Traian MUNTEANU, Romeo PADURARU, Emil ROSU, Marian GAICEANU, Teodor DUMITRIU, Cristian DACHE

University of "Dunarea de Jos" Galati
Faculty of Automatic Control, Computers, Electrical and Electronics Engineering

Energy Saving Control for DC Motor Drive Systems

***Abstract**. By using conventional speed and current controllers or other advanced control methods on DC electric drive system, good dynamic and stationary performances can be obtained. The main drawback of these drives is the obtained diminished electrical energy during the transient regimes, i.e. starting, braking or reversing. In dynamic regimes, the conversion efficiency is diminished to about half while during the stationary regime the efficiency is increased. The paper objective is to validate a new control, optimal type, which minimizes the consumption of the necessary energy to perform a given state trajectory. Three problems are presented in this paper: the problem formulation and the energy saving control solution, the numerical simulation, and experimental validation, on a dedicated laboratory platform. A comparison between two control methods is shown, conventional and optimal, at the level of simulation and experimental tests. An original control, named indirect control, was proposed and used for laboratory tests. The experimental and numerical results confirm the performances of the proposed control method.*

***Streszczenie.** Stosując konwencjonalne metody sterowania silnikami DC można uzyskać zadawalające włąsicowśoi statyczne i dynamiczne. Wadą większości tych rozwiązań jest duży pobór mocy w stanach przejściowych. W artykule zaprezentowane nowe rozwiązanie napędu optymalizowane pod kątem minimalizacji konsumpcji energii. Porównano dwa systemy: konwencjonalny i optymalizowany. (**Napęd DC optymalizowany pod kątem oszczędności energii**).*

Keywords: optimal control, energy saving, DC drive system.
Słowa kluczowe: napęd DC, oszczędność energii.

Introduction

The low-cost and reliable induction motors with field-oriented control are widely used in industrial applications. However DC motors with constant or weakening field are still in working in many electric drives like rolling mills, paper machines, and unwinding and rewinding machines [4], [5]. Moreover, the rated power of these drives is great, from hundreds to thousands kW. The control of drives has two aspects: constant field, where linear control techniques are easily applied, and field-weakening when nonlinearities, product type, appear. Actually DC motor drives with constant field are controlled by a conventional method using P and/or PI controllers [3]. All proposed controls take into consideration high dynamic and stationary performances, but did not say anything about conversion efficiency. In many papers there are approaches to improve steady state conversion efficiency, especially for induction machines and under light-load conditions, such as, loss model control (LMC), [7], [8], search control (SC), [9], or another methods [13], [14], but disregarding dynamic regimes. An overview concerning multi-objective optimal control in paper [6] is presented. It is well known that during the transient regimes, e.g. starting and stopping, the conversion efficiency is diminished to about half with respect to stationary regimes. There are researches in the frame of drawn energy minimization for the dynamic regimes as starting, stopping or reversing for DC drives with constant field [16], [17], [18], and AC induction drives [10], [11], [12], [15]. These approaches are based on very strong mathematical instrument, optimal control theory, being formulated various problems as minimum time or energy [2].

The paper deals with three problems: the formulation and solution of the minimum energy control problem, the laboratory validity, and the numerical and experimental results.

In Section 2, the optimal control approach oriented to minimize the expenditure energy for the dynamic regimes of DC constant field drive system is presented. Using a model of a DC drive system and adequate performance functional criteria, a linear quadratic minimum energy problem, Bolza type, was formulated. The solution of the control problem is presented in Section 3. The numerical simulation results are given in Section 4. In Section 5 there are developed some aspects concerning the choice of weighting matrices which assure magnitude limits for the electric and mechanic parameters, and the robustness to the load variation. The laboratory platform and experimental results are presented in Section 6. The numerical and experimental results confirm the utility as well as the properties of the proposed control. The conclusions are given in Section 7.

Problem formulation

The drive system model

A DC drive system controlled by armature voltage, under constant field, is an invariant dynamic system, controllable and it is described by the following differential equations

$$\begin{aligned} \frac{d\omega(t)}{dt} &= -\frac{F_v}{J}\omega(t) + \frac{c}{J}i_A(t) - \frac{1}{J}m_S(t) \\ \frac{di_A(t)}{dt} &= -\frac{c}{L_A}\omega(t) - \frac{R_A}{L_A}i_A(t) + \frac{1}{L_A}u(t) \end{aligned} \tag{1}$$

In state-space form the differential equations (1) become

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{G}\mathbf{w}(t) \tag{2}$$

In equation (2) the state is given by

$$\mathbf{x}(t) = \begin{bmatrix}\omega(t) & i_A(t)\end{bmatrix}^T \tag{3}$$

where, $\omega(t)$ and $i_A(t)$ are the angular speed and armature current; $\mathbf{u}(t)$ is the armature voltage as input vector; $\mathbf{w}(t)$ is the load torque $m_S(t)$ as the perturbation vector; F_V - viscous friction; L_A - armature inductance; R_A -armature resistance; c - motor constant; J - inertia; $\mathbf{A},\mathbf{B}$ and $\mathbf{G}$ are the constant matrices.

