Rev. Roum. Sci. Techn.– Électrotechn. et Énerg.
Vol. 63, 2, pp. 217–222, Bucarest, 2018

IMPROVING ACCURACY AND ORDER OF ASTATISM OF ROLLING MILL DRIVES USING FEEDFORWARD COMPENSATION

YAKHELEF YASSINE[1], BOULOUH MESSAOUD[2]

Key Words: Direct current (dc) drive control system, Proportional-integral (PI) controller, Reduced order state observer, Accuracy performance, Order of astatism, Feed-forward compensation.

In steel and paper rolling mill industrial plants, where dc drive systems are widely used, improving dynamic and steady state performance properties plays a significant role in achieving a good quality of product. In this paper we intend to study the steady state performance of those systems in response to changed input reference, where an optimized transfer function based feed-forward compensating technique is proposed and applied to enhance their order of astatism without inserting additional integrators in the forward path of the closed loop system and therefore achieving improvement of the corresponding tracking error accuracy performance. The simulation results have shown a noticeable and important achievement in accuracy performance of the studied system when subjected to changing input reference.

1. INTRODUCTION

Feedback control systems are built to modify the behaviour of a process so it behaves in a specific desirable way over time. In other words, the primary objective of feedback system is to make the system's output trajectories follow the imposed input trajectories. The separately excited dc drive systems, widely used in paper and steel rolling mill industries, are considered as high performance motion control systems which are characterized by their good dynamic and steady state input reference tracking and load disturbance rejection requirements [1]. The PI controller is, on the other hand, extensively used to build the speed feedback system where the drive motor speed should be precisely controlled to give the desired performance. This is found highly effective if both set point and load disturbance changes are small. However, in event of substantial speed and /or torque variation, as the case of rolling mill plants, these conventional control systems become unable alone to track accurately these variations and preventing, therefore, the deviation from the desired performance. Since, on the other hand, the quality of product in these industrial plants is closely related to the steady state accuracy performance, the improvement of these performances in presence of external input variation and change is crucial.

In an attempt of overcoming non desirable effects of load torque and other mechanical parameters variation on drive performances, researchers have, continuously, worked to design compensating control techniques and ensuring, therefore, high operational performances. In this vein, the design and implementation of state observer based drive control system represents the best choice that preserves simplicity, reliability and cost effectiveness of whole drive control system. This, however, did not definitely solve the problem of enhancing accuracy performance and following with high order of astatism the changed input reference.

Attention is, particularly, given to this subject throughout the multitude of methods and techniques which are proposed in literature. Traditionally, it is used to improve the accuracy performance of a closed loop control system by the proportional gain method [2], which consists of exploiting the inverse proportionality relationship that exists between the system steady state error and the loop static gain and reducing the former by increasing the loop gain. This method, although efficient of allowing obtaining a speed response with a very small steady state error, it degrades the system's transient performance by increasing the percent overshoot. Another method known as integral control [3] is also used to improve both systems' order of astatism and accuracy by modifying the control structure and adding integral terms in the forward path of the control loop. The main drawback of this method is that these added integrators may lead to instability of the system.

The sliding mode control (SMC) is used with PI controller in [4, 5] as a robust and simple control technique to ensure stability and desired tracking performance for especially systems characterized by uncertainties and disturbance variation. Although its effectiveness in achieving the performance objectives, this method suffers from a major drawback of chattering phenomenon, which can be reduced using other techniques. Due to the fact that SMC method exhibits robustness and high disturbance rejection capability, it is used alone in [6] to replace the proportional integral derivative (PID) controller and improving the accuracy performance affected by the cutting forces of the machine tool systems.

In an attempt of combining the advantages of sliding mode control and the adaptive control approach, the method named as adaptive sliding mode control is proposed in [7] to compensate model uncertainties of flexible-joint manipulator nonlinear dynamic systems and ensuring robust stability and accuracy performance. An accurate steady state response with zero error has also been obtained using this combined technique in [8], where the control chattering is thereafter eliminated.

An adaptive neural network (NN) control scheme is also used in [9] to study and improve the tracking performance of induction motor speed control drive systems under variable reference input signal. The achieved performance is judged satisfactory using both simulation and experimental laboratory results even in the presence of much strong mechanical friction and other non linear characteristics. The method is also applied in [10] for the same purpose on the speed and position controlled dc motor drive system.

