EDUKATIVNA LABORATORIJSKA POSTAVKA KASKADNE REGULACIJE MOTORA JEDNOSMERNE STRUJE BAZIRANE NA DSPACE1104 PLATFORMI

EDUCATIONAL LABORATORY SETUP OF DC MOTOR CASCADE CONTROL BASED ON DSPACE1104 PLATFORM

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U ovom radu je predstavljena edukativna laboratorijska postavka upravljanja motorom jednosmerne struje u realnom vremenu baziranog na dSPACE1104 platformi. Laboratorijska postavka omogućava sagledavanje principa upravljanja motorom jednosmerne struje i određivanja parametara regulacionih petlji struje i brzine motora. U radu je najpre detaljno opisan korišćeni hardver (digitalni kontroler, energetska pretvarač i neophodne kartice za izolaciju i prilagođenje signala) a potom softverski model upravljačke strukture izrađen u MATLAB/Simulinku. dSPACE kontroler povezan je sa realizovanim Simulink modelom što omogućava jednostavno i brzo generisanje upravljačke aplikacije (eng. rapid control prototyping), odnosno interakciju simulacije sa realnim upravljačkim sistemom. Takođe, na ovaj način omogućeno je jednostavno podešavanje parametara regulatora struje i brzine kao i praćenje odziva regulisanih veličina. Ovaj rad naglašava edukativni aspekt realizovane laboratorijske postavke upravljanja motorom jednosmerne struje. Potrebne vrednosti pojačanja regulatora struje i brzine dobijene su matematičkom analizom modela upravljanja a potom su simulacioni rezultati upoređeni sa rezultatima dobijenim eksperimentalnim putem na realnom sistemu. Na ovaj način studentima koji pohađaju kurs Regulacija elektromotornih pogona je omogućeno da bolje razumeju princip rada savremenih digitalnih kontrolera u pogonu motora jednosmerne struje. Realizovana laboratorijska postavka otvara mogućnost za analizu energetske efikasnosti elektromotornog pogona u zavisnosti od načina upravljanja odnosno primene različitih upravljačkih algoritma brzom izradom prototipa.

Ključne reči: dSPACE, jednosmerni motor, regulacija, laboratorijska postavka, podešavanje regulatora.

Abstract: This paper presents an educational laboratory setup for real time DC motor cascade control, based on dSPACE1104 platform. The laboratory setting allows consideration of the principles of DC motor control and determination of the parameters of current and speed regulation loops. Detailed description of used hardware (digital controller, the power converter and necessary cards for isolation and signal conditioning) is firstly given, and then the software model of the control structure made within MATLAB / Simulink package. dSPACE controller is linked with the realized Simulink model, which allows easy and rapid creating of the control application (rapid control prototyping) i.e. interaction of the simulation with the real control system. Also, in this way it is possible to easily adjust the controller parameters of current and speed loops and to track the responses of the regulated variables. This paper emphasizes the educational aspect of the realized laboratory setup for DC motor control. Required values of the controller gains for current and speed loop were found by mathematical analysis of the control model and subsequently simulation results were compared with the results obtained experimentally with the real system. In this way, students which attend the course of electric drives control are enabled to better understand the operating principle of modern digital controllers in DC motor control drive. Realized laboratory setup opens the possibility to analyze the energy efficiency of electrical drive depending on the control mode and application of the various control algorithms by rapid prototyping.

Key words: dSPACE, DC motor, control, laboratory setup, regulator tuning

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1 Introduction

In the last few decades, direct current motors (DC motors) have been significantly repressed from industrial applications with alternating current motors (AC motors) especially in small and medium power range. This expansion of AC motors usage is due to their design robustness and the sudden fall in prices and dimensions of drive controllers caused by the rapid development of power electronics in the last few decades [1]. In addition, DC motors continue to successfully cover applications of very small power, such as small home appliances, computer utilities, toys, etc., as well as high-power applications where their replacement with AC motors is economically unjustified.

Also, the development of DC and AC machines control algorithms today is significantly simplified. There are considerable number of digitally-based development systems on the market, which allow rapid development and testing of motor control algorithms [2]-[4]. In the paper [5], a detailed comparison of these control platforms and their capabilities based on DSP and FPGA processors has been made. Most of these platforms nowadays are usually based on rapid control prototyping (RCP) techniques which allow testing the control system on real-time machine with real I/O interfaces connected to real-world systems. RCP decreases development time by allowing corrections to be made early in the product process. By giving engineering a sight to the product early in the design process, mistakes can be corrected and changes can be made while they are still inexpensive. The dSPACE platform, together with the MATLAB/Simulink software user environment, is a powerful tool for learning and testing of control algorithms which are applied in electric motor drives. The dSPACE platform allows simulation and verification of implemented algorithms in short period of time without the need for advanced programming knowledge. The dSPACE system is quite popular in control platforms and is widely used in automation systems and car manufacturing industries.

