= i_{rd} + \frac{d}{dt}\psi_{rd} - (w_e - w_r)\psi_{rq} \\ v_{rq} &= i_{rq} + \frac{d}{dt}\psi_{rq} - (w_e - w_r)\psi_{rd} \end{aligned} \tag{2}$$

Here; $v_{rd} = v_{rq} = 0$ for squirrel cage IMs [1].

Stator and rotor flux given in these equations (Matrix expression):

$$\begin{bmatrix} \psi_{sq} \\ \psi_{sd} \\ \psi_{rq} \\ \psi_{rd} \end{bmatrix} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \begin{bmatrix} i_{sq} \\ i_{sd} \\ i_{rq} \\ i_{rd} \end{bmatrix} \tag{3}$$

Flux equations in the air gap:

$$\begin{aligned} \psi_{mq} &= L_m (i_{sq} - i_{rq}) \\ \psi_{md} &= L_m (i_{sd} - i_{rd}) \end{aligned} \tag{4}$$

The equation of torque generated by the motor:

$$T_m = \frac{3}{2}\frac{p}{2} L_m (i_{rd} i_q - i_{rq} i_{sd}) \tag{5}$$

The equation of electrical torque generated by the motor:

$$T_e = T_L + J\frac{2}{p}\frac{d}{dt}w_r + \frac{2}{p}Bw_r \tag{6}$$

2.2. Mathematical Expressions of SC

SC simulation was performed with the angle and amplitude ratio obtained by calculating from the reference frequency entered into the system. Reference voltage equations are given below for three phases [12].

$$\begin{aligned} V_a &= V_m \sin(\theta) \\ V_b &= V_m \sin(\theta - 2\pi/3) \\ V_c &= V_m \sin(\theta + 2\pi/3) \end{aligned} \tag{7}$$

2.3. Mathematical Expressions of DFs

DF's simple mathematical model;

$$DF = ref\_f - \frac{w_e}{2\pi} \tag{8}$$

2.4. Methods for Control of IMs

2.4.1. SC method

IM simulation model of SC method is shown in Figure 1. Here, SC simulation will be carried out with the angle and amplitude ratio obtained by calculating from the reference frequency entered into the system. Current, torque and speed graphics will be obtained by running the motor at idle and load [54].

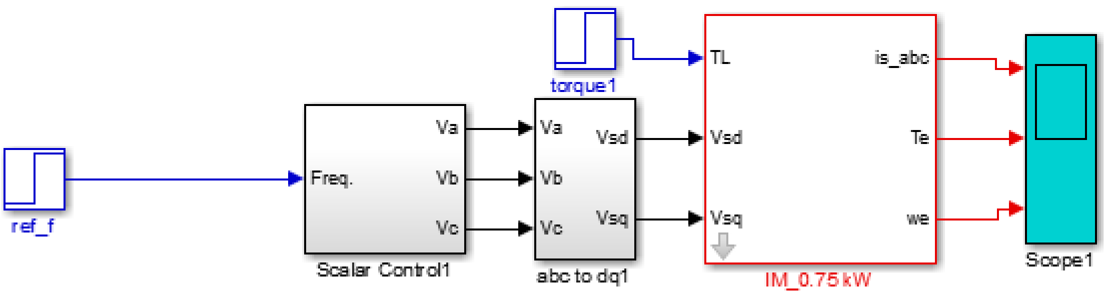


Figure 1. Simulation of SC Method

2.4.2. PI+SC method

IM simulation model of PI+SC method is shown in Figure 2. Here, PI sets the control input, reduces errors, and will work to achieve the desired reference frequency value. Current, torque and speed graphics will be obtained by running the motor at idle and load.

2.4.3. DF+SC method

IM simulation model of DF+SC method (The proposed method) is shown in Figure 3. Here, DF will be performed by adding the difference between the frequency obtained from motor speed and reference frequency to SC input. Current, torque and speed graphics will be obtained by running the motor at idle and load [55].