The quadratic performance criteria

The control problem is to find an admissible control, armature voltage $\mathbf{u}^*(t)$, which transfers the system (2) from the initial state

$$\mathbf{x}(0) = \begin{bmatrix}0 & 0\end{bmatrix}^T \tag{4}$$

to a desired state

(5) $$\mathbf{x}_1 = \left[\omega_1 \quad i_{A1}\right]^T,$$

in the fixed time t_1 with minimization of energy consumption. In order to minimize the input energy, the quadratic performance criteria in the form

(6) $$J = \frac{1}{2}\left[\mathbf{x}(t_1) - \mathbf{x}_1\right]^T \mathbf{S}\left[\mathbf{x}(t_1) - \mathbf{x}_1\right] + \frac{1}{2}\int_0^{t_1}\left[\mathbf{x}^T(t)\mathbf{Q}\mathbf{x}(t) + \mathbf{u}^T(t)\mathbf{R}\mathbf{u}(t)\right]dt$$

is associated to system (2), where weighting matrices $\mathbf{S}$ and $\mathbf{Q}$ are positive semidefined, and $\mathbf{R}$ is a positive defined matrix.

The purpose of the first term of criteria (6) is to guarantee a small square error between the final free state $\mathbf{x}(t_1)$ and the desired final state (5). If the matrix $\mathbf{S}$ has the form

(7) $$\mathbf{S} = \begin{bmatrix} s_1 & 0 \\ 0 & s_2 \end{bmatrix}$$

the first term of criteria (6), called the terminal cost, is given by

(8) $$\lambda(t_1) = \frac{1}{2}\left[\mathbf{x}(t_1) - \mathbf{x}_1\right]^T \mathbf{S}\left[\mathbf{x}(t_1) - \mathbf{x}_1\right] = \frac{1}{2}s_1\left[\omega(t_1) - \omega_1\right]^2 + \frac{1}{2}s_2\left[i_A(t_1) - i_{A1}\right]^2$$

Concerning the angular speed, the final error can be controlled by adecquate chose of s_1. On the other hand, the final armature current, i_{A1}, is unknown, its value being determinate by load torque. Choosing $s_2 = 0$ and $i_{A1} = 0$ the armature current will be free to have any value.

The direct minimization of drawn energy can be achieved by introducing input power

(9) $$P_I = u_A(t)i_A(t) = u(t)x_2(t)$$

in performance criteria (6). This approach is unfortunately because term (9) is nonlinear, state-control product, and problem can not be solved in above formulation. The second posibility takes into consideration motor power losses.

There are more power losses which are determinated by the angular speed:

eddy current losses

(10) $$p_F = k_F\omega^2(t)$$

hysteresis power losses

(11) $$p_H = k_H\omega(t)$$

and viscous power losses

(12) $$p_V = F_V\omega^2(t)$$

Also the output mechanic power has the form

(13) $$p_O = m_R(t)\omega(t)$$

(14) where k_F, k_H, F_V are constant coefficients.

In the same way as above, by seting

(15) $$\mathbf{Q} = \begin{bmatrix} q_1 & 0 \\ 0 & q_2 \end{bmatrix}$$

the second term of the equation (6) is related by

(16) $$\frac{1}{2}\int_0^{t_1}\left[\mathbf{x}^T(t)\mathbf{Q}\mathbf{x}(t)\right]dt = \frac{1}{2}\int_0^{t_1}\left[q_1\omega^2(t) + q_2 i_A^2(t)\right]dt$$

The first term from (16) will minimize the energy expended in magnetic core, for viscous friction, and for mechanic losses. Also, in the same manner, the output energy. Obviously, the above terms have different form, liniar or quadratic, while criteria is quadratic.The liniar components p_H and p_V, included in (16) as quadratic form, shall produce the same effect, most likely stronger.

The second term from (16) minimizes armature winding losses, the most important constituent part of the drive dissipation energy. The last term

(17) $$\frac{1}{2}\int_0^{t_1}\left[\mathbf{u}^T(t)\mathbf{R}\mathbf{u}(t)\right]dt = \frac{1}{2}\int_0^{t_1}\left[ru^2(t)\right]dt$$

where

(18) $$\mathbf{R} = \left[r\right],$$

keeps the control $\mathbf{u}(t)$ within the admissible limits.

The specified terminal time t_1 corresponds to the desired duration to achieve the final state ω_1. Usually terminal time is choosing by comparison with actual drive systems controlled by conventional automation. Therefore the control problem is a well known control approach, i.e. the quadratic linear problem with free end point, specified terminal time and without constraints, Bolza type, [1].

