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Stability robustness and accuracy improvement of double PI based DC drive system subjected to load torque changes

***Abstract**. In this research paper, we intend to study the issue of improving the stability robustness and accuracy performance of double Proportional-Integral and reduced order state estimator based speed controlled DC drive system when subjected to sudden change of load torque disturbance, where an optimized transfer function based feedforward compensating technique is proposed and applied for this purpose. The simulation results have shown a significant improvement of systems' accuracy performance and stability robustness to variable load torque.*

Streszczenie.** W tym artykule badawczym zamierzamy zbadać kwestię poprawy stabilności, wytrzymałości i dokładności systemów napędowych DC sterowanych prędkością w oparciu o podwójną proporcjonalność-całkę i estymator stanu zredukowanego, gdy są poddawane nagłej zmianie zakłócenia momentu obrotowego obciążenia, gdzie zoptymalizowana funkcja przenoszenia W tym celu zaproponowano i zastosowano technikę kompensacji opartą na wyprzedzaniu. Wyniki symulacji wykazały znaczną poprawę dokładności i odporności systemów na zmienny moment obciążenia.* (Poprawa stabilności, wytrzymałości i dokładności układu napędowego prądu stałego opartego na podwójnym PI, poddanego zmianom momentu obrotowego obciążenia***)

Keywords: Stability robustness, double proportional-integral controller, load torque change, optimized feedforward function.
Słowa kluczzowe: Stabilność, podwójny sterownik proporcjonalnie-całkujący, zmiana momentu obciążenia,

Introduction

The direct current (dc) motor based drive control system represents the backbone of the various industrial applications and processes, particularly, this is because of its good dynamic and steady state input reference tracking and load disturbance rejection requirements [1]. Regarding the utilization of this drive system, a precise control of its speed is a crucial issue for many applications where the proportional-Integral (PI) control type is with no doubt the most and widely used control algorithm for this purpose [2, 3, 4], due mainly to its attractive advantageous properties [5,6]. As such, this controller is highly recommended as a direct solution for most of industrial control problems, including process control, motor drives, automotive systems, flight control, instrumentation, etc.,

However, in many industrial processes where the dc motor drive system is employed, aspects of joint elasticity and nonlinearities are inherent characteristics because of the long shaft linking the load to the driving motor. This situation causes torsional vibration particularly while operating under sudden and abrupt changes and variation on the load or input setpoint sides, which can greatly affect the quality of the product and even influence the stability and other performances of the closed loop control system. It is found that for small and light sudden changes of the load torque disturbances, the use of simple or double conventional PI speed controller can, if properly tuned [7-14], be satisfactory to compensate for their influence and impact on the dynamic and steady state behaviour of the drive control system, hence ensuring the required quality as well as the accuracy performance of its output response [15], but for substantial and significant changes of this control parameter, this conventional control algorithm alone cannot withstand and preserve the satisfactory operational performance of these systems. To solve this relevant and serious control problem, researchers are working to apply approaches and control techniques capable of compensating the undesirable effects of sudden and abrupt load torque changes and variation on the operational performances of the whole control system and hence the quality of the end product. In this respect, the design and implementation of speed controlled dc drive system based on state estimator seemed to be appropriate and convenient, particularly for systems characterized by inherent high elasticity and nonlinearity in such a way that the whole control system is maintained reliable, simple and cost effective [16].

In recent years, researchers however are interesting with assessing and evaluating the already designed and implemented feedback control system performances, where the aim is to study the problems of how well such control systems meet with the design requirements and finding control techniques that ensure an effective load-disturbance rejection and good transient and steady state response to such sudden changes hence leading to improved robustness and accuracy of the system. In view of this purpose, the design of state estimator did not attain the required performance improvements of robustness and accuracy of the control system subjected particularly to load change and variation [13], hence, alternative methods and techniques have been proposed where at the beginning, a method inspired from the inverse proportionality between the steady state error and the static loop gain of the feedback system is proposed in [17] to progressively reduce the system's steady state error therefore increasing its accuracy by correspondingly increasing the static loop gain. The main drawback of this method is that it leads to a significant increase of system's percent overshoot which may affect its stability. In [18], the method named as integral control is proposed to ameliorate the control systems' accuracy and stability robustness through an insertion of additional integral terms in the forward path of the control loop which can unfortunately render the system unstable. Another approach based on sliding mode control as an efficient and uncertainty robust control method is also applied in conjunction with PI controller [19, 20] and alone replacing the PID controller [21,22]. The use of this technique although is effective of ensuring both stability robustness and accurate tracking to setpoint or load torque changes and variation, it suffers from the chattering phenomenon that unfortunately limits its employment. An adaptive version of sliding mode control is also applied in [23, 24] to obtain an accurate input trajectory tracking of a flexible joint manipulator.