Substantial number of papers published in the scientific literature present the possibilities of various control algorithms for AC and DC motors based on dSPACE platform [6]-[8]. The papers clearly show the advantages of dSPACE platform regarding simplicity of creating a control application for the entire system. In [9] is in detailed described the development of control algorithms of DC machine and Induction machine.

This paper presents a laboratory setup for speed control of DC motor placed in laboratory for Electric Machines Drives and Control [10] within the Faculty of Technical Sciences in Čačak, University of Kragujevac, Serbia. The experiment is intended for students who are following the course of Control of Electric Drives at bachelor as well as master studies level. The course gives students a knowledge about various control methods of electric drives based on DC and AC motors and well as systems analysis in open and closed control loop. The speed control of electric motors accomplished by power electronic converters (controlled rectifiers and inverters) is analyzed using the computer simulation. Students learns how to design electric drives with speed, position and current (torque) controllers. A practical implementation of designed controllers is reserved for classes in laboratory where students can tune up the controller parameters and observe real-time responses of characteristic motor quantities. The main objective of the experiment presented in this paper is a cascade speed control of DC motor. It is accomplished by power electronics converter and current and speed controllers. The lab experiment, which is the integral part of the course, is focused on practical implementation of controllers earlier designed and tuned using MATLAB/Simulink.

2 Hardware description of laboratory setup based on dSPACE 1104

dSPACE 1104 is a complete real-time control system based on a 603 PowerPC 64-bit floating-point processor running at 250 MHz. For advanced I/O purposes the platform includes slave DSP subsystem based on the TMS320F240 DSP microcontroller (16-bit, 150MHz). For purposes of rapid control prototyping (RCP), specific interface connectors and connector panels provide easy access to all input and output signals of the board. A/D and D/A inputs and outputs are provided through BNC connectors, I/O and PWM signals through dSUB 37-pin and incremental encoder interface through dSUB 15-pin connectors [11].

dSPACE platform has enabled communication with models created in the MATLAB/Simulink environment. Simulink model can be easily converted to a code suitable for dSPACE processor that further, in real time, controls the application or I/O units. It extends the C code generator Simulink Coder™ (formerly Real-Time Workshop) for the seamless, automatic implementation of Simulink and

Stateflow models on the real-time hardware as it is shown in Fig.1. This significantly simplifies the process of iterations in the development of control prototypes and applications, without requiring specific programming skills from users.

Fig.1 – Connections between MATLAB and dSPACE [12]

In this paper, the following resources of dSPACE 1104 platform were used to realize the cascade control of the DC motor speed:

- PWM control unit for two-phase control (H-bridge), of three-phase voltage converter,
- A/D converter for measuring the motor current,
- A/D converter for voltage measurement of DC circuit,
- INC unit for measuring the motor speed.

In addition to the listed dSPACE platform's I/O units, laboratory setup of cascade speed control consists of:

- Power converter (H-bridge) up to 1kW,
- Current sensor CMS3005,
- Signal conditioning and isolation board,
- Isolated DC power supply,
- DC motor with encoder,
- PC with Control Desk software.

Fig.2 shows the block structure of the laboratory setup for DC motor speed control.

Fig.2 – Block structure of the laboratory setup for DC motor speed control.

In order to isolate all control signals from power electronic circuit, a special board with 7 opto-coupler galvanic isolation was made (6 for PWM signals and 1 for braking circuit signal). In this laboratory setup only 4 PWM signals was used to control 4 states of IGBT switches in H-bridge enabling positive and negative motor voltage supply. Fig.3 shows the board for signal isolation together with the power converter.

For motor current measurement, CMS3005 sensor was used. The CMS3000 current sensor family is designed for highly dynamic electronic measurement of DC, AC, pulsed and mixed currents with integrated galvanic isolation. CMS3005 has very high dynamic response (bandwidth up to 2 MHz) without the hysteresis that is present in iron core based designs.

Incremental encoder HEDSS HKT3006 with 500 pulses per rotation in two phases (2000 pulse/rotation after generation of quadrature-clock and direction signals) and zero phase with reference pulse was used for the speed measurement and positioning. Fig.4 shows current sensor and incremental encoder adapter boards.

Fig.3 – Signal isolation board and power converter in H-bridge

Fig.4 – Current sensor board (left) and incremental encoder adapter board (right)

Fig.5 shows the complete realized laboratory setup of DC motor cascade control with the computer control application. A block diagram of DC motor speed cascade control in Simulink is given in Fig.6.