The solution of optimal control problem

The solution of the problem exists and is unique if the system (1) is controllable and completely observable and the weighting matrices carry out the above conditions [1]. The conditions are clearly met. The solution of the optimal problem is given by [1],

(19) $$\mathbf{u}^*(t) = -\mathbf{R}^{-1}\mathbf{B}^{\mathbf{T}}\mathbf{y}(t)$$

$\mathbf{x}(t)$ and $\mathbf{y}(t)$, the cost vector, being solutions of the canonical Euler-Lagrange system,

(20) $$\begin{bmatrix} \dot{\mathbf{x}}(t) \\ \dot{\mathbf{y}}(t) \end{bmatrix} = \begin{bmatrix} \mathbf{A} & -\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^{\mathbf{T}} \\ -\mathbf{Q} & -\mathbf{A}^{\mathbf{T}} \end{bmatrix}\begin{bmatrix} \mathbf{x}(t) \\ \mathbf{y}(t) \end{bmatrix} + \begin{bmatrix} \mathbf{G} \\ \mathbf{0} \end{bmatrix}\mathbf{w}(t)$$

with the boundary conditions: the initial state, equation (4), and the transversality condition [1]

(21) $$\mathbf{y}(t_1) = \left[\frac{\partial\lambda(t)}{\partial\mathbf{x}}\right]_{t=t_1} = \mathbf{S}\left[\mathbf{x}(t_1) - \mathbf{x}_1\right]$$

Taken into consideration the transversality condition (21) the cost vector has to have the form

(22) $$\mathbf{y}(t) = \mathbf{P}(t)\mathbf{x}(t) + \mathbf{v}(t)$$

where $\mathbf{P}(t)$ is the solution of differential matrix equation, Riccati type, RDME,

(23) $$\dot{\mathbf{P}}(t) + \mathbf{P}(t)\mathbf{A} + \mathbf{A}^{\mathbf{T}}\mathbf{P}(t) - \mathbf{P}(t)\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^{\mathbf{T}}\mathbf{P}(t) + \mathbf{Q} = \mathbf{0}$$

and $\mathbf{v}(t)$ is the solution of the associate differential vector equation, ADVE,

(24) $$\dot{\mathbf{v}}(t) + \mathbf{A}^{\mathbf{T}}\mathbf{v}(t) - \mathbf{P}(t)\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^{\mathbf{T}}\mathbf{v}(t) + \mathbf{P}(t)\mathbf{G}\mathbf{w}(t) = \mathbf{0}$$

Taking into consideration the boundary condition (21), the solutions $\mathbf{P}(t)$ and $\mathbf{v}(t)$ must be calculated recursively and backward in time, from t_1 to 0. On the other hand the equations (23) and (24) are nonlinear. The integration of system (20) also needs all the future values of the perturbation vector $\mathbf{w}(t)$, including $\mathbf{w}(t_1)$, which is unachievable. Obviously, the system (20) cannot be solved.

In [2] a non-recursive solution which can be computed at any time t has been proposed. Thus there are defined two changes of coordinates. The first defines the remaining time until final time t_1 by

(25) $$\tau = t_1 - t$$

and the new state, cost, and perturbation vectors

$$(26)\qquad \begin{bmatrix}\mathbf{m}(\tau)\\ \mathbf{n}(\tau)\\ \mathbf{o}(\tau)\end{bmatrix}=\begin{bmatrix}\mathbf{x}(t)\\ \mathbf{y}(t)\\ \mathbf{w}(t)\end{bmatrix}$$

with transversality condition in form

$$(27)\qquad \mathbf{n}(0)=\mathbf{S}\left[\mathbf{m}(0)-\mathbf{x_1}\right]$$

This change of coordinates eliminates calculus backward in time. The second change defines the other new state and cost vectors as

$$(28)\qquad \begin{bmatrix}\mathbf{p}(\tau)\\ \mathbf{q}(\tau)\end{bmatrix}=\mathbf{W^{-1}}\begin{bmatrix}\mathbf{m}(\tau)\\ \mathbf{n}(\tau)\end{bmatrix}$$

where $\mathbf{W}$ is the eigenvectors matrix of system (20). The calculus of solution can be made easily via the eigenvalues and eigenvectors of the system (20). The eigenvalues are symmetrical with respect to the imaginary axis and they are not pure imaginary [1]. Additionally, if the matrices ***Q*** and ***R*** are chosen conveniently, the eigenvalues are real numbers. The system (20) under change of coordinates (28) gets the form

$$(29)\qquad \begin{bmatrix}\dot{\mathbf{p}}(\tau)\\ \dot{\mathbf{q}}(\tau)\end{bmatrix}=\begin{bmatrix}\mathbf{\Lambda} & \mathbf{0}\\ \mathbf{0} & \mathbf{-\Lambda}\end{bmatrix}\begin{bmatrix}\mathbf{p}(\tau)\\ \mathbf{q}(\tau)\end{bmatrix}-\mathbf{W^{-1}}\begin{bmatrix}\mathbf{G}\\ \mathbf{0}\end{bmatrix}\mathbf{o}(\tau)$$

where

$$(30)\qquad \mathbf{\Lambda}=\begin{bmatrix}\lambda_1 & 0\\ 0 & \lambda_2\end{bmatrix}$$

is positive eigenvalues matrix. On the other hand, the system will be solved numerically using a sampling period *T*. Over the sampling period the perturbation vector ***w(t)*** can be considered having a constant value. This value can be easily estimated by a state observer or a load torque estimator. The sampling period has a small value and the above hypothesis holds. In the above conditions the solution of the system contains both negative and positive exponential terms, generated by positive and negative eigenvalues, which is a major disadvantage. In [2] a procedure to eliminate the positive eigenvalues is indicated. Finally the solution of the optimal problem gets the form

$$(31)\qquad \mathbf{u}^*(t)=\mathbf{-R^{-1}B^TP}(t_1-t)\mathbf{x}(t)+\mathbf{R^{-1}B^TK_1}(t_1-t)\mathbf{x_1}+\mathbf{R^{-1}B^TK_2}(t_1-t)\mathbf{w}(t)$$

where $\mathbf{P}(t_1-t)$ is the non-recursive RDME solution, and $\mathbf{K}_1(t_1-t),\mathbf{K_2}(t_1-t)$ solution components.