The intelligent and adaptive based methods were also used and applied to improve the accuracy tracking and robustness of both ac and dc drive systems subjected to variable operating conditions. In this context, Adaptive Model Predictive Control in [25], Neural Networks structure in [26-28] as well as hybrid Neuro-Fuzzy control structure used in [29] are justified to give satisfactory results of significant improvement regarding robustness and steady state accuracy tracking of the system particularly operating under strong nonlinearity and sudden variable disturbance conditions.

The main contribution of this work is to make concrete the idea of combining the use of the novel optimized feedforward compensation as a simple, reliable and cost effective control method with that of integral based technique via the use of double PI speed controller instead of a simple PI controller studied and reported in [30] to achieve more improvement in accuracy performance and stability robustness of a reduced order state estimator based DC drive speed control system when subjected to sudden load torque changes. To present the content of this study with the corresponding obtained results, the rest of the paper is organized as follows: in section 2 we present the mathematical equations that describe and model the dynamics of the dc driving motor. Correspondingly, we give a brief description of the whole control system structure subjected to this study. In section 3, we fundamentally perform a theoretical study and evaluation of how the accuracy performance and stability robustness of the system are dependent on the load torque variation and change, where in the first subsection, the effect of system's class and load torque changing profile are addressed, whereas in the second subsection, it is explained and applied the proposed feedforward compensator with the obtained results on achieved performance are justified, interpreted and discussed in the third subsection. Finally, the control quality and effectiveness of the proposed and applied control technique are pointed out in the conclusion.

Dynamics of the studied control system

We perform this study of assessment and improvement of accuracy performance and robustness to load torque variation on a double PI and reduced order state estimator based speed controlled dc drive system, where the driving motor is the separately excited dc motor which is linked to the mechanical load via a long shaft. The dynamics of the driving motor is described by the following mathematical equations [13]:

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

$$T_e = J \frac{\mathrm{d}\omega(t)}{\mathrm{d}t} + \beta\omega(\mathrm{t}) + T_L \tag{2}$$

$$E_b = K_b \omega(t) \tag{3}$$

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

Where the variables and parameters involved in the above equations are defined as follows: V_a : is the input terminal voltage, (V); E_b : is the back e.m.f, (V); R_a : is the rotor resistance, (Ω); I_a : is the rotor current (Amp); L_a : is the rotor inductance, (H); J : represents the inertia moment of the motor rotor and load, (Kg.m^2); T_e : represents the developed electromagnetic torque, (N.m); $\omega(t)$: is the final rotational velocity of the shaft and the load, (rad/s); β : is the viscous friction coefficient of the mechanical system, (N.m.s/rad); K_b : represents the motor constant (V.s/rad); and K_t : is the torque constant, (N.m/Amp).

The double PI and reduced order state estimator based feedback control system scheme built to control the dc motor speed is fundamentally consisted of two control loops; the outer feedback loop where a doubled conventional PI controller is inserted to control the output speed of the driving motor whereas the current control loop is built around a simple PI current controller. The functioning of this proposed control structure is due to the fact that the actual values of speed and current used in these two control loops respectively are estimated via the reduced order state estimator designed for this purpose. With the availability of these values, the double PI speed controller generates the reference value for the current controller which controls the PWM based power converter and hence issuing the appropriate and desired motor input voltage corresponding to the desired speed response. This control system subjected to the present study is represented by the block diagram of Fig.1.