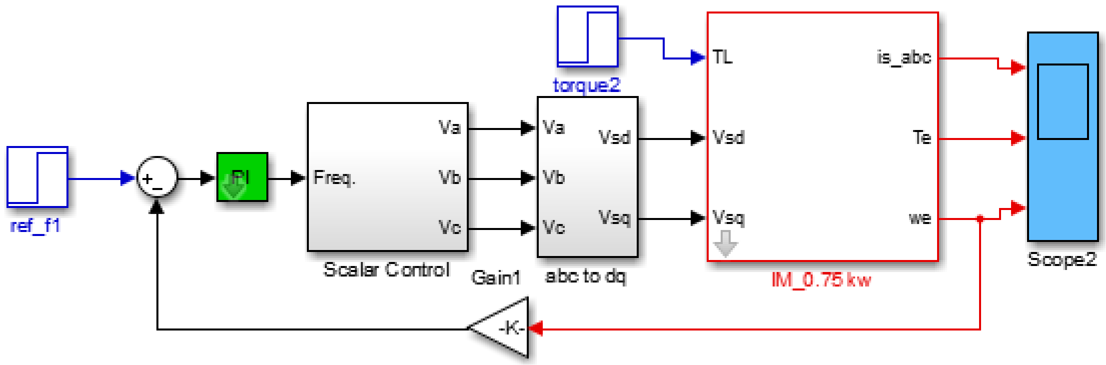


Figure 2. Simulation of PI+SC Method

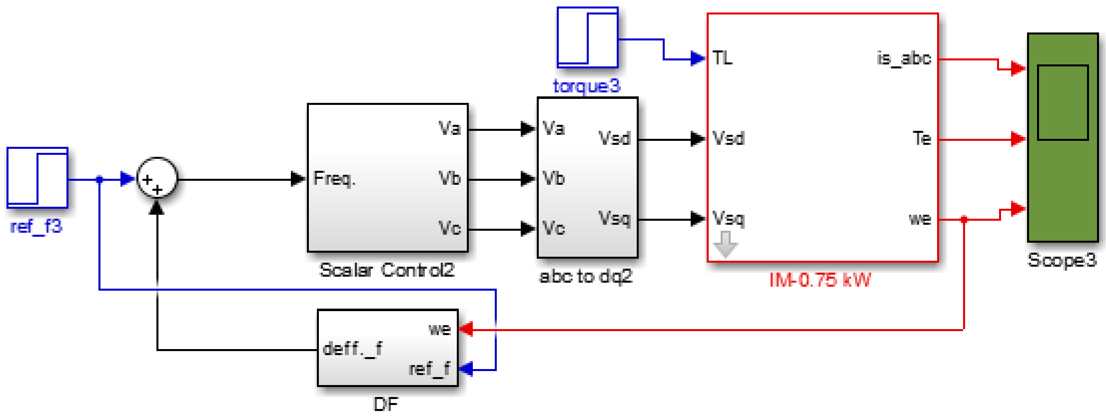


Figure 3. Simulation of DF+SC Method

3. RESULTS

Four simulation tests graphs and tables are given below. The simulation tests conducted are shown in the table and then on the graph. The first simulation test input information is given in Table 1 and simulation test results are shown in Figure 4.

The motor current, torque and speed graphs is given Figure 4 (a), respectively. Consequences are 5 Hz and 0 Nm in Figure 4 (a), 5 Hz and 0.25 Nm in Figure 4 (b), 5 Hz and 0.5 Nm in Figure 4 (c). It is seen that the motor current is equal to each other in three simulation tests. Also, it is understood that the motor torque graph is at the desired value. However, when speed graphs examined it is understood that the SC method could not be successful by the motor load torque increases. But DF+SC gave the same results with PI+SC method and it is observed that this method is successful at speed control.