[1] University of Boumerdes, department of Infotronics, Boumerdes, Algeria, E-mail: mr.yakhelef@yahoo.fr
[2] University "8 May 1945" of Guelma, P.O. Box 401, Guelma, Algeria, E-mail: boulouhmessaoud@gmail.com

The hybrid fuzzy-neural networks controller is, on the other hand, applied in [11], to adaptively improve both robustness and accuracy performance of induction motor speed control system. The tracking performance of the system was satisfactorily illustrated under a variable load torque with the external disturbance introduced by disturbing the load during trajectory control. The same approach is also used in [12] to improve the control performance of the dc drive under transient and steady state conditions.

The feed-forward compensation is an alternative approach widely employed to enhance the quality and performance of control system in different engineering branches. It consists of altering the structure of the control system by adding a compensating branch in the forward path of the closed loop system. Many techniques have used this approach to improve the tracking and accuracy performance of feedback control systems. In the literature, the neural network (NN) based feed-forward method is used in [13] to ameliorate the accuracy performance of PID based nonlinear control systems characterized with an input disturbance. The obtained results have mentioned a satisfactory reduction of the steady state error after a certain learning number. The fuzzy logic control combined with PI controller has also been used in [14] as a feed-forward compensator to improve the already implemented sliding mode based positioning control system. Other forms of feed-forward compensators are also studied in [15].

In this paper, a novel and simple feed-forward compensating control technique is proposed and applied to improve both accuracy and order of astatism of PI speed controlled and reduced order state observer based dc drive system particularly designed for steel and paper rolling mill industrial applications [17]. Therefore, its structure is organised as follows: Section 2 is devoted to present the dc motor model that is used in the drive as well as its speed control functional structure consisted mainly of PI-type controller in conjunction of a designed reduced order state observer. The bulk of the work done is however presented in Section 3, where the theoretical background of set point change effect on the accuracy performance of the drive system is thoroughly assessed and analysed in the first subsection, whereas in the second subsection, the proposed feed-forward compensator is explained and applied to achieve improvement of system's accuracy performance, a fact that is justified by the simulation results. Finally, the potential control performance and quality that can be achieved with the proposed compensation scheme is pointed out in the conclusion.

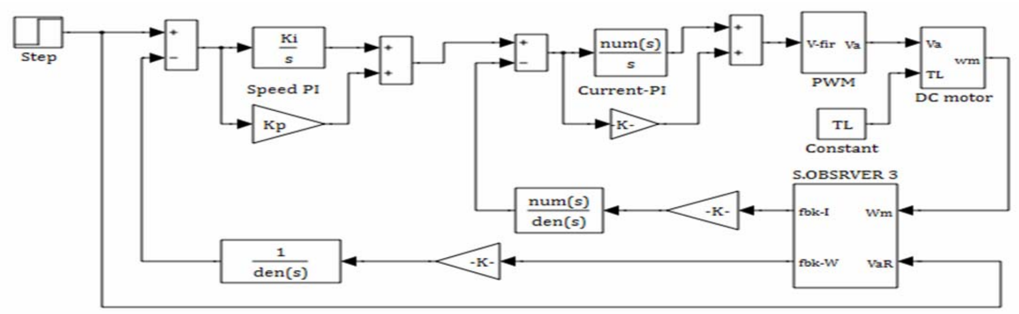

Fig. 1 – Simulink block diagram model of PI speed controller and reduced three order state observer based dc drive system.

2. DESCRIPTION OF THE STUDIED DC DRIVE CONTROL SYSTEM

2.1. MODEL OF DC MOTOR

In this study, the dc motor is used to drive a mechanical load characterised by the inertia J and load torque T_L, which is taken constant. The dynamics of this electromechanical system is described by the following equations [16]:

$$V_a = R_a I_a + L_a \frac{\mathrm{d}I_a}{\mathrm{d}t} + E_b \tag{1}$$

$$T_e = J \frac{\mathrm{d}\omega_m}{\mathrm{d}t} + \beta_m \omega_m + T_L \tag{2}$$

$$E_b = K_b \omega_m \tag{3}$$

$$T_e = K_t I_a \quad , \tag{4}$$

where the physical parameters are: V_a – the input terminal voltage (source), [V]; E_b – the back e.m.f, [V]; R_a – the armature resistance, [Ω]; I_a – the armature current [A]; L_a – the armature inductance, (H); J – the inertia moment of the motor rotor and load, [kg.m^2]; T_e – the motor torque, [N.m]; ω_m – the speed of the shaft and the load (angular velocity), [rad/s]; β_m – the coefficient of viscous friction of the mechanical system, [N.m.s/rad]; K_b – the motor constant [V.s/rad]; K_t – the torque factor constant, [N.m/A].