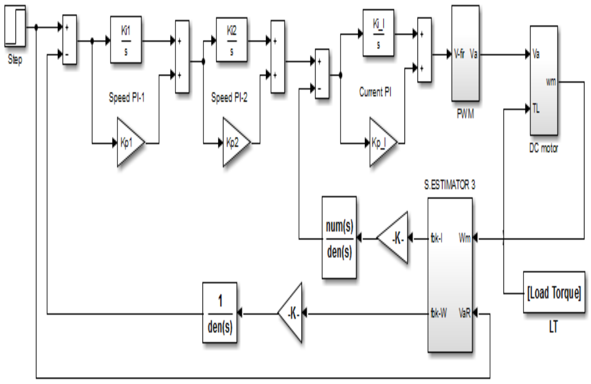

Fig.1 Simulink block diagram model of double PI speed controller and reduced order state estimator based DC drive system

Analysis of system's robustness to load change

Among the fundamental targeted objectives and requirements of designing any feedback control system after ensuring its stability is achieving an improved steady state and a good robustness to sudden load torque changes and variation. In order to tackle this accuracy study and assessment, we define in a broader manner the quantity of steady state error e_{ss} as:

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

With $r(t)$ and $y(t)$ are respectively the input setpoint and the controlled output signals.

The accuracy assessment and analysis that we intend to perform in this work is based on the steady state error value which is ideally equals zero and practically very close to zero to indicate a system of high degree of stability and steady state accuracy tracking capability. To theoretically carry out this study, we simplify the control system represented by the block diagram of Fig.1 with that represented in Fig.2.

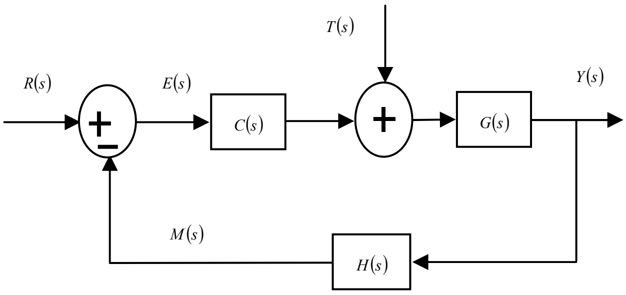

Fig.2 General block diagram of a control system

With *R(s)* represents the reference input signal, *Y(s)* and *M(s)* are, respectively, the actual and measured output speed signals. On the other hand, *E(s)* is the tracking error signal of closed loop system, and *C(s)*, *G(s)* and *H(s)* are, respectively, the corresponding transfer functions of the controller, the controlled plant and the state observer (the feedback path).

Accordingly, the total steady state error variable is defined in the frequency domain as:

$$E(s)=R(s)-M(s) \tag{6}$$

$$E(s)=\frac{R(s)}{1+H(s)C(s)G(s)}-\frac{H(s)G(s)T(s)}{1+H(s)C(s)G(s)} \tag{7}$$

This total steady state error of the control system can also be formulated as:

$$E(s)=E_R(s)+E_T(s) \tag{8}$$

Where:

$E_R(s)=\frac{R(s)}{1+H(s)C(s)G(s)}$ is the tracking error due to the input reference signal and $E_T(s)=-\frac{H(s)G(s)T(s)}{1+H(s)C(s)G(s)}$ is the tracking error due load torque disturbance signal.

If we define the transfer functions $C(s)$, $G(s)$ and $H(s)$ as:

$$C(s)=\frac{N_C(s)}{D_C(s)}=K_c\,\frac{(b_{mc}s^{mc}+b_{mc-1}s^{mc-1}+\ldots+1)}{\left(a_{nc}s^{nc}+a_{nc-1}s^{nc-1}+\ldots+1\right)} \tag{9}$$

$$G(s)=\frac{N_P(s)}{D_P(s)}=K_p\,\frac{(b_{mp}s^{mp}+b_{mp-1}s^{mp-1}+\ldots+1)}{\left(a_{np}s^{np}+a_{np-1}s^{np-1}+\ldots+1\right)} \tag{10}$$

$$H(s)=\frac{N_H(s)}{D_H(s)}=K_h\,\frac{(b_{mh}s^{mh}+b_{mh-1}s^{mh-1}+\ldots+1)}{\left(a_{nh}s^{nh}+a_{nh-1}s^{nh-1}+\ldots+1\right)} \tag{11}$$