Table 1. The first simulation tests input information

Tests	ref_f (Hz)	ref_Te (Nm)
1	5	0
2	5	0.25
3	5	0.5

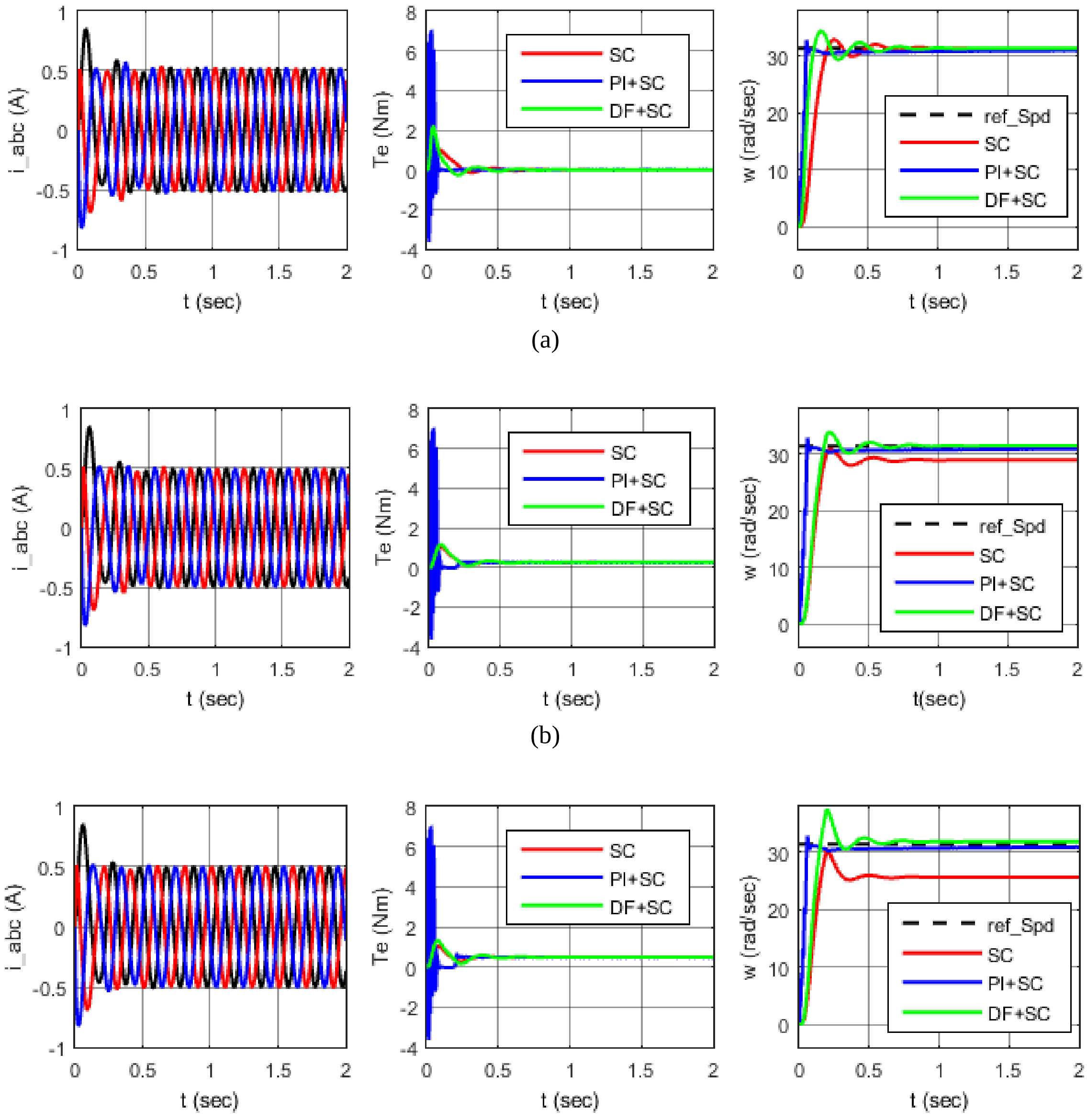


Figure 3. The first simulation test results

The second simulation test input information is given in Table 2 and simulation test results are shown in Figure 5. The motor current, torque and speed graphs is given Figure 5 (a), respectively. Consequences are 10 Hz and 0 Nm in Figure 5 (a), 10 Hz and 0.25 Nm in Figure 5 (b), 10 Hz and 0.5 Nm in Figure 5 (c). It is seen that the motor current is equal to each other in these three simulation tests. Also, it is understood that the motor torque graph is at the desired value. However, when speed graphs examined it is understood that the SC method could not be successful by the motor load torque increases. But DF+SC gave about the same results with PI+SC method and it is observed that this method is successful at speed control.

Table 2. The second simulation tests input information

Tests	ref_f (Hz)	ref_Te (Nm)
1	10	0
2	10	0.25
3	10	0.5

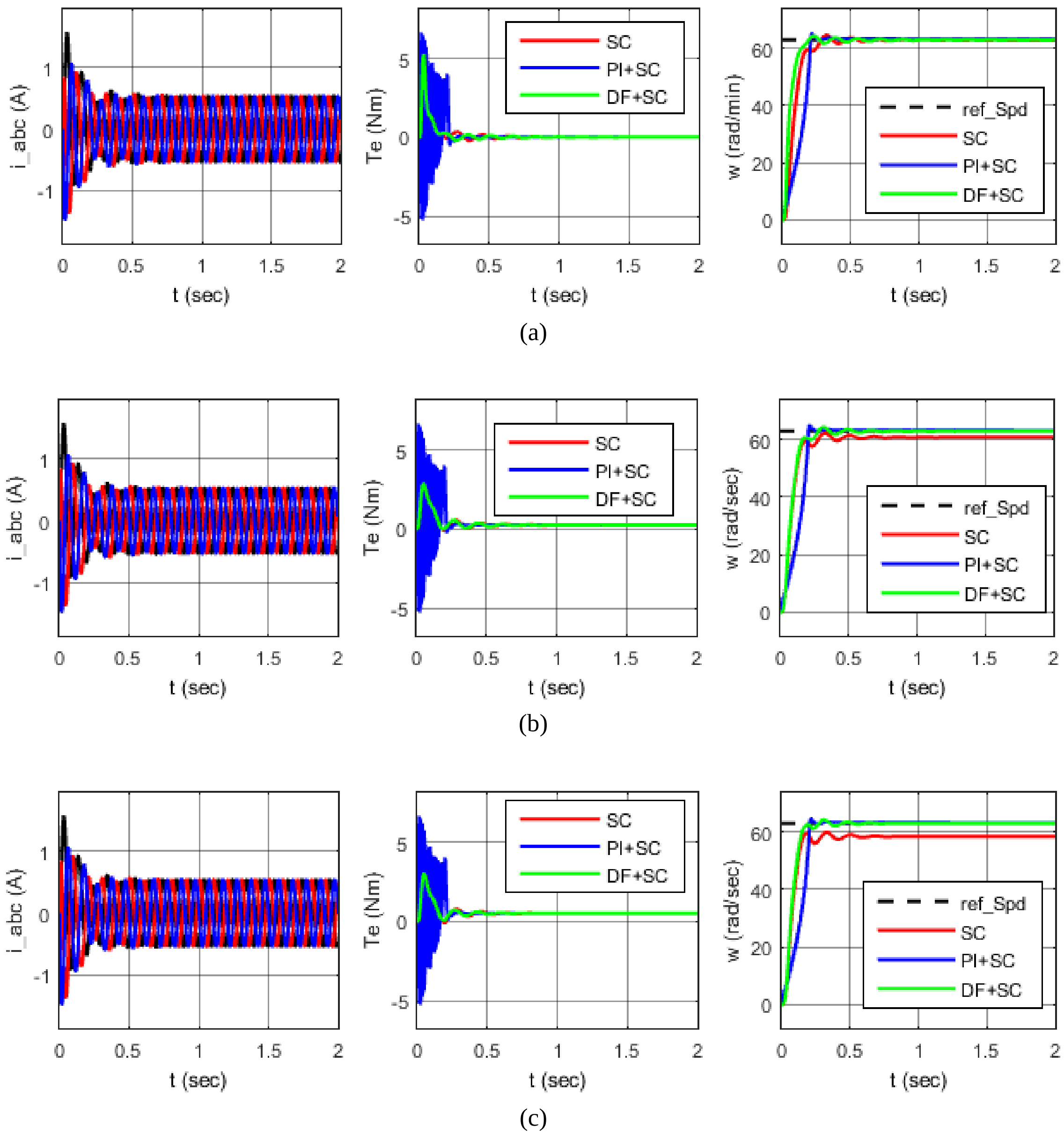
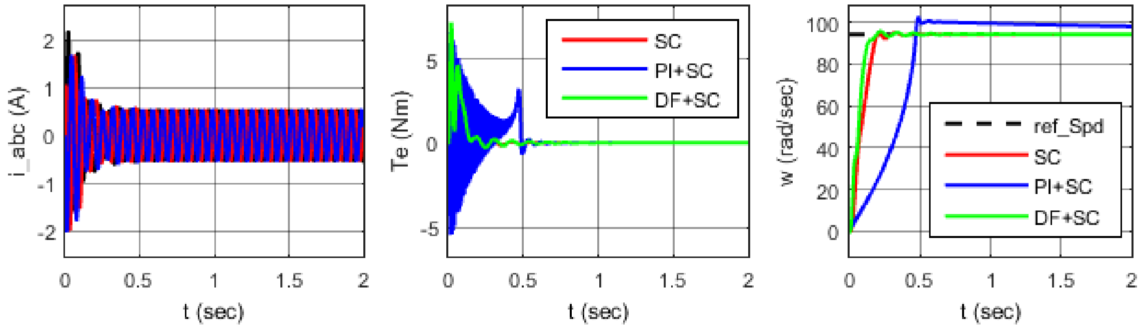