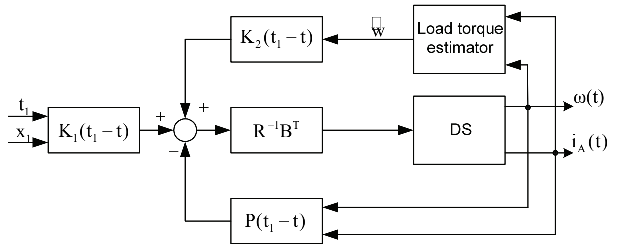

Fig.1. The structure of the optimal control

The optimal control solution (31) has three components: the state feedback; the reference to achieve the desired final state $\mathbf{x_1}$; the compensating feedforward of the perturbation $\mathbf{w}(t)$ effect, Fig.1. The solution is a non-recursive one and can be computed for any value of *t*, from initial time *t=0* to the final time t_1.

The optimal problem was formulated and solved for a starting period. The stopping, as reverse of the starting, is also optimal. The reversing, as sum of two optimal trajectories, in accordance with optimality Bellman theorem, is also optimal [1].

Numerical results

The system (1) was numerically simulated using a discretized model and Matlab-Simulink software. The system parameters are:

- D.C. motor: $2.2kW, 420V, 6.95A, 192.586 rad/\sec$, $L_A=40.5mH, R_A=10.7\Omega$;
- rated load torque: $12.47Nm$;
- maximum armature current $I_{AM}=2I_{AN}=13.9A$;
- total inertia: $0.026Kgm^2$;
- converter a.c.-d.c.: $0\pm 520V, 25A, 4$ *quadrants*;
- viscous friction $F_V=0.011Nms/rad$;

The conventional control, angular speed and current PI controllers, was simulated for following conditions:

- a starting from 0 to the rated angular speed, $\omega_1=192.586 rad/\sec$; the load torque $m_S=8Nm$; 0.6 second ramp speed reference, Fig. 2;
- a full reversing from $\omega_0=192.586 rad/\sec$ to $\omega_1=-192.586 rad/\sec$; 1.2 second ramp speed reference; the load torque $m_S=8Nm$, Fig. 4.

The optimal control was simulated for the same dynamic regimes and angular speeds, the final times being 0.6, and 1.2 seconds respectively, Fig. 3 and Fig. 5.

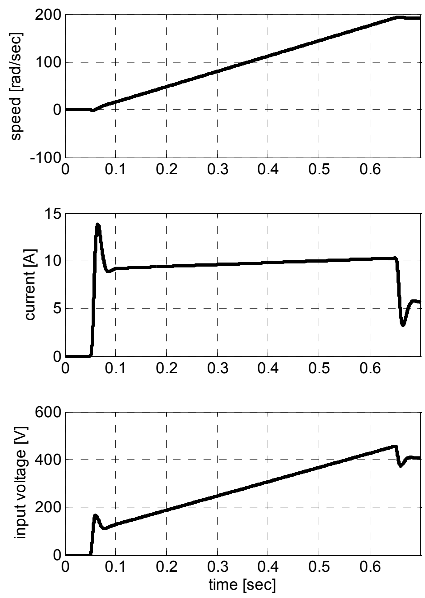

Fig.2 Conventional control

There are some differences between the two types of control, especially regarding the variations of current and speed, Fig.2, 3, 4 and 5. In the optimal case the armature current has a greater value at the end of dynamic regime, while in the conventional case at beginning. The speed rising is not a ramp, like for conventional control. Also, the initial speed derivative is smaller for optimal control. On the other hand the optimal control has high dynamic performances, without overshoots, and good robustness.

results confirm that the optimal control proposed increases the conversion's efficiency of the drive system.