And we denote $G_{OL}(s)$ to be the feedforward open loop transfer function of the whole control system, from control theory, we can express $G_{OL}(s)$ as:

$$G_{OL}(s)=H(s)C(s)G(s)=\frac{N_{OL}(s)}{s^{\alpha}D_{OL}(s)}$$

$$G_{OL}(s)=\frac{K_{OL}\left(1+b_1s+b_2s^2+\ldots+b_ms^m\right)}{s^{\alpha}\left(1+a_1s+a_2s^2+\ldots+a_ns^n\right)} \tag{12}$$

Where'α' is the system's class, which practically reflects the steady state accuracy performance of the feedback control system. Accordingly, the two components of the system's total steady state error can be respectively rewritten as:

$$E_R(s)=\frac{R(s)}{1+H(s)C(s)G(s)}=\frac{R(s)}{1+G_{OL}(s)} \tag{13}$$

$$E_T(s)=-\frac{s^{\alpha}D_C(s)N_P(s)N_H(s)}{N_{OL}(s)+s^{\alpha}D_{OL}(s)}T(s) \tag{14}$$

Considering the fact that the system is initially operating under the step setpoint applied at the input reference, using the final value theorem, the end result of steady state error component due setpoint input can be expressed as:

$$e_{ss}^R=\lim_{t\to\infty}e_{ss}^R(t)=\lim_{s\to 0}sE_R(s)=\lim_{s\to 0}\frac{C_0s^{\alpha+1}}{\left(s^{\alpha}+K_{OL}\right)} \tag{15}$$

With C_0 is a constant that corresponds to the final value of the system's steady state response.
Similarly, the tracking error due to load torque disturbance can finally be expressed as:

$$e_{ss}^T=\lim_{t\to\infty}e_{ss}^T(t)=\lim_{s\to 0}sE_T(s)$$

$$e_{ss}^T=\lim_{s\to 0}-\frac{s^{\alpha+1}.D_C(s)N_P(s)N_H(s)}{N_{OL}(s)+s^{\alpha}D_{OL}(s)}T(s) \tag{16}$$

Using the expressions (9), (10), (11) and (12), the steady state error component due to load torque signal becomes:

$$e_{ss}^T=\lim_{t\to\infty}e_{ss}^T(t)=\lim_{s\to 0}-\frac{s^{\alpha+1}.K_pK_h}{K_{OL}+s^{\alpha}}T(s) \tag{17}$$

Consequently, the total steady state error of whole control system is expressed as:

$$e_{ss}=\lim_{s\to 0}\frac{C_0s^{\alpha+1}}{\left(s^{\alpha}+K_{OL}\right)}-\lim_{s\to 0}\frac{K_pK_h.s^{\alpha+1}}{\left(s^{\alpha}+K_{OL}\right)}T(s) \tag{18}$$

It is clearly noticeable that the final value of the total steady state tracking error is dependent, in addition to the open loop static gain K_{OL} and the class of the feedback control system α, on the load torque disturbance signal $T(s)$, which allows us to theoretically study its effect on the value of the steady state error when it undergoes some variation or change. To undertake this study and assessment, we consider the load torque signal to be represented by the following polynomial of order "*q*" as:

$$d(t)=\frac{t^q}{q!}u(t)=K_q.t^q.u(t),\, t\geq 0 \tag{19}$$

Where, K_q and $u(t)$ are respectively an arbitrary adjustable constant and the unit step signal.
Using Laplace transform, the frequency domain representation of (19) can be given as:

$$T(s)=\frac{K_q}{s^{q+1}} \tag{20}$$

From (18) and (20), the value of the total steady state error of the control system under variable and sudden change of the load torque is finally expressed as:

$$e_{ss}=\lim_{s\to 0}\frac{C_0s^{\alpha+1}}{\left(s^{\alpha}+K_{OL}\right)}-\lim_{s\to 0}\frac{K_qK_pK_h.s^{\alpha}}{s^q\left(s^{\alpha}+K_{OL}\right)} \tag{21}$$

Load change effect on system accuracy and stability

A closed loop control system is assessed regarding its accuracy and robustness to load torque variation and change by observing the value of its total steady state error, where it is considered accurate if its response can perfectly follow the sudden change and variation occurred in the load torque signal. We desire this value to be ideally equals zero or a very small value close to zero.