Figure 4. The second simulation test results

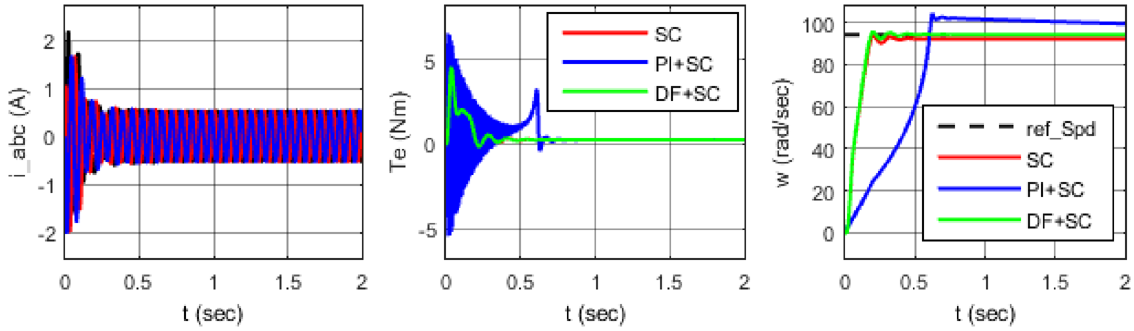
The third simulation test input information is given in Table 3 and simulation test results are shown in Figure 6. The motor current, torque and speed graphs is given Figure 6 (a), respectively. Consequences are 15 Hz and 0 Nm in Figure 6 (a), 15 Hz and 0.25 Nm in Figure 6 (b), 15 Hz and 0.5 Nm in Figure 6 (c). It is seen that the motor current is equal in these three simulation tests. Also, it is understood that the motor torque graph is at the desired value at SC and DF+SC methods but it is not at the desired value at PI+SC method. When speed graphs examined it is understood that SC and PI+SC methods could not be successful by the motor load torque increases. For this simulation test, it is observed that DF+SC method is successful at speed control.

Table 3. The third simulation tests input information

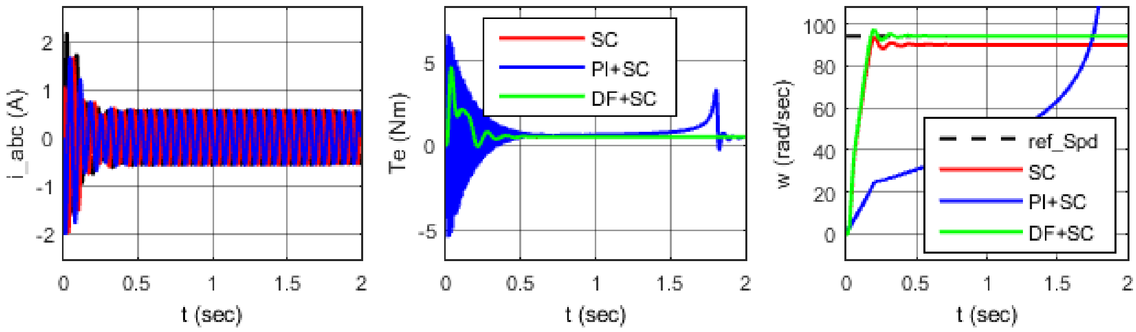
Tests	ref_f (Hz)	ref_Te (Nm)
1	15	0
2	15	0.25
3	15	0.5



(a)



(b)



(c)