2.2. STRUCTURE OF CONTROL LOOP

In this paper, the closed loop control of the drive system is of cascade topology. It has basically two feedback loops; the outer loop is a speed feedback loop which consists of a PI type controller, and an inner current feedback loop of PI type controller, found generally in paper and steel rolling mill industries. The speed controller output is the reference for the current controller and the output of the current controller is the input to the pulse width modulated (PWM) generator that controls the motor input voltage, with the speed and current feedback signals are supplied via the designed reduced three order state observer [17].

Using Matlab/Simulink program [18], the elaborated block diagram which describes the functional structure of the studied drive system is depicted in Fig.1.

3. SYSTEM'S ACCURACY PERFORMANCE ASSESSMENT FOR VARIABLE SET POINT

A second property that we desire in any feedback control system after stability is its accuracy performance robustness against external input changes and disturbances. We quantify the accuracy of such system in terms of steady-state error defined, in the time domain, as the difference between the reference signal $r(t)$ and the measured controlled signal $y(t)$ as time tends to infinity. This is expressed as:

$$e_{ss} = \lim_{t\to\infty}\left[r(t) - y(t)\right]. \quad (5)$$

Traditionally, the steady state error is a standard measure of performance that is widely used in assessing the accuracy of control system; therefore, an accurate control system is that of ideally zero steady state error.

For the sake of assessing quantitatively the accuracy performance of the system at hand, in the frequency domain we represent the above simulink block diagram of Fig. 1 by the following general block diagram with R(s) represents the reference input signal. Y(s) and $Y_{es}(s)$ are, respectively, the actual and estimated output speed signals. $E(s)$ is the tracking error signal of closed loop system $G_C(s)$, $G_P(s)$ and $H(s)$ are, respectively, the corresponding transfer functions of the controller, the controlled plant and the state observer (the feedback path).

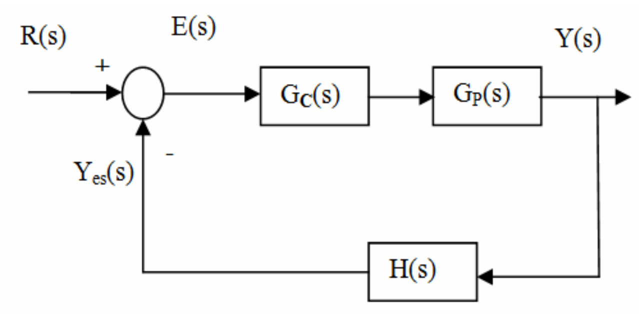

Fig. 2 – General block diagram of DC drive control system with only set point input disturbance.

By referring to this block diagram, we define, in frequency domain, the control tracking error as:

$$E(s) = R(s) - Y_{es}(s) = R(s) - \frac{T_{OL}(s)}{1+T_{OL}(s)}R(s)$$

$$E(s) = \frac{1}{1+T_{OL}(s)}R(s) \quad , \quad (6)$$

with $T_{OL}(s)$ represents the open loop transfer function of the feedback system, which is expressed in a more generalized manner as:

$$T_{OL}(s) = \frac{Y_{es}(s)}{E(s)} = \frac{K_m\left(1+b_1 s + b_2 s^2 + ... + b_m s^m\right)}{s^{\alpha}\left(1+a_1 s + a_2 s^2 + ... + a_n s^n\right)}. \quad (7)$$

The parameter α is called the order of astatism of the open loop transfer function of the system, which physically represents the number of integrators in the forward path of the feedback system.