To investigate the effect of load torque change and variation on the system's accuracy property and stability robustness, we have used the standard and elementary control signals to stimulate the system and simulating the variation and change of the load torque value. These are the step, ramp, parabolic and third degree polynomial, which respectively correspond to the values $q = 0, q = 1, q = 2$ and $q = 3$ in (20). The theoretical values of the total steady state error of systems having classes of 0, 1, 2, and 3 are calculated and summarized in Table 1.

Table 1. Values of the total response error according to system's class and load torque profile

System's class: α	$\alpha = 0$	$\alpha = 1$	$\alpha = 2$	$\alpha \geq 3$
Step: (q = 0)	$\frac{K_0 K_p K_h}{1 + K_{OL}}$	0	0	0
Ramp: (q = 1)	∞	$\frac{K_1}{K_c}$	0	0
Parabola: (q = 2)	∞	∞	$\frac{K_2}{K_c}$	0
Polynomial:(q=3)	∞	∞	∞	∞

The theoretical values of the total response error shown in the above table, which reflect the accuracy property of the control system response and its robustness when subjected to changing and variable load torque signal, are being simulated regarding the control system at hand. The results showing the speed tracking error response are mentioned in Fig.3.

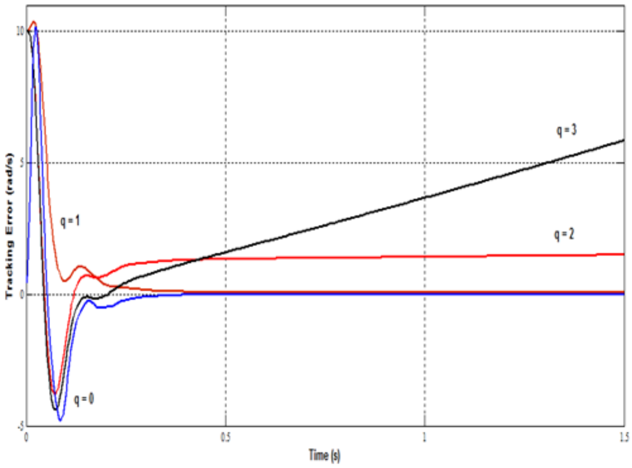

Fig.3. Speed tracking total error response of double PI and reduced order state estimator based DC drive system due to load torque changes

It is clearly seen that the system's speed response is of zero steady state error for a step-type and ramp-type load torque changes, however, this error exhibits a constant value different of zero when a parabolic load signal change is applied and it fully diverges to infinity in responding to a polynomial of degree three load change; a fact that indicates the poor accuracy and bad robustness of the control system to this load parameter change and variation.

Proposed method to improve the accuracy robustness

From the theoretical point of view and by referring to the results aforementioned in Table 1, we clearly notice the dependency of the accuracy performance of the control system on both system's class and open loop static gain K_{OL} in such a way that the high accuracy is strongly related to high system's class. Moreover, it is possible, for an applied load torque change, to reduce a constant nonzero value of steady state error by increasing the system's static gain and hence achieving a significant improvement of accuracy performance.

Using these techniques to solve this problem of system's accuracy robustness degradation due to an eventual load torque change is not unfortunately a good idea, because increasing the loop static gain or the class of the system, which involves adding more integral terms in the forward path of the system, may explicitly violate the stability performance of the whole control system [2, 15]. In this vein and in attempt of contributing to solve this crucial control problem, we propose in this work a novel control idea which consists of supplementing the double PI and reduced order state estimator based speed control system with a supplemented feedforward compensator. The application of this technique is realized according to the block diagram shown in Fig.4.