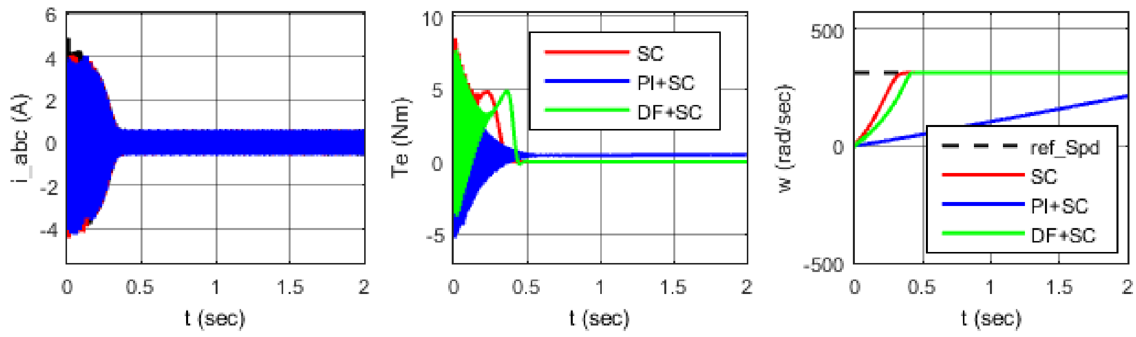
Figure 5. The third simulation test results

The fourth simulation test input information is given in Table 4 and simulation test results are shown in Figure 7.

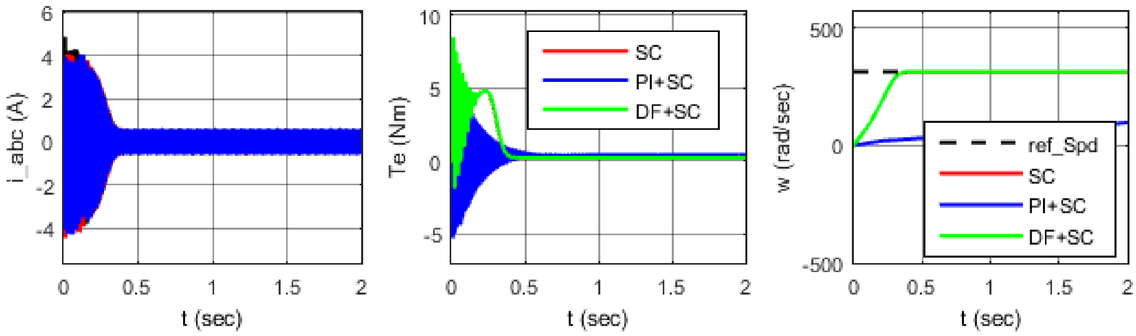
The motor current, torque and speed graphs is given Figure 7 (a), respectively. Consequences are 50 Hz and 0 Nm in Figure 7 (a), 50 Hz and 0.25 Nm in Figure 7 (b), 50 Hz and 0.5 Nm in Figure 7 (c). It is seen that the motor current is equal in these three simulation tests. When examining torque graphs in three methods, it is seen that the desired result is obtained by SC and DF+SC methods. When speed graphs examined it is understood that SC and DF+SC methods are successful by the motor running at idle and load but PI+SC control is not successful.

Table 4. The fourth simulation tests input information

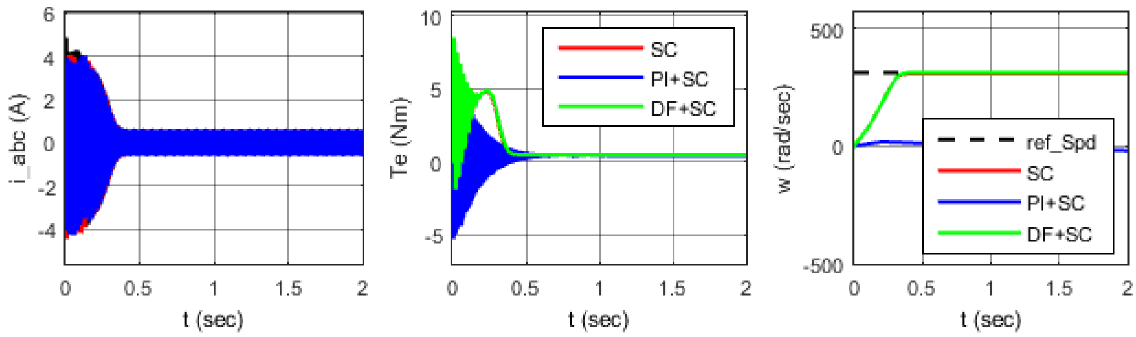
Tests	ref_f (Hz)	ref_Te (Nm)
1	50	0
2	50	0.25
3	50	0.5



(a)



(b)



(c)

Figure 6. The fourth simulation test results

Figure 8 is presented for a better understanding of the performance of the proposed method. A frequency of 25 Hz was applied to the IM. The results obtained from different load moments are shown on the same graph and the traceability of the results has been increased.

In Figure 8 (a) shows the torque graph, (b) the velocity graph. Figure 8 (b) shows that the motor operates at a constant speed. It is understood that the motor has 0%, 0.25% and 0.51% speed error respectively when operating at 0, 0.25 and 0.5 Nm load torque.

4. CONCLUSION

In this study, IM' Scalar Speed Control with Difference Frequency were performed. The results obtained from this study can be listed as follows.

- SC: It shows desired performance in all speed during idling. When working in load, at low speeds it does not show the desired performance. The desired control results are obtained when working at high speed in idle and load [17].
- PI+SC: Coefficients determined for PI controller shows desired performance in specific speed ranges. Nevertheless, while the range of speed and torque changes it does not demonstrate the required performance [19], [22].
- DF+SC: This proposed method indicates the desired control performance in each case tested.

- The obtained results indicate that the proposed method will contribute speed control operations done in industrial areas.

When considering developments in this area, much more work can be made.