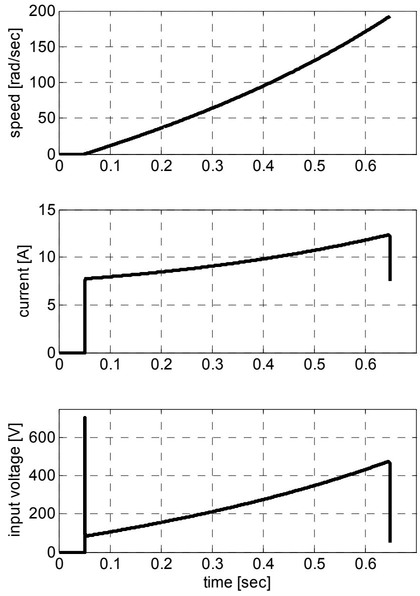

Fig.3 Optimal control

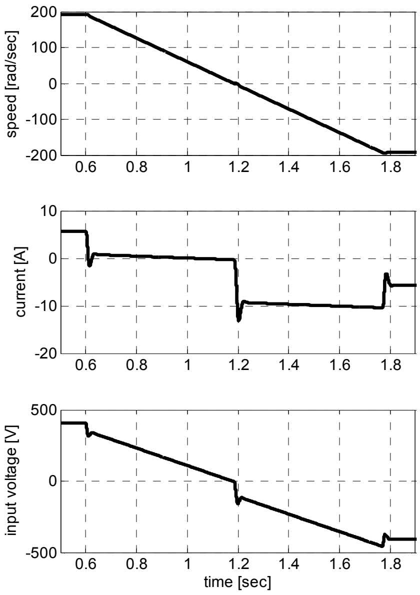

Fig.4 Conventional control, reversing

There is an important voltage overshoot, much more than rated voltage, Fig.3 and 5, which can not be realized by converter. It is a tipically output of optimal controller. There are two solution: a filter on control $\mathbf{u}^*(t)$; the value of $\mathbf{R}$ matrix.

The energy components are presented in Table 1. As regards the accumulated energy in inertia, W_J , and in armature inductance, W_L , approximately have the same values since the final states are the same for the two types of control. The input energy, W_I , is smaller in the case of optimal control, from 7.41 % to 10.65 %, while the output energy, W_O , with 14.94% to 17.85%. The same behaviour takes place for W_{RA} , the copper armature losses energy, the reducing being about 1-2 %, and W_V ,viscous friction energy, smaller with 22.65 to 25.36%. The simulation results confirm that the optimal control proposed increases the conversion's efficiency of the drive system.

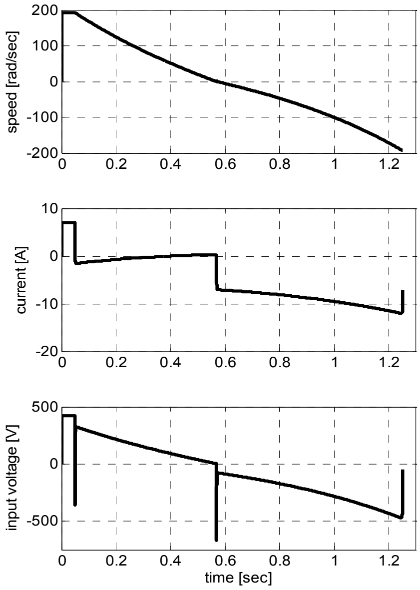

Fig.5 Optimal control, reversing

Also, the optimal control provides dynamic performance similar to conventional control methods and preserves the mechanical and electrical parameters within admissible limits.

Some aspects regarding new control

Weighting matrices

In the above formulation the optimal problem is one without constraints. Obviously there are magnitude limitations for the armature voltage and current at the rated or maximum value. The introduction of the constraints transforms the problem into a nonlinear one, the solution finding being difficult if not impossible. The constraints problem can be avoided by adequate choice of weighting matrices S , Q and R .

Weighting matrix S. Concerning the last formulation the square error (8) will be smaller if s_1 is greater. By simulation, the error (8) becomes practically zero if $s_1 \geq 3.10^4$.

Weighting matrix Q. The form of Q matrix is given by equation (9). The term q_2 penalizes the energy expended in the armature winding, and obviously the large values of the armature current i_A . The armature current i_A versus q_2 is plotted in Fig. 6. For small values of q_2 the current values are unacceptable, while for larger values, the current is smaller than the maximum limit. Take into consideration the maximum armature current $q_2 = 8200$ was adopted. The term q_1 *has* two major influences. For the great values the input energy decreases significantly, Fig. 7. On the other hand the speed derivative diminishes, Fig.8. At first sight q_1 must have a large value. Because so values generate large final armature current, was adopted $q_1 = 75$.

Table 1 Energetic analysis

Type of regime	Time [sec]	Torque [Nm]	Control	W_I [Ws]	W_O [Ws]	W_{RA} [Ws]	W_L [Ws]	W_J [Ws]	W_V [Ws]
Starting	0.6	8.0	Conventional	1687	493	620	0.36	482	89.9
			Optimal	1562	405	606	1.35	482	67.1
			$\frac{\text{optimal}}{\text{conventional}}$[%]	92.59	82.15	97.74	-	-	74.64
Reversing	1.2	8.0	Conventional	1739.3	947.5	621.1	0.47	0.38	171.5
			Optimal	1554	806	615	0.136	0.45	133
			$\frac{\text{optimal}}{\text{conventional}}$[%]	89.35	85.06	99.00	-	-	77.55

Weighting matrix R. The form and the function of R matrix are given by the equation (17). The term r penalizes the voltage $\mathbf{u}(t)$ for the large values. In Fig. 9 the control $\mathbf{u}(t)$, for the beginning of a starting period, is plotted. For the smaller values of r the armature voltage gets inadmissible values. Taken in consideration rated voltage was adopted $r = 1$, value which assures a relative good limitation and performances. The voltage rising (Fig.9) indicates a high gradient $du(t)/dt$, physically unachievable by the converter. The converter time constant modifies the gradient which becomes admissible, while dynamic and energy components practically do not modify.