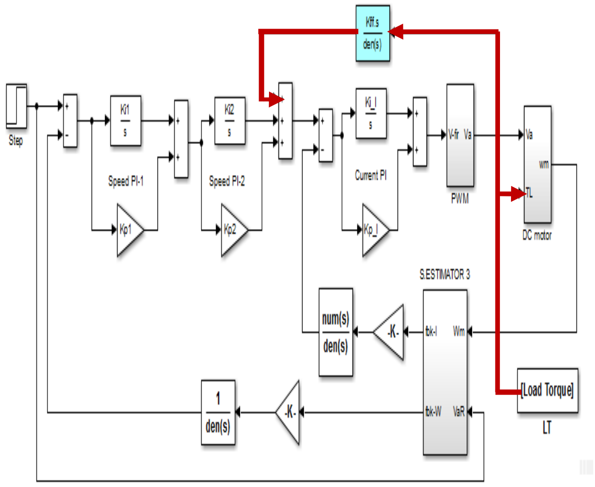

Fig.4. Block diagram of double PI and reduced order state estimator based DC drive system with supplemented feedforward compensation

As it can be seen from this figure, the additional feedforward compensation used with the double PI speed controller consists of inserting in the forward path of the control system the first order transfer function given by:

$$G_{FF}(s) = \frac{K_{ff}.s}{s+1} \tag{22}$$

With K_{ff} is a constant, which is determined to be the solution of the minimization problem, defined upon the square of system's total tracking error $e(t)$ as:

$$\min_{K_{ff}} \left(K_{ff} e_{ss}^2(t) \right) \tag{23}$$

The solution of the above optimization problem has led to obtain $K_{ff} = 1.1208$ which makes the added feedforward compensation transfer function fully identified.

In order to investigate the effectiveness of this technique regarding the improvement of accuracy and stability robustness to sudden load torque change, we simulated the block diagram of Fig.4 for the load signals corresponding respectively to constant nonzero and divergent value of the system's total steady state error. The obtained results that illustrate the evolution of the error value corresponding to these two cases before and after applying the compensation are shown in Fig.5.

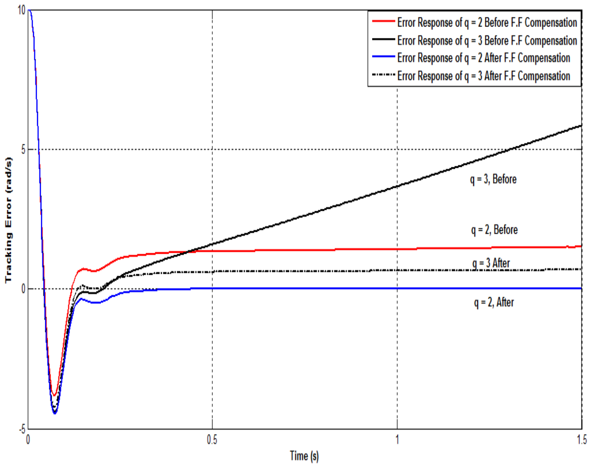

Fig.5. Simulation results showing achieved improvement in stability robustness and accuracy of DC drive system subjected to load torque changes and using supplemented feedforward compensation

Results interpretation and discussion

The obtained results mention clearly the improvement that is achieved on both the quality and performance properties of the total final error response of the control system subjected to accuracy and stability robustness study and assessment after using the supplemented feedforward optimized transfer function combined with the integral based control method which is consisted in inserting an extra integrator in the controller part via the use of double PI speed controller. This performance improvement and amelioration can be seen from the fact that a constant and divergent error value of the control system is compensated to respectively zero and constant values after applying the optimized feedforward transfer function and the double PI controller. This is an important result that clearly shows an achieved improvement of accuracy tracking capability and robustness to load torque sudden changes with guaranteed stable steady state response of the control system.

Conclusion

In this research work, we have presented the results obtained regarding the study, analysis and improvement of the steady state accuracy and stability performance of double PI and reduced order state estimator based speed controlled DC drive system when subjected to sudden load torque changing conditions. A detailed theoretical assessment and analysis of the load torque variation effect on the accuracy and stability robustness of the control system's final response is firstly tackled. The exhibited negative effect of this load parameter variation has been verified by simulating the system at hand for different load torque changing profiles. In order to preventing the control system of undergoing such performance degradation, the idea of inserting a supplemented feedforward optimized transfer function to the control scheme is seemed to be effective and has enabled reducing the constant value of the total steady state error to zero whereas the divergent error value is compensated to stabilize at a constant level.

These satisfactory results show, in overall, that the achieved accuracy and stability improvement of the studied control system are robust to sudden changes and variation of load torque.

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