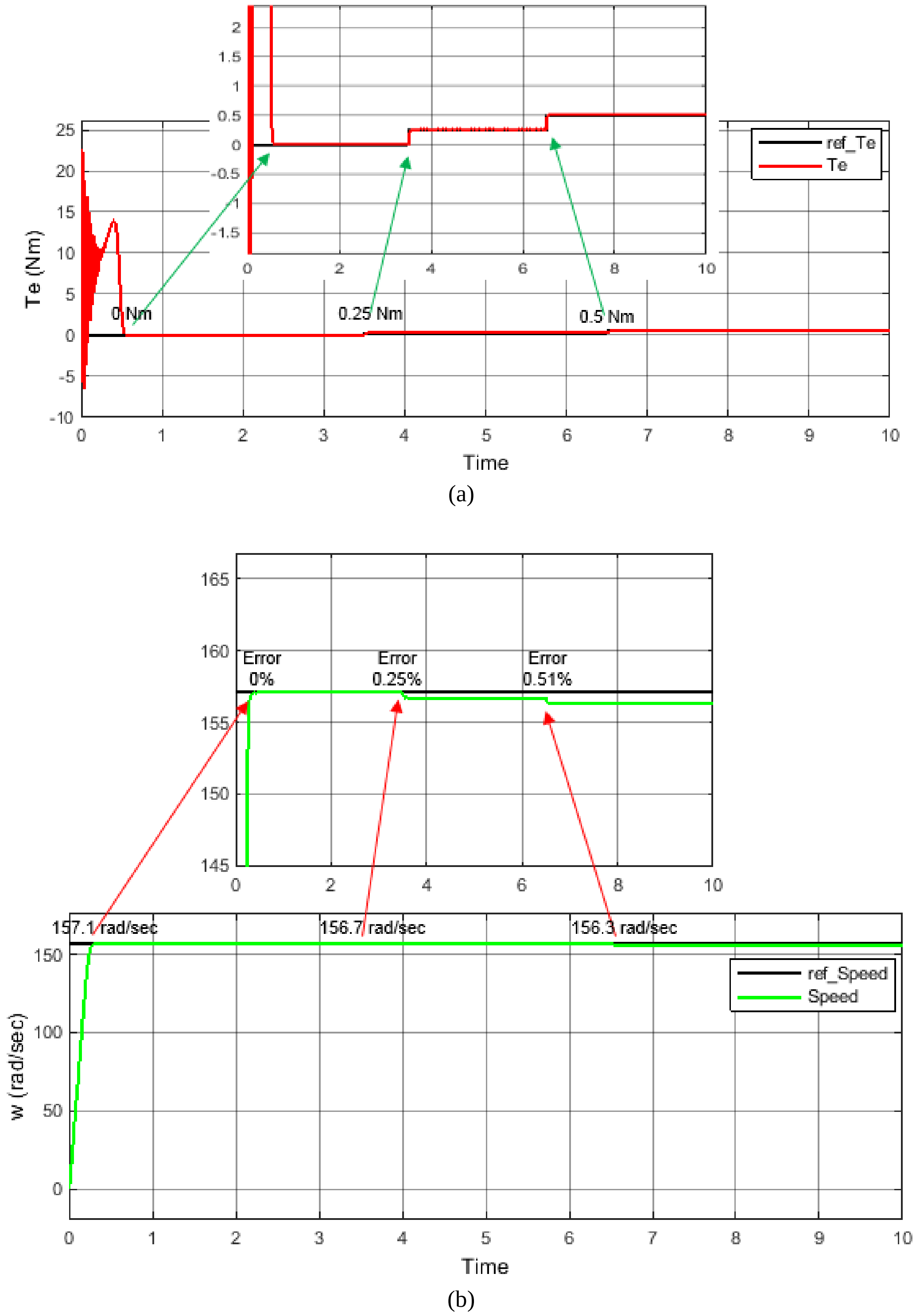


Figure 8. Performance analysis of motor at constant speed and different load moments

SYMBOLS AND ABBREVIATIONS

i_{sd}, i_{sq} : *dq* currents

Ψ_{sd}, Ψ_{sq} : *dq* fluxes

L_s : Statore inductance

L_r : Rotor inductance

L_m : Mutual inductance

r_s : Stator resistance

T_L : Load torque

w_e : Electric angular speed
w_r : Rotor angular speed
J : Inertia constant
B : Friction constant
p : Number of poles

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REFERENCES

[1] Bose B.K., "***Modern Power Electronics and AC Drives***", Upper Saddle River, NJ: Prentice-Hall PTR, (2002).

[2] Kouro S., Bernal R., Miranda H., Silva C.A., and Rodriquez J., ″High-Performance Torque and Flux Control for Multilevel Inverter Fed Induction Motors", ***IEEE Transaction on Power Electronics***, 22(6): 2116–2123, (2007).

[3] Wang C.C. and Fang C. H., ″Sensorless Scalar Controlled Induction Motor Drives with Modified Flux Observer", ***IEEE Journals & Magazines***, 22(8): 61 – 61, (2002).

[4] G. Fouad, ″AC Electric Motors Control Advanced Design Techniques and Applications", Wiley, New Delhi, India, 2013.

[5] Paula S. J., Jeromeb J., Kakania S., 'Active Rectifier Based Harmonic Compensator for a Direct Torque Controlled Induction Motor Drive', ***IETE Journal of Research***, 61(6): 573-580, (2015).