Obviously, in addition to the elements of the forward path (T_{OL}), the tracking error strongly depends also on the form of input disturbance signal $R(s)$. Consequently, to study and analyze the effect of sudden changes of this disturbance signal, the following polynomial form of order 'q' in the time domain is being used.

$$r(t) = \frac{t^q}{q!}u(t) = K.t^q.u(t), \; t \ge 0, \quad (8)$$

with K and $u(t)$ represent respectively an arbitrary constant and the unit step function.

In the frequency domain, this reference signal is expressed as:

$$R(s) = \frac{K}{s^{q+1}}. \quad (9)$$

3.1. INFLUENCE OF SYSTEM'S ORDER OF ASTATISM ON ITS ACCURACY PERFORMANCE

The accuracy performance of feedback control system is measured by its ability to track the variation and change of input reference signal. This ability is defined by the value of the steady state error expressed by (5).

Assuming the stability of the system and using the final value theorem, the steady state error can be evaluated as:

$$e_{SS} = e(\infty) = \lim_{t\to\infty} e(t) = \lim_{s\to 0} sE(s). \quad (10)$$

From (6), (7) and (9), this value at steady state becomes:

$$e_{SS} = e(\infty) = \frac{K.s}{s^{q+1}\left(1+\frac{K_m}{s^{\alpha}}\right)} = \frac{K.s^{\alpha-q}}{s^{\alpha}+K_m}. \quad (11)$$

In order to study the effect of input disturbance changes, the stimulating standard input signals of step, ramp, parabolic and order three polynomial, which are respectively corresponding to the cases of $q = 0$, $q = 1$, $q = 2$ and $q = 3$ in (9) are used, where the theoretical values of steady state error of systems having order of astatism 0, 1, 2, and 3 are calculated and summarized in Table 1.

Table 1

Values of steady state error according to systems order of astatism and input set point form

Order of astatism (α)	$\alpha = 0$	$\alpha = 1$	$\alpha = 2$	$\alpha = 3$
Step ($q = 0$)	$\frac{K}{1+K_m}$	0	0	0
Ramp ($q = 1$)	∞	$\frac{K}{K_m}$	0	0
Parabola ($q = 2$)	∞	∞	$\frac{K}{K_m}$	0
Polynomial of ($q = 3$)	∞	∞	∞	$\frac{K}{K_m}$

