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doi:10.15199/48.2019.12.16

Time-Optimal Position Control of DC Motor Servo Drive

Abstract*. Time optimal position control method is obtained differently on the basis of position, speed and motor current responses to DC motor voltage steps by applying dynamic programming method. As the result, the position overshoot and chattering is completely eliminated.*

Streszczenie. *Metodę optymalno-czasowej regulacji położenia uzyskano inaczej czyli na podstawie odpowiedzi położenia, prędkości oraz prądu silnika DC po skokowej zmianie napięcia DC zasilającego silnik prądu stałego oraz stosując metodę programowania dynamicznego. W rezultacie całkowicie wyeliminowano przeregulowanie położenia oraz zjawisko zwane „chattering". (**Optymalno-czasowe sterowanie położeniem servo-napędu z silnikiem prądu stałego**).*

Keywords: time-optimal control, position control, dynamic programming, DC motor.
Słowa kluczowe: sterowanie czasowo-optymalne, regulacja położenia, programowanie dynamiczne, silnik prądu stałego,

Introduction

The servo-drives features are still not sufficient for researches and users all over the world. They still tent to improve performance and methodology for the position control systems in different applications.

The difficulty and complexity of control system are very high, because of many non-linearities that exist in servo-drives. In active magnetic bearing system the levitation force nonlinearly depends on air gap [1], [2]. In electrical motors the excitation magnetic flux [3] nonlinearly scales machine electromagnetic torque and motor electromotive force. In machines magnetic core happen the nonlinear phenomena of edgy currents and hysteresis [4]. Passive frictional torque nonlinearly [5] depends on the speed of motor electromechanical subsystem. Motor torque control [6] accuracy depends on motor electromotive force [7]. Control systems are usually implemented as nonlinear sampling computer systems [8]. Taking into account all nonlinearities existing in servo-drive directly leads to complex implementation of control method.

In order to simplify control method, scientists in their control system design usually replace the nonlinear servo-drive with the simplified linear model [9], [10], [11] and they apply linear PID controllers. However, the nonlinear control method features with better results. In paper [11] by implementation of the linear–quadratic regulator (LQR), authors shortened position control time in relation to linear PID controller, but control method is sensitive on load torque existence. Scientists [12] compared the position control systems features of two systems with linear integer-order PID controller and fractional-order PID position controller. As the result of comparison [12], the position control time of system with fractional-order PID controller is shorter than with integer order PID controller. However, position overshoot still exists in case of fractional-order PID controller, but is very much lesser.

Model Reference Adaptive Control [13] is an alternative method that makes nonlinear servo-system behaving like linear reference model.

In paper [14], the nonlinear sliding mode control with linear model of servo-system with DC motor is simulated. It is proved, that the position control system with nonlinear second sliding mode controller has better performance than that with PI linear controller while disturbance and machine parameters variation. However, authors [14] did not show motor electromagnetic torque jerking and chattering phenomenon as the consequence of sliding mode controller operation.

In position control applications usually happens nonlinear phenomena and scientists propose the nonlinear controllers [1], [2], which fit into servo-drive nonlinearities. In servo-system with elastic electromechanical subsystems the predictive control [15] computes the future state of the variable stiffness elasticity actuator model and computes its output. In paper [15] model is nonlinear, because of spring variable stiffness modelling.

Position time optimal control is sometimes called "bang-bang control" [16] switching between two saturation maximal reference currents. Authors [16] eliminated sliding mode control disadvantages such as chattering and motor electromagnetic torque jerking by introducing small area of linear position controller operation. As the result, chattering is dampened, but with small price, because control becomes near-optimal-control [16]. Authors noticed that near time optimal control need load torque compensator in order to decrease the steady state position control to zero.

In paper [17] it is noticed that load torque influences the motor maximal acceleration and deceleration and nonlinear optimal control method should be modified. The exemplary load torque estimator is described in paper [18].

To sum up, generally the control technique operation is the consequence of the assumed complexity model of DC motor servo-drive and of the perceived physical phenomena. However, all mentioned control methods do not take into account the nonlinear switching converter model and its output voltage limitations.