[6] Tuncer S., 'High-Performance Vector Control Strategy For Multilevel Inverter Fed Induction Motor', ***Journal of the Faculty of Engineering and Architecture of Gazi University***, 30(1), 119-130, (2015).

[7] Zou X., Zhu P., Kang Y. and Chen J., 'Speed identification for vector control of induction motors with voltage decoupling control principle', ***38th IAS Annual Meeting, Conference Record of the Industry Applications Conference***, 12-16 Oct., (2003).

[8] A. Djahbar, B. Mazari, and M. Latroch, 'Control strategy of three-phase matrix converter fed induction motor drive system', ***The IEE Pulsed Power symposium***, 8-8 Sept., Basingstoke, UK: IEEE, (2005).

[9] Singh B., Garg V., Bhuvaneshwari G., 'A 24-pulse AC-DC converter employing a pulse doubling technique for vector-controlled induction motor drives', ***IETE Journal of Research***, 54(4): 314-322, (2008).

[10] Sen P.C., 'Electric Motor Drives and Control Past Present, and Future', ***IEEE Transactions on Industrial Electronics***, 37(6): 562-575, (1990).

[11] Ebrahim A., '***Adaptive nonlinear induction motor control.***' PhD Thesis, The University of Alabama, Alabama, (2007).

[12] Haitham A., Atif I., Jaroslaw G., '***High Performance Control of AC Drives With Matlab/Simulink Models***', Noida, India: Wiley, (2012).

[13] Bay Ö., Görgünoğlu S. "Design and Implementation of 3-Phase Induction Motors Speed Controller by Using Low Cost 8-Bit Microcontroller". ***Journal of Polytechnic***, 12(3): 143-150, (2009).

[14] Irmak E. and Vadi S., "Asenkron Motorlarda Frekans Değişimi ile Hız Kontrolü Deneyinin Bilgisayar Üzerinden Gerçekleştirilmesi", ***Journal of The Faculty of Engineering and Architecture of Gazi University***, 21(1): 57-62, (2011).

[15] Ilango G. S., Rajasekar N., "An improved energy saving v/f control technique for solar powered single-phase induction motor", ***Energy Conversion and Management***, 50(12): 2913-2918, (2009).

[16] Liu Y., Piepenbreier B., "Comparison of Stabilization Methods for V/f controlled Induction Motor Drive System", ***PCIM Europe 2014, International Exhibition and Conference for Power Electronics, Intelligent Motion***, 20-22 May., Nuremberg: IEEE, (2014).

[17] Bose B. K., 'Adjustable Speed AC Drives-A Technology Status Review', ***Proceedings of the IEEE***, 70(2): 116-135, (1982).

[18] Jisha L. K., Thomas A. P., 'A comparative study on scalar and vector control of Induction motor drives, International conference on Circuits', ***Controls and Communications (CCUBE)***, IEEE Conference Publications; 27-28 Dec. 2013; Bengaluru, India: IEEE, (2013).

[19] Rubaai A., Kotaru R., 'Online identification and control of a DC motor using learning adaptation of neural networks', ***IEEE Transactions on Industry Applications***, 36(3): 935-942, (2000).

[20] Menghal P.M., Laxmi A.J., 'Dynamic modeling, simulation & analysis of induction motor drives', ***International Conference on Science Engineering and Management Research (ICSEMR)***, 27-29 Nov., Chennai: IEEE, (2014).

[21] Draou A., Miloud A., Miloud Y., 'A Variable Gains PI Speed Controller In a Simplified Scalar Mode Control Induction Machine Drive - Design and Implementation', ***International Conference on Control, Automation and Systems***; 27-30 Oct., South Kore, (2010).

[22] Özçıra S., '***Control Methods of Permanent Magnet Synchronous Motor and Industrial Applications***.' MSc, Yıldız Technical University, İstanbul, Turkey, (2007).

[23] Trzynadlowski A.M., ***Control of Induction Motors***, London, UK: Academic Press, (2001).

[24] Krishnan R., ***Electric Motor Drives-Modeling Analysis and Control***, NJ, USA: Prentice-Hall, (2001).

[25] Irmak E. and Vadi S., "Asenkron Motorlarda Frekans Değişimi ile Hız Kontrolü Deneyinin Bilgisayar Üzerinden Gerçekleştirilmesi", ***Journal of The Faculty of Engineering and Architecture of Gazi University***, 21(1): 57-62, (2011).

[26] Zhang Y., ve et al., "A Novel Speed Estimation Method of Induction Motors Using Real-Time Adaptive Extended Kalman Filter", ***Journal of Electrical Engineering & Technology***, 13(1): 287-297, (2018).

[27] Xin Z. and et al., "An improved flux observer for field-oriented control of induction motors based on dual second-order generalized integrator frequency-locked loop", ***IEEE Journal of Emerging and Selected Topics in Power Electronics***, 5(1): 513-525, (2017).

[28] Ehsani M., et al., ***Modern electric, hybrid electric, and fuel cell vehicles***, UK: CRC Press, (2018).

[29] Zhou Z. and et al., "Neural network-based discrete-time command filtered adaptive position tracking control for

induction motors via backstepping", ***Neurocomputing***, 260: 203-210, (2017).

[30] Wang N., Haisheng Y. and Xudond L., "DTC of induction motor based on adaptive sliding mode control", ***2018 Chinese Control And Decision Conference (CCDC)***. IEEE, (2018).