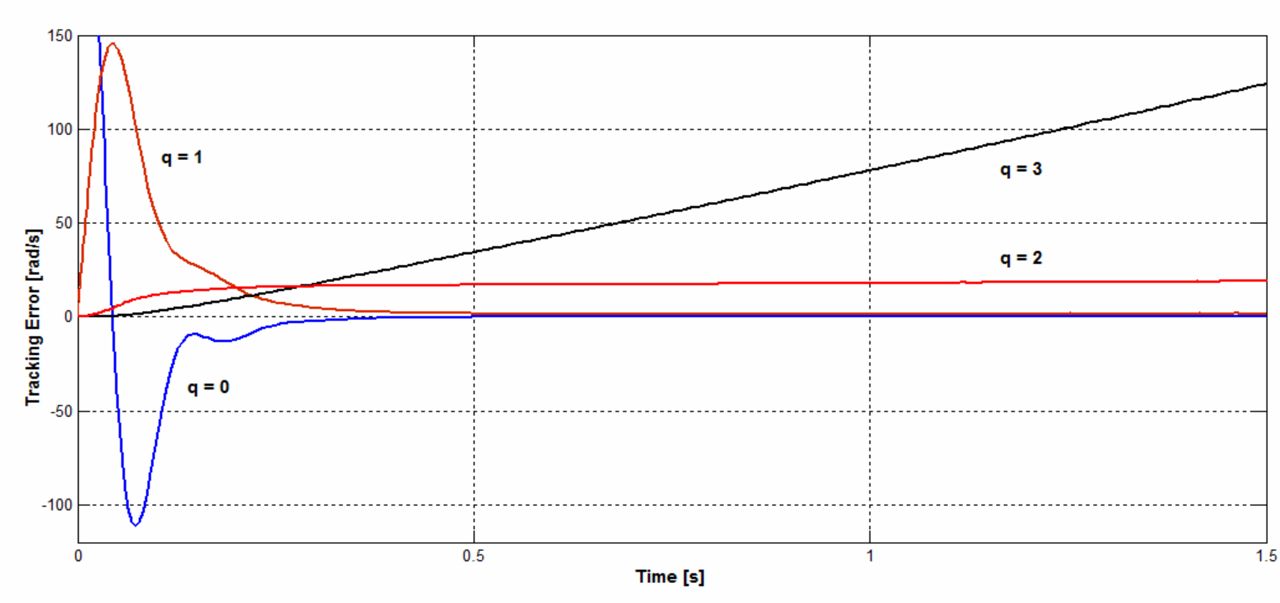

Fig. 3 – Speed tracking error response of PI and reduced order state observer based dc drive system due to input set point changes.

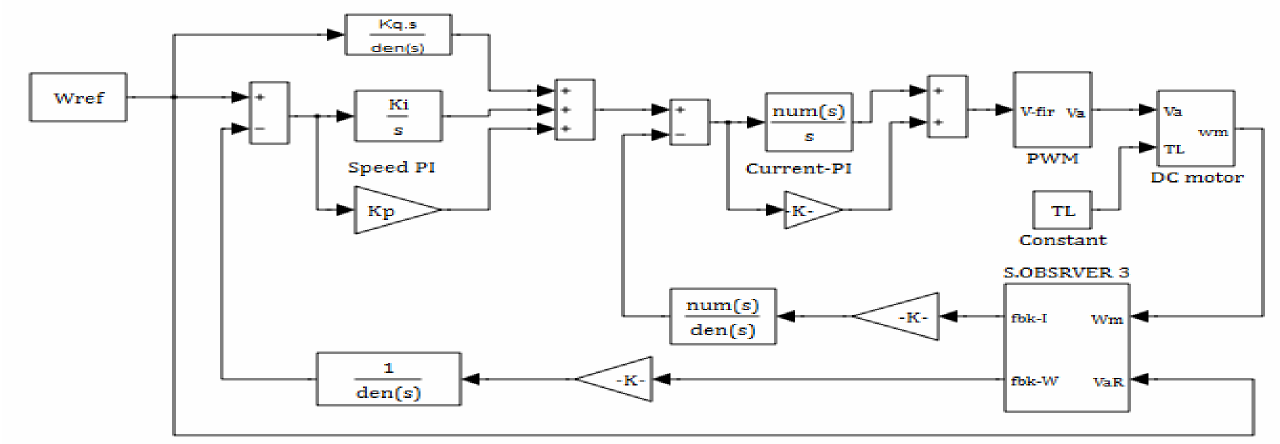

Fig. 4 – Block diagram of PI and state observer of order 3 based dc drive system with feed forward compensation.