Paper originality

Position control method proposed in paper is bases on nonlinear model of DC/DC switching transistor converter that take into account the square shape of voltage supplying DC motor. It was observed and noticed, that DC/DC converter output voltage consists of many voltage steps. As the consequence, signals of motor position, motor speed and motor current are the composition of many step responses to supply motor voltage steps after every switching process. In addition, information that motor supply voltage is limited and constant between switching processes directly leads to possibility to planning the time optimal control process. Using dynamic programming method, on the basis of the motor position, speed, current step responses the new fully time optimal position control of DC motor servo drive is obtained. New nonlinear controller operation replaces the linear position controller operation [16] in near optimal control method. Co continue, the motor speed and current step responses are easily obtained on the basis of second order linear DC motor model whereas the position step response can be calculated on the basis of speed step response [19], [20], [21].

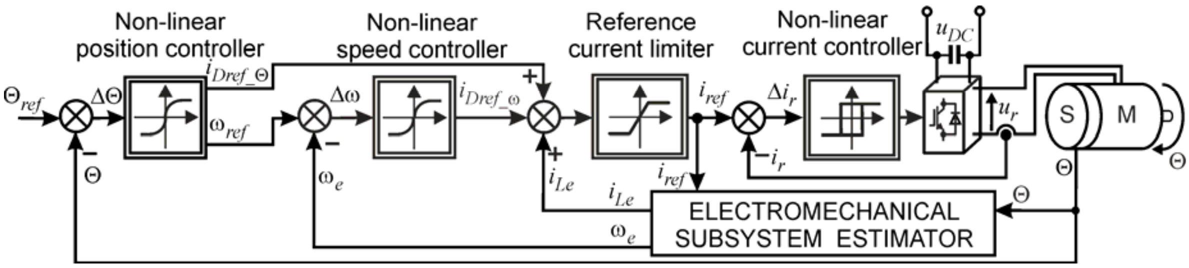

Fig.1. Scheme of position control system

Position control system operation

The fully time optimal position control is obtained in system, shown in fig.1, consisting of DC motor M, position sensor S, DC/DC H-bridge transistors converter, nonlinear current controller, nonlinear speed controller, nonlinear position controller and electromechanical subsystem estimator [19], [20], [21]. The current controller has hysteresis for the transistor converter switching frequency limitation. The electromechanical subsystem estimator calculates motor speed ω as a feedback for speed controller and it calculates load current i_{Le} for load torque compensation on the basis of motor angular position Θ and motor reference current i_{ref}.

The new element of position control scheme is the additional feed-forward signal i_{Dref_Θ} generated by the position controller. The additional reference current signal i_{Dref_Θ} helps the nonlinear speed controller to improve speed control accuracy in transient states.

The nonlinear position control operation and the speed controller operation are based on the Bellman dynamic programming method, like it is shown in fig.2 and in fig.3. Because of the fact, that all signals in system are step responses, the mathematical description of input and output controller signals are known in advance. That fact is utilized to find the operation method for position controller.

Firstly, in fig.2 the position control error $\Delta\Theta$ is calculated as the difference between reference position Θ_{ref} and motor position Θ. Than, the equation describing position error response $\Delta\Theta(t)$ on motor voltage step is solved. As the result, on the basis of the value $\Delta\Theta$ the argument time "t" is calculated. Next, the obtained time "t" is substituted into equation describing motor speed response ω_{ref} and motor dynamic current i_{Dref_Θ} response on motor supply voltage u_r step. As the result of calculation of step responses the output signals of position controller i_{Dref_Θ} and ω_{ref} are obtained. Such algorithm leads to optimal control, because motor response time can not be shorter than step response time forced by the limited motor supply voltage.

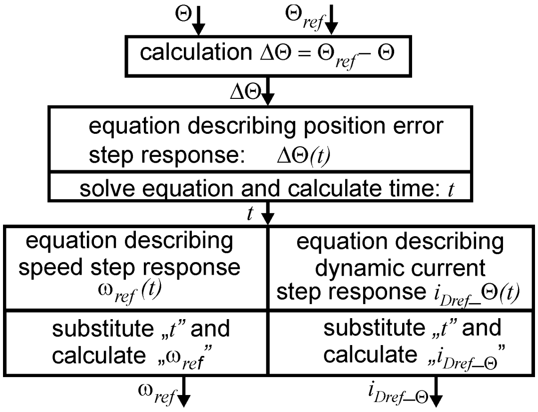

Fig.2. Calculation method of output signals of position controller

The nonlinear speed controller operates similarly in fig.3. Firstly, the speed control error is calculated as the difference between reference speed ω_{ref} and motor speed ω. Next, the equation describing speed error response ω(t) on motor voltage step as a function of time is solved. As the result, on the basis of the value $\Delta\omega$ the argument time "t" is calculated. Finally, the obtained time "t" is substituted into equation describing motor dynamic current i_{Dref_ω} response on motor supply voltage u_r step.