[31] Lftisi F. and Rahman M.A., "A novel finite element controller map for intelligent control of induction motors, Information Technology", ***Electronics and Mobile Communication Conference (IEMCON)***, 2017 8th IEEE Annual. IEEE, (2017).

[32] Nozaki Y., Takafumi K. and Eisuke M., "Analysis of linear induction motors for HSST and linear metro using finite difference method", ***Proc. LDIA2005***, Tokyo, 168-171, (2005).

[33] Zhao J. and Bose B.K., "Evaluation of membership functions for fuzzy logic controlled induction motor drive", ***In IECON-Proceedings***, 1: 229-234, (2002).

[34] Rashed M., Peter M. and Stronach F.A., "Nonlinear adaptive state-feedback speed control of a voltage-fed induction motor with varying parameters", ***IEEE Transactions on Industry Applications***, 42(3): 723-732, (2006).

[35] Paice D.A., "Induction motor speed control by stator voltage control", ***IEEE Transactions on power Apparatus and systems***, 2: 585-590, (1968).

[36] Feng Y. and et al., "Speed Control of Induction Motor Servo Drives Using Terminal Sliding-Mode Controller", ***Advances in Variable Structure Systems and Sliding Mode Control—Theory and Applications***, 115: 341-356, (2017).

[37] Guo Y. and et al., "Speed-sensorless direct torque control scheme for matrix converter driven induction motor", ***The Journal of Engineering***, 13: 432-437, (2018).

[38] Lin F.-J., Shen P.-H. and Hsu S.-P., "Adaptive backstepping sliding mode control for linear induction motor drive", ***IEE Proceedings-Electric Power Applications***, 149(3): 184-194, (2002).

[39] Kubota H., Kouki M. and Takayoshi N., "DSP-based speed adaptive flux observer of induction motor", ***IEEE transactions on industry applications***, 29(2): 344-348, (1993).

[40] Holtz J., "Sensorless control of induction motor drives", ***Proceedings of the IEEE***, 90(8): 1359-1394, (2002).

[41] Li J., Hai-Peng R. and Yan-Ru Z., "Robust speed control of induction motor drives using first-order auto-disturbance rejection controllers", ***IEEE Transactions on Industry Applications***, 51(1): 712-720, (2015).

[42] Otkun Ö., Doğan R. Ö. and Akpınar A. S., "Neural Network Based Scalar Speed Control of Linear Permanent Magnet Synchronous Motor", ***Journal of the Faculty of Engineering & Architecture of Gazi University***, 30(3): 395-404, (2015).

[43] Rao G. M. and Srikanth G., "Comparative Study of Maximum Torque Control by PI ANN of Induction Motor", ***International Journal of Applied Engineering Research***, 13(7): 4620-4625, (2018).

[44] Bulut M., Kurt M., Demirtaş M ., "Application of Genetic-Fuzzy Controller to a DC Motor", ***Journal of Polytechnic***, 7(4): 277-283, (2004).

[45] Hui L., Yunfei L., Xin D. and Huajug Z., "Optimization of Adaptation Gains of Full-order Flux Observer in Sensorless Induction Motor Drives Using Genetic Algorithm", ***Information Technology Journal***, 8(4): 577-582, (2009).

[46] Douiri M. R., Belghazi O., Cherkaoui M., "Recurrent Self-Tuning Neuro-Fuzzy for Speed Induction Motor Drive", ***Journal of Circuits, Systems and Computers***, 24(9): (2015).

[47] Ustun S. V. and Demirtaş M., "Optimal tuning of PI coefficients by using fuzzygenetic for V/f controlled induction motor", ***Expert Systems with Applications***, 34(4): 2714-2720, (2008).

[48] Chen C., Lai C. and Sun W., "Fuzzy Testing for Regression Coefficient of Fuzzy Numbers", ***Journal of Testing and Evaluation***, 41(1): 1-6, (2012).

[49] Orłowska-Kowalska T., Blaabjerg F., Rodríguez J., ***Advanced and Intelligent Control in Power Electronics and Drives***, Springer, New York, (2014).

[50] Krim S., Gdaim S., Mtibaa A., et al., "Design and Implementation of Direct Torque Control Based on an Intelligent Technique of Induction Motor on FPGA", ***Journal of Electric Engineering and Technology***, 10(4): 30-40, (2015).

[51] Shun-Yuan W., Chwan-Lu T., Shou-Chuang L., et al., "An Adaptive Supervisory Sliding Fuzzy Cerebellar Model Articulation Controller for Sensorless Vector-Controlled Induction Motor Drive Systems", ***Sensors***, 15(4): 7323-7348, (2015).

[52] Adiuku C.O., Beig A.R., Kanukollu S., 'Sensorless closed loop V/f control of medium-voltage high-power induction motor with synchronized space vector PWM', ***IEEE 8th., GCC Conference and Exhibition (GCCCE)***, 1-4 Feb., Muscat: IEEE, (2015).

[53] Sarıoğlu M. K., Gökaşan M., Boğosyan O., '***Induction Machines and Control***', İstanbul: Birsen Press, (2003).

[54] Soliman H. M., "Studying the Steady State Performance Characteristics of Induction Motor with Field Oriented Control Comparing to Scalar Control." ***European Journal of Engineering Research and Science***, 18-25, (2018).

[55] Kiran K., Sukanta D. and Diksha S., "Model predictive field oriented speed control of brushless doubly-fed reluctance motor drive." ***2018 International Conference on Power, Instrumentation, Control and Computing (PICC)***. IEEE, (2018).