Fig.5 – Experimental laboratory setup of DC motor control based on dSPACE 1104

Fig.6 Block diagram of DC motor cascade control in Simulink

3 Simulation model of DC motor control and control strategy

The complete control structure model was implemented in MATLAB/Simulink. Firstly, calibration of the current and voltage sensors was performed, i.e. a specified ratio V/A for the current and V/V for the voltage sensor. After A/D conversion performing, the measured units were reconstructed into SI system units as shown in Fig.7a and Fig.7c.

Fig.7 – a) Current reconstruction, b) PWM duty cycle determination, c) DC power supply voltage reconstruction and d) motor speed calculation

The cascade control structure is the standard principle of control in single-current DC drives. The control system of this structure consists of two or more loops according to the explicit hierarchy. The inner loop is current at the lowest level of the hierarchy, in which the output of the PI controller defines the duty cycle of the PWM signal. In Fig.7b, a portion of the model is shown, which defines the PWM duty cycle in the branches of the inverters a and b. Power converter in H-bridge amplifies PWM signals defining motor voltage supply. At the higher level of hierarchy is a speed loop with a speed-feedback and a speed controller, the output of which defines the current reference value for the inner loop.

The execution time of the algorithm was $T_s = 100\mu s$, which corresponded to the frequency of the motor current reading (10kHz). The velocity reading time was increased to 5ms to reduce the impact of restricted resolution of the speed sensor (pulse per revolution) on the speed calculation (Fig.7d).

The complete model of cascade control realized in Simulink is shown in Fig.8.

Fig.8 – MATLAB/Simulink model of cascade DC motor control

3.1 The synthesis of the current loop

Fig.9 shows a simplified block diagram of the current loop obtained by neglecting the electro-motor force (EMF), i.e. the influence of the mechanical part of the model, which is justified by the fact that electrical transients are much faster than mechanical ones, and turn out faster than the speed i.e. EMF, arrives to change significantly.

Fig.9 Block diagram of current loop PI control

Table 1. PI parameters of the current loop

Method	K_{Pi}	K_{Ii}
Compensation method	$L_d/K_d T' = 0.225$	$R_d/K_d T' = 67.2$

application of the compensation method. With this procedure, the aperiodicity of the response of the given time constant was achieved.

Using estimated motor parameters given in the Appendix (Table A) and adopting the desired time constant of the current loop to be $T' = 0.5\text{ms}$, which in this way becomes of the first order, current control parameters were obtained and are shown in Table 1.

3.2 The synthesis of the speed loop

Fig. 10 shows the block diagram of the speed loop in which the current loop is displayed by a first order function after applying the compensation method.

Fig.10 - Block diagram of speed loop PI control

Table 2 gives the parameters of the PI controller synthesis after applying different methods. Firstly, compensation of the mechanical time constant T_m , and modulus optimum were performed [13].

Table 2. PI parameters of the speed loop

Method	$K_{P\omega}$	$K_{I\omega}$
Compensation and modulus optimum methods	$J/2K_r T' = 0.1436$	$B/2K_r T' = 0.1203$
Symmetrical optimum method	$J/2K_r T' = 0.1436$	$J/2K_r T'^2 = 71.794$
Tunning PI parameters	0.012	0.015
Tunning PI parameters	0.012	0.1
Tunning PI parameters	0.012	0.2
Tunning PI parameters	0.012	0.3

After applying these methods, the entire dynamics of the speed loop could be described by the first-order transfer function, with the time constant $2T' = 1\text{ms}$. Then the symmetrical optimum method was applied, whereby the transfer function of the speed loop becomes of second-order, having a pseudo-periodicity of the response and the corresponding dynamics [13]. In order to show the influence of the increase of the integral gain to the dynamics of the response, experiment with the PI tuning option

was performed too, where the parameter $K_{P_{\omega}}$ was kept at a constant value and the parameter $K_{I_{\omega}}$ was gradually increased.

4 Control environment – Graphical user interface

Realization of Graphical user interface (GUI) is provided through Control Desk software. Control Desk is the dSPACE experiment software for seamless electronic control unit (ECU) development. It performs all the necessary tasks and gives you a single working environment, from the start of experimentation right to the end. Control Desk allows defining different switches, buttons, sliders, graphs etc. in order to control simulation (experiment) parameters as well as graphically present obtained results which makes GUI environment pretty much conformable and easy to handle.

GUI developed for cascade control of DC motor is shown in Fig.11. On the top of the left side, control buttons for start and stop simulation and PWM signal are placed. These buttons allow separate control of simulation/experiment state and state of the PWM output. Stop signal for PWM output is used for software motor current limit when current exceeds defined level (8A). Digital values of DC power supply voltage and applied motor voltage were placed under on the left side together with values of sampling time and consumed time (turnaround time) both numerically and graphically. Parameters of motor current and speed controller are in boxes with stressed borders as well as box for defining speed reference. Controller parameters can be changed even during running the experiment. Speed reference can also be defined with a slider bar. Right part of the GUI is reserved for graphical results of current and speed responses together with their reference values.