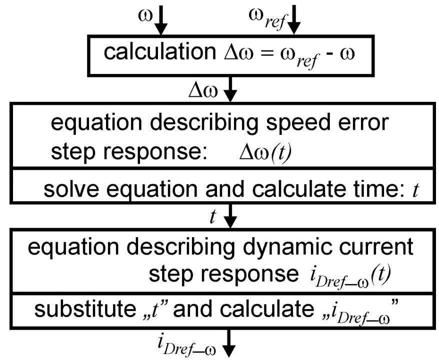

Fig.3. Calculation method of output signal of speed controller

As the result of calculation method shown in fig.2 and fig.3, in place of linear operation mentioned in paper [16], the position controller and the speed controller have nonlinear static characteristic, which shape depending on the motor supply constant voltage, the motor load torque, the maximal motor current, maximal motor speed and motor model parameters. The proposed position control method correctness is verified with simulation investigations.

Simulation investigations

The simulation aims are to verify the control method correctness and to check possibility to obtain the fully-time-optimal position control process without overshoot.

The following parameters of the simulation model are assumed: reference position Θ_{ref}=0,5rad, permissible maximal speed Ω_{MAX}=6, permissible maximum current of the converter and motor I_{MAX}=5A, voltage supplying the DC/DC H-bridge converter u_{DC}=325V, load torque T_L=0,4Nm, resistance of the motor winding R_a=4,65Ω, motor wiring inductance L_a=0,07H, motor excitation coefficient k_M=1,35Nm/A, equivalent moment of inertia of the entire electromechanical subsystem J=0,0328kg·m^2.

The position control process simulation in fig.4 is divided into nine stages A, B, C, D, E, F, G, H, I. Simulation starts from stage A and ends with stage I in which the position control error equals to zero. Motor does not rotate ω=0rad/s and motor current with value of i_{Le} compensates the active load torque. In stages A and I the chattering and motor torque jerking do not exists, too.

The fully-time-optimal position control process is only if all stages B, C, D, E, F, G, and H are time-optimal. To continue, after the reference position step to Θ_{ref}=0,5rad in stage B, the nonlinear position controller, the nonlinear speed controller and nonlinear current controller become saturated and current controller forces maximal motor voltage u_{DC} in fig.5.

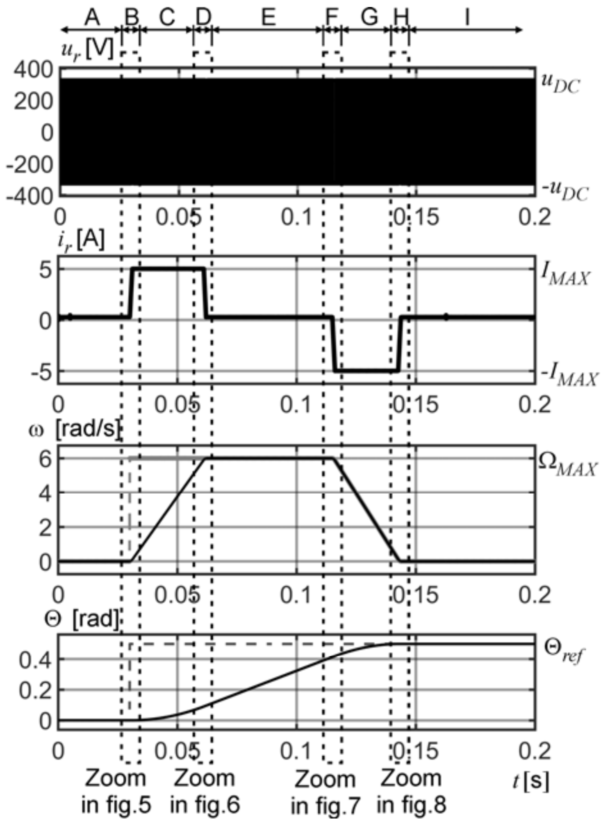

Fig.4. Motor voltage, motor current, motor speed and motor position during time-optimal position control process