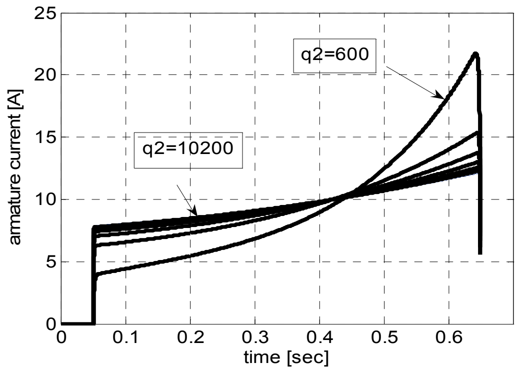

Fig.6 Armature current versus q2

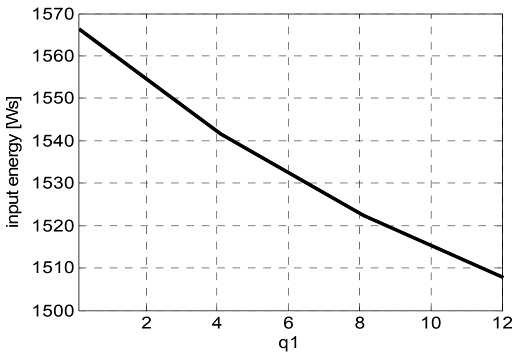

Fig.7. Input energy versus q1

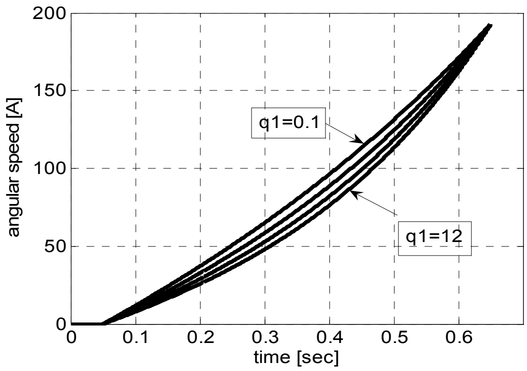

Fig.8. Angular speed versus q1

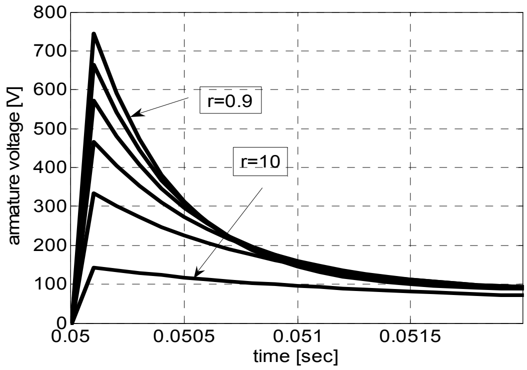

Fig.9. Armature voltage versus r

The feed-forward control component

The optimal control, equation (31), contains a compensating load feed-forward component. A starting period with an initial load torque of $m_s = 3Nm$, which increases at value of $m_s = 8Nm$ at the time $t > 3\sec$, in Fig. 10 is plotted. It can be observed the followings: a very good robustness regarding to perturbation; the speed trajectory does not modify; the load torque step is completely rejected; the voltage and current rise to the new values, normally one. This component control can be operating if the load torque is known. A state observer or a load torque estimator can deliver, on line, the necessary information.

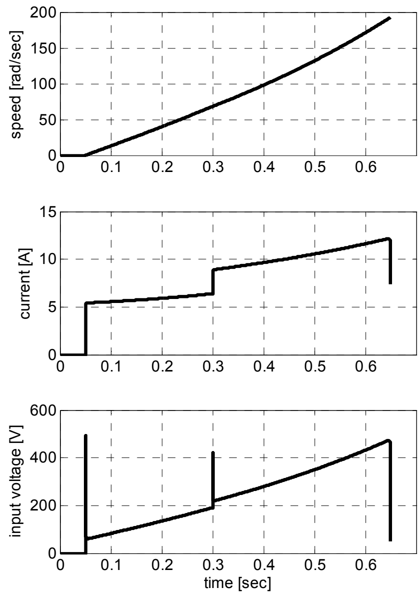

Fig.10. Load component

Simulation schema

The proposed control is operating only for dynamic regimes as starting, stopping and reversing. On the other hand the conventional control features very good stationary performance. Obviously the two controls must be mixed. In conclusion, for a good dynamic and stationary performances and improved conversion efficiency, there are two different types of control, which must operate on different working regimes. Therefore the applicability needs the choice of operating control and the commutations from a control to another. Obviously the outputs of two controllers can be at different levels. Certainly the commutations some oscillations occur. To overcome these unpleasant situations the simulation control diagram, named integrate control, Fig. 12, is proposed.

The proposal uses the conventional control configuration, i.e. speed and current controllers, Fig. 12.

The input, the desired dynamic trajectory $\omega_o^*(t)$, is calculated on-line using the optimal control solution, equation (31). For steady state regimes the speed will have a value in accordance with the final value of dynamic trajectory. The conventional control will track the optimal trajectory $\omega_o^*(t)$ with an error. This means that the control is a suboptimal one. Typically, the speed and current controllers are PI type, which ensure good dynamics, the rejection of perturbation in steady states and a minimum tracking error.