Fig.11 – Graphical user interface with control parameters and motor current and speed responses

5 Experimental results

Prior to the synthesis of the controller, the estimation of the resistance and inductance value in the armature circuit was made. The experiment was performed with a locked rotor, applying Nonlinear least square method and Trust-Region-Reflective Algorithm [14]. At the end of the process of estimation, the dynamics of the estimated current was closely followed the dynamics of the measured current, which confirmed the quality of the parameter estimation of the armature circuit. Simulink model and resulted electrical time constant are shown in Fig.12. The results of the evaluation together with the catalog data are shown in Table A in the Appendix.

Then, an experiment of the current response to the given reference was carried out, wherein the current controller was adjusted as described in section 3.1. and Table 1. The results are shown in Fig.13.

From Fig.13 it is evident that the current rapidly reaches its reference value, and achieves the given time constant of $T' = 0.5\text{ms}$ which corresponds to the results obtained by the simulation. This

rapid response of the motor armature current provides a wide bandwidth, i.e. high dynamic characteristics of the motor and the drive generally.

Fig. 12 Simulink model for LR estimation and the resulting electrical constant

Fig. 13 Current loop input-output signals with compensation method (zoomed view - right)

Prior to the synthesis of the speed controller parameters, the parameters of the mechanical part of the motor J , B and K_T (Appendix, Table A) were also estimated. Fig. 14 shows the Simulink model of the speed loop for motor parameters estimation. The obtained mechanical time constant is $T_m = 1.194\text{s}$.

Fig. 14 Simulink model of the speed loop for estimation of motor parameters and the resulting mechanical constant

Fig. 15 shows the results of tuning the speed loop parameters using the methods presented in Table 2. Due to insufficient encoder resolution, in order to reduce the error of speed detection, the speed had to be read at the minimum sampling rate of 5ms. Modulus optimum method as well as the symmetrical optimum method yielded to fast responses with the rise time of about 1ms (Fig. 15a and Fig. 15b). In order to successfully apply these methods, the reading time of velocity should be at least 0.5ms. Due to the unsatisfied sampling theorem, the experimental responses with sampling rate of 5ms would be unstable. Hence, for modulus optimum method as well as the symmetrical optimum method only the results of the simulation (Fig. 15a and Fig. 15b) with reference signals are shown.

After applying PI parameter tuning option from Fig. 15c - Fig. 15f, quickly reaching of the reference speed can be seen, with the dynamics conditioned by the choice of the controller. It can be noticed that the increase of the integral gain K_I decreases the rise time, but also increases the overshoot and the settling time, reflecting negatively to the system response characteristics. Dynamic speed response characteristics were also determined by the limit of the speed controller or the maximum value of the current on its output. This value was set to 7A to avoid large current impacts on the DC power supply and reaction of the protection. It also can be seen that the experimental results match the simulation results.

Fig.15 Speed responses to specified reference signals and different PI controller gains

The complete cascade speed control was also tested by setting a reference value of 1000 rpm with cyclic shift of speed sign and PI gains: $K_{Pi} = 0.225$ and $K_{Ii} = 67.2$, for current controller and $K_{P\omega} = 0.012$ and $K_{I\omega} = 0.015$ for speed controller. The obtained current and motor responses are shown in Fig. 16.

Fig.16 Measured motor current (left) and speed (right) with their reference values

6 Conclusion

In this paper, the educational laboratory setup for real-time cascade control of DC motor based on the dSPACE 1104 platform is described. The basic idea in designing and realization of this setup is to provide to students of the Faculty of Technical Sciences in Čačak, who attend the course of Control of electrical drives, another opportunity to practice on the most advanced laboratory equipment used for the control and regulation of electric motors.

Controller synthesis methods were applied to achieve the desired speed responses with the limitation of the motor current and achieving the aperiodicity in the current signal of the assigned dynamic.

The possibility of connecting the dSPACE controller with the realized Simulink model gives a unique quality of the achieved setup and provides the possibility for its further improvement and upgrading by testing the various control algorithms.

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8 Appendix

Table A. DC PM motor parameters 3418090, NEMA34

Motor parameters		Estimated motor parameters	
U_{an}	90 V	R_a	1.344 Ω
I_{an}	9A	L_a	4.5 mH
n_n	3200 rpm	J	2.6133 10^{-5} kgm ²
K_T	0.182 Nm/A	B	2.1886 $\cdot 10^{-5}$ kgm ²

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