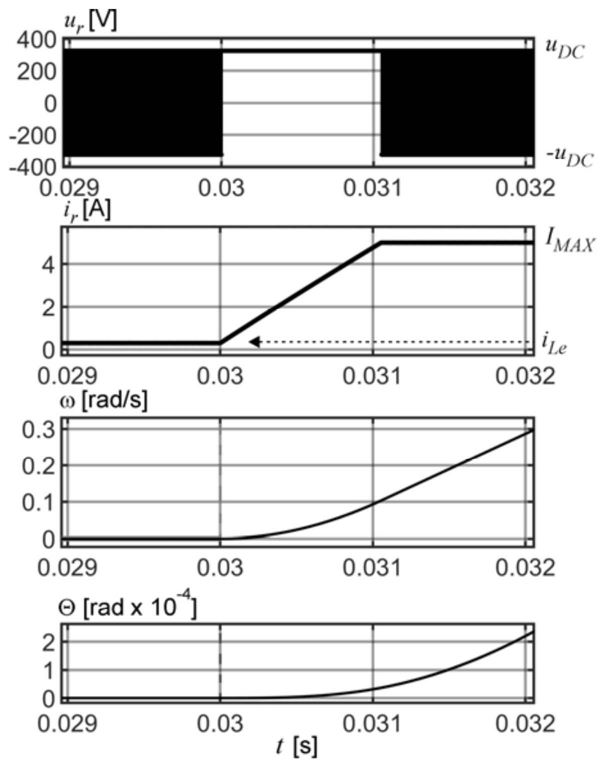

Fig.5. Motor voltage, motor current, motor speed and motor position during first step of motor supply voltage

The motor position response is time optimal, because it is forced by maximum supply voltage u_{DC}, as is shown in fig.5. Stage C is also time optimal position response, because it is forced by maximal motor current I_{MAX}, as it is shown in fig.4. Stage D depicted in fig.4 and in fig.6 is also time-optimal, because motor position response is forced by voltage that can not take absolute higher value than u_{DC}. At the end of stage D motor has maximal speed Ω_{MAX}.

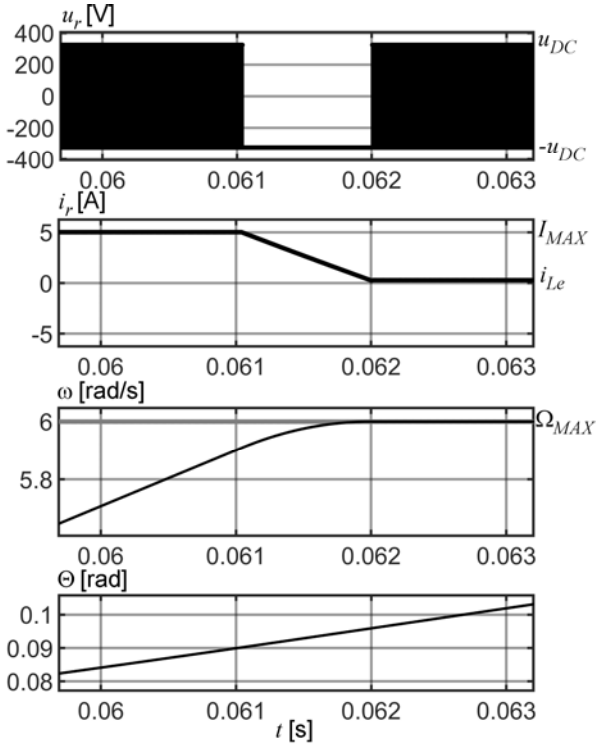

Fig.6. Motor voltage, motor current, motor speed and motor position during second step of motor supply voltage