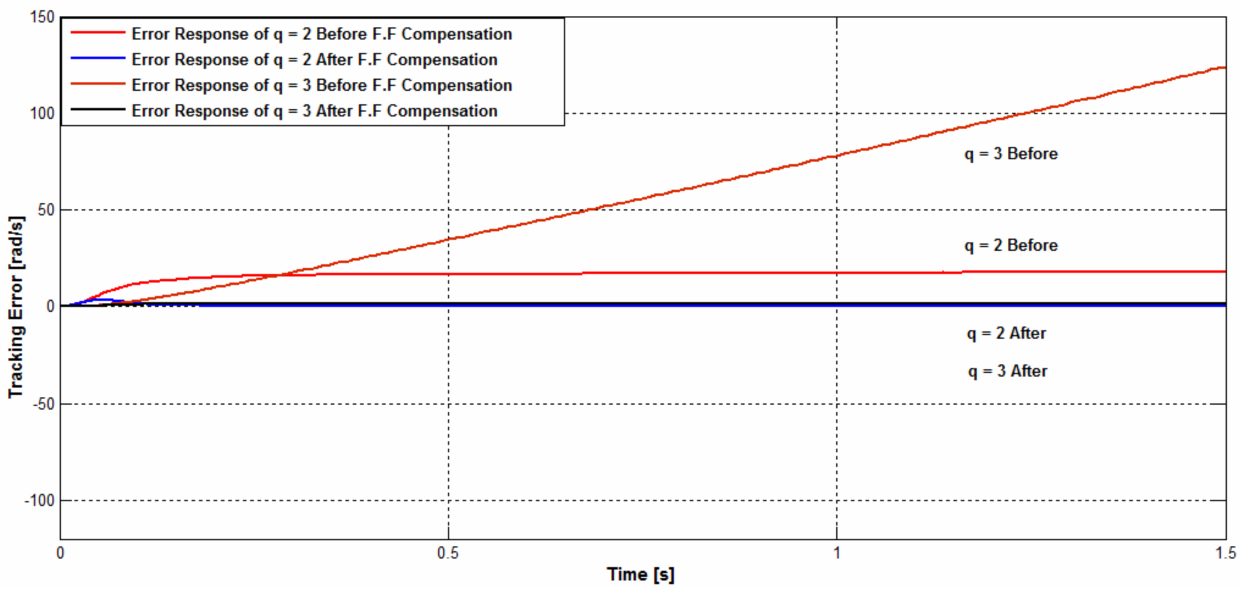

Fig. 5 – Achieved improvement of dc drive system accuracy and order of astatism under input set point changes using feed-forward compensation.

The above theoretical evaluation and assessment of system's accuracy performance regarding the variation and changes of input disturbance is being simulated using the system at hand. The simulation results showing the corresponding speed error response are depicted in Fig. 3.

Obviously, the system responds perfectly with zero steady state error for step and ramp inputs. However, this response presents constant nonzero error for parabolic input and becoming completely divergent when the input changes to a polynomial of order three. As a result, this control system which has an order of astatism equals one (corresponding to zero steady state error), cannot respond accurately to the changed reference input.

3.2. IMPROVING SYSTEM'S ACCURACY BY FEED-FORWARD COMPENSATION

Theoretically and according to the results of Table 1 above, we notice that the higher the order of astatism of the system, the better is the accuracy of the system response to set point changes ($e_{ss} = 0$). Furthermore, it is possible to improve, for a given input signal, the accuracy of the system response which has a constant value of steady state error by increasing the static gain (K_m) of the open loop transfer function.

Unfortunately, improving the system accuracy by either increasing the order of astatism (adding more integrators), or increasing the static gain has an explicit degradation effect on the phase margin and renders the system unstable [2, 3].

To solve this problem, we propose, in this paper, a feed-forward compensating technique to improve accuracy performance and order of astatism for systems subjected to sudden input reference changes. The block diagram showing the simulation of this technique under simulink program is depicted in Fig. 4.

As it is mentioned in the block diagram, we propose to use in the feed forward path the compensating transfer function of a general form as follows:

$$T_{FF}(s) = \frac{K_q s}{s+1}, \qquad (12)$$

where the constant K_q is determined by solving the square of error based minimization problem described as follows:

$$\min_{K_q} \left(K_q e^2(t) \right), \qquad (13)$$

where *e(t)* represents the tracking error signal of the system.

Using the Matlab function "fminsearch" from optimization tool box [19] and the simulink environment, the constant is found to be $K_q = 0.2644$ which completely identifies the transfer function of the used feed-forward compensator.

This optimal transfer function is then applied and the whole system is simulated under the input signal form that has previously resulted in constant and nonzero steady state error. The simulation result that shows the error response before and after compensation is depicted in Fig. 5.

These comparative error responses clearly reveal that using the proposed feedforward compensator, we were able to reduce a constant and even divergent steady state error to zero. This means that the system's order of astatism has been increased from one to three with guaranteed accurate and stable steady state response to reference input change.

4. CONCLUSION

In this paper, the PI controller and reduced three order state observer based dcC drive speed control system, widely used in paper and steel rolling mill industries is considered for accuracy performance optimization to variable input set point. A theoretical analysis and assessment of system's accuracy performance under the effect of input set point change is first given, where the correlation existing between the accuracy performance of the system and its order of astatism is mentioned. These theoretical results have been verified by simulating the system at hand for different set point profiles tracking capability. The simulation results have shown that the system has an order of astatism equals one and can only track with zero steady state error the input reference change from unit step to ramp. If the input set point is further changed, the system rather responds inaccurately with constant or divergent steady state error. When the proposed feed-forward compensation technique is applied, the response that has exhibited both constant and divergent values of steady state error has been compensated to zero. This result infers the fact that the feedforward compensator makes the controller answers directly to the change of the desired speed reference before the error is built up.