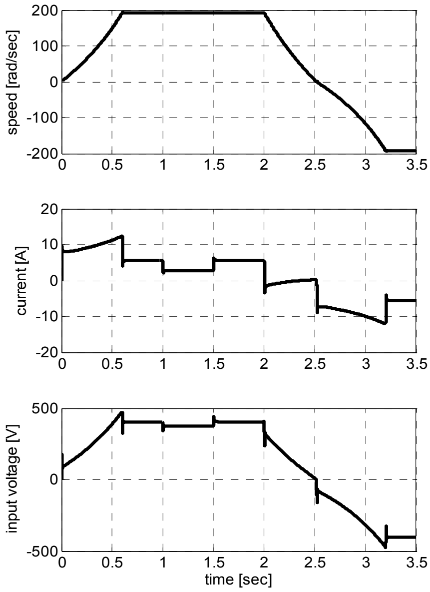

Fig.11 Dynamic and steady state behaviour

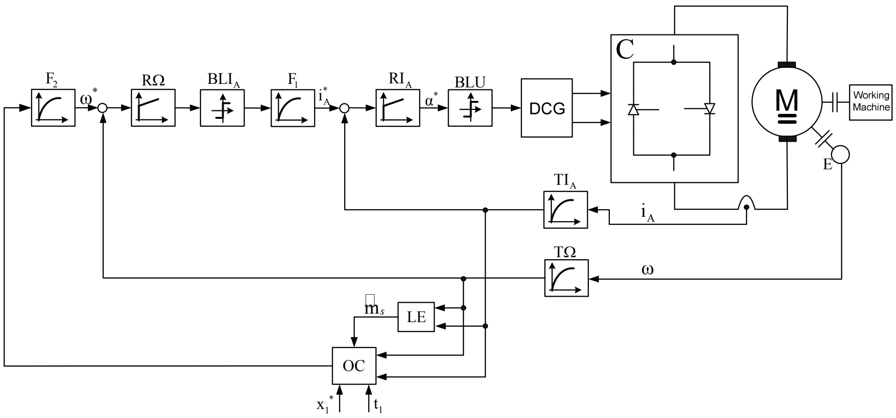

Fig.12 Suboptimal control schema

In Fig.12 such a control scheme is presented where: C - four quadrants AC - DC converter; DCG – gate driver; RI_A and RΩ – current and speed PI controllers; TI_A and TΩ – current and speed transducers; F1 and F2 – first order filters; BLI_A and BLU – current and firing angles limitation; LE – load estimator; OC – optimal control calculus; E – encoder.

The simulation results for a starting [0-0.6 sec], a reversing [2-3.2 sec], and a steady state period are presented in Fig.11. On the all time the load torque is $m_S = 8Nm$ except the period [1 – 1.5 sec] when the load torque is $m_S = 3Nm$. The tracking error

(32) $$\varepsilon(t) = \omega_0^* - \omega(t)$$

where ω_0^* is the optimal and $\omega(t)$ suboptimal trajectory, appears in three different situations: at the beginning of starting period; at the border of two regimes, dynamic and steady state; as an effect of load variation, Fig.13. The errors are less than 0.6%. On the steady state regime the error becomes zero, corresponding to the well known performance of the conventional control. The armature current and speed variations are normally and it is preserved the effect of feed forward component. The energy components do not change significantly. For instance, the input energy changes from 1562 [Ws] in case of optimal starting to 1566 [Ws] for suboptimal one.

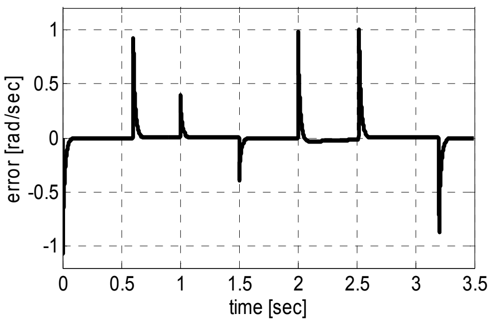

Fig.13 Tracking error

The real-time experimental system and results

The laboratory implementation of optimal law control takes into account the above proposal which has to track optimal speed trajectories, but with the difference that it is obtained by off-line simulation. The laboratory platform, presented in Fig. 14, consists of several parts: industrial converter AC-DC, DC machine, magnetic powder brake Frato 2002, incremental encoder, Signal Conditioning Unit (SCU) and acquisition board, dSPACE 1104. The parameters of the experimental system are the same as for simulation.