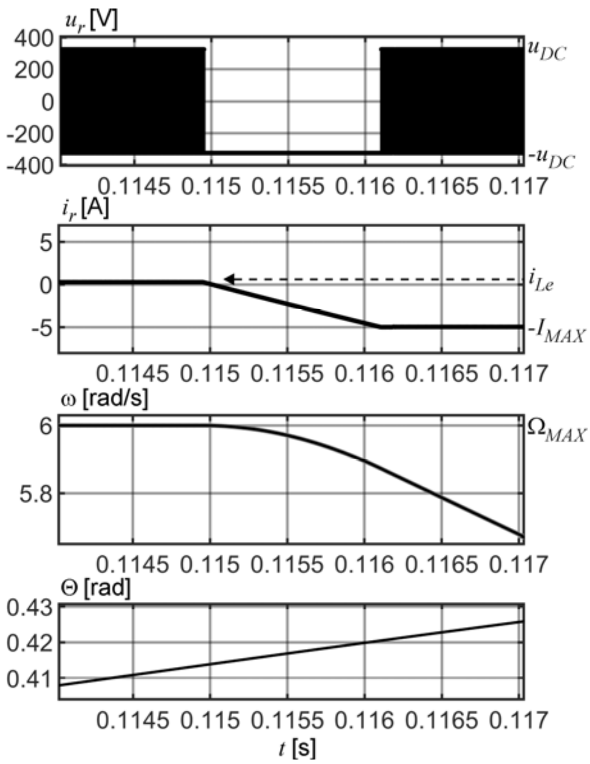

Fig.7. Motor voltage, motor current, motor speed and motor position during third step of motor supply voltage

Stage E, revealed in fig.4, is also time-optimal position control process, as the result of motor maximal speed Ω_{MAX}, assumed to be safe for mechanical system. Stage F disclosed in fig.4 and in fig.7 is time-optimal position control process, too, as the fact being caused by maximal supply voltage u_{DC}. Stage G is also time-optimal position control process, because position response is forced by maximal motor current $-I_{MAX}$, as it is depicted in fig.4. In stage H shown in fig.8, the time-optimal position control process also happens, because it is forced by maximal voltage u_{DC}.

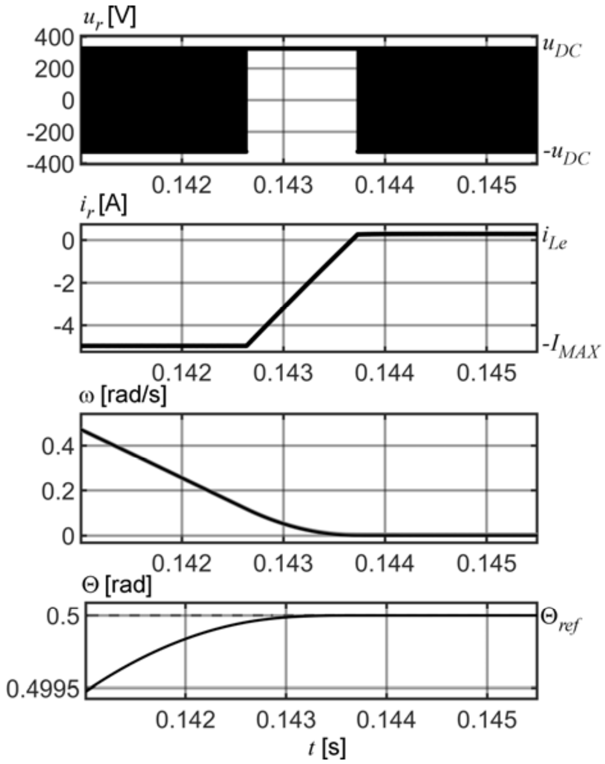

Fig.8. Motor voltage, motor current, motor speed and motor position during fourth step of motor supply voltage

Conclusion

To sum, up, the recognition of the facts that DC/DC converter output voltage is limited and consists of many voltage steps motivated author to overwork new nonlinear position controller, in place of linear operation described in [16]. In addition, simulation results acknowledge the control method correctness. New position nonlinear control features with no chattering and no motor torque jerking and no position overshoot. It can be called as time-optimal position control system, because control time is minimal as the result of every stage control process being obtained by application of the maximal voltage or the maximal current or the maximal speed.

This work was supported by Ministry of Science and Higher Education in Poland under work No. S/WE/1/2018.

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