Overall, the system's order of astatism is incremented by two and its accuracy performance to input set point sudden changes is accordingly improved with guaranteed system stability.

Received on, April 11, 2017

REFERENCES

1. M. Schleicher, F. Blasinger, *Control Engineering, a Guide for Beginners*, 3rd ed., Jumo GmbH and Co, Fulda, Germany, January 2003.
2. J.J. D'Azzo, C.H. Houpis, S.N. Sheldon, *Linear Control System Analysis and Design with MATLAB*, Fifth Edition, Revised and Expanded, Marcel Dekker, Inc., New York, 2003.
3. Q. Chen, *Reset Control Systems: Stability, Performance and Application*, Ph.D. Dissertation, University of Massachusetts Amherst, September 2000.
4. A.J. Koshkouei, K.J. Burnham, *Control of DC Motors using Proportional Integral Sliding Mode*, Control Theory and Applications Centre, Coventry University, Coventry CV1 5FB, UK, 2008.
5. C. Milosavljevic, *Variable structure systems of quasi relay type with proportional-integral action*, The Scientific Journal Facta Universitatis, Series–Mechanics, Automatic, Control and Robotics, **2**, *7*, pp. 301–314 (1997).
6. T.H. Chiew, Z. Jamaludin, A.Y. Bani Hashim, K. J. Leo, L. Abdullah, N. A. Rafan, *Analysis of tracking performance in machine tools for disturbance forces compensation using sliding mode control and PID controller*, International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS, **12**, *6*, pp. 34–40 (2012).
7. C. Schmid, *Adaptive sliding-mode control of nonlinear systems using neural network approach*, Proceedings of the 17th International Conference on Process Control, Strbske Pleso, Slovakia, June 9–12, 2009, pp. 346–352.
8. Y. Stepanenko, Y. Caos, CH. Y. Su, *Variable structure control of robotic manipulator with PID sliding surfaces*, International Journal of Robust and Nonlinear Control, **8**, pp. 79–90 (1998).

9. M. Zerikat, S. Chekroun, *Adaptation learning speed control for high-performance induction motor using neural neworks*, International Journal of Signal, System Control and Engineering Application, **2**, *1*, pp. 15–21 (2009).
10. K.B.M. Krishna, B.V.S. Goud, *Speed control of DC motor through position and speed tracking system using neural networks*, International Journal of Electronic Engineering Research, **5**, *1*, pp. 87–103 (2013).
11. M. Zerikat, S. Chekroun, *High performance speed tracking of induction motor using an adaptive fuzzy-neural network control*, International Journal of Sciences and Techniques of Automatic Control and Computer Engineering, Special Issue (CEM), pp. 516–531, December 2008.
12. M. Gökbulut, B. Dandil, C. Bal, *A hybrid neuro-fuzzy controller for brushless DC motors*, Springer, 2006, pp. 125–132.
13. Ch.K. Song, G. Khim, *Improvement of tracking accuracy of positioning systems with iron core linear DC motors*, International Journal of Precision Engineering and Manufacturing, **6**, *1*, pp. 31–35 (2005).
14. M. Mihajlov, V. Nikolić, D. Antić, *Position control of an electro-hydraulic servo system using sliding mode control enhanced by fuzzy PI controller*, the Scientific Journal, Facta Universitatis, series–Mechanical Engineering, **1**, *9*, pp. 1217–1230 (2002).
15. M. Malek, P. Makys, M. Stulrajter, *Feedforward control of electrical drives – rules and limits*, Advances in Electrical and Electronic Engineering, **9**, *1*, pp. 35–42 (2011).
16. F. Gurbuz, E. Akpinar, *Stability analysis of a closed-loop control for a pulse width modulated DC motor drive*, Turkish Journal of Electrical Engineering, **10**, *3*, pp. 427–438 (2002).
17. L.V. Akimov, V.T. Dolbnia, V.I. Kolotilo, *Electric DC Drive Control Systems with State Observers*, Kharkov State Polytechnic University, KHSPU, Ukraine, 1998.
18. Matlab/Simulink, V 7.3 (R2009a), the MathWorks, Inc., 2009.
19. Matlab Optimization Toolbox, V 4.2 (R2009a), The MathWorks, Inc., 2009.