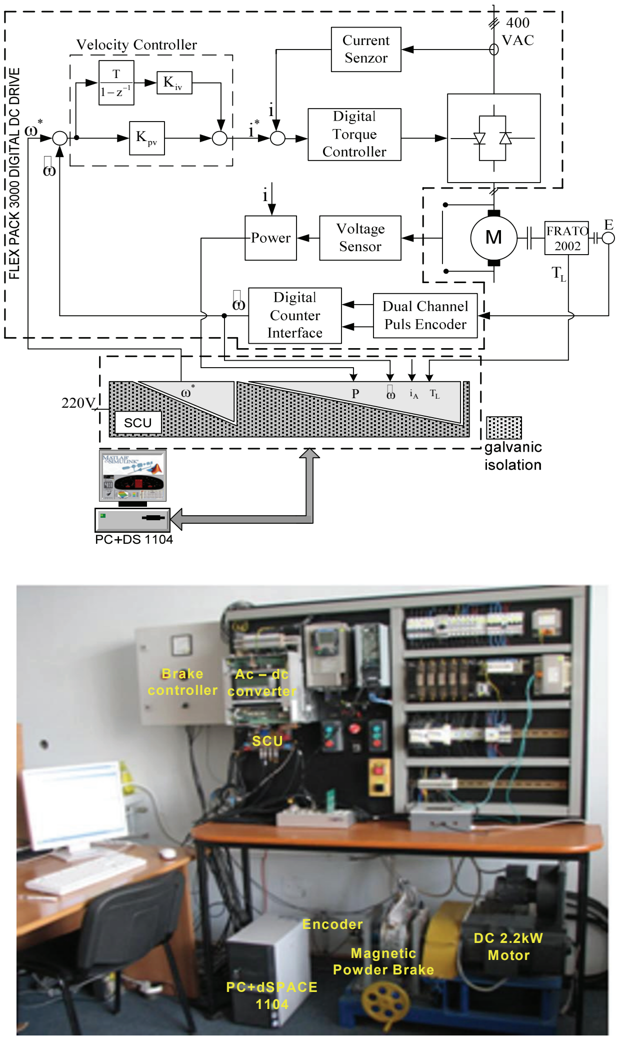

Fig.14. Structure and photo of laboratory platform

The DC drive system with above rating parameters has been tested in the following conditions:

- a starting to final angular speed $\omega_1 = 130[rad/\sec]$, final time $t_1 = 1\sec$, under the load torque $m_S = 8Nm$ and conventional current and speed control with ramp speed reference;

- a reversing regime from $\omega_0 = 130[rad/\sec]$ to $\omega_1 = -130[rad/\sec]$, $t_1 = 2\sec$, $m_S = 8Nm$ and speed ramp reference.

The conventional control is presented in Fig. 15, 16, 17 and 18: angular speed, armature voltage, armature current and load torque, respectively. All the responses, angular speed, voltage, and current, are normal, the dynamic behavior is very good and the variations are well known from practice and literature.

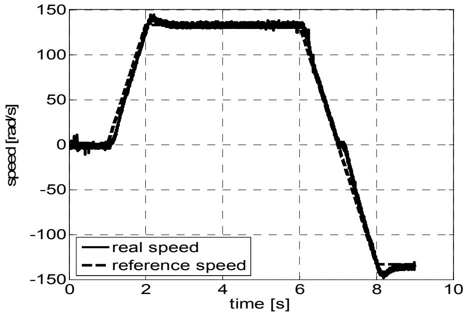

Fig.15 Reference and acquisition of speed for conventional control

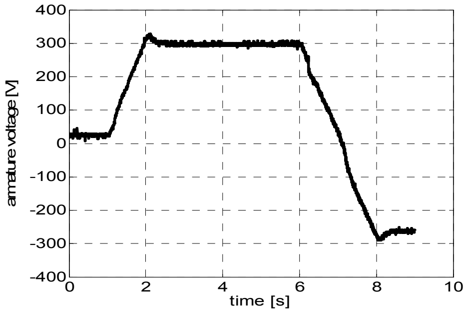

Fig.16 Armature voltage acquisition for conventional control

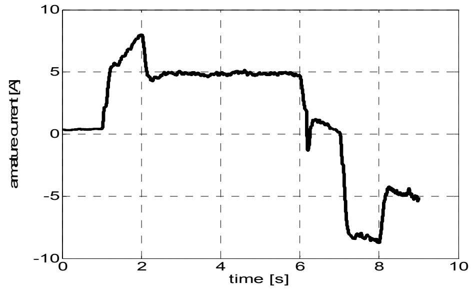

Fig.17 Armature current acquisition for conventional control

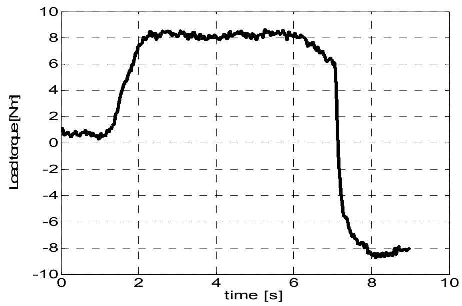

Fig.18 Load torque acquisition for conventional control

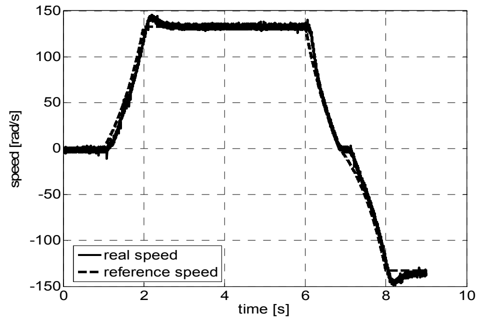

Fig.19 Reference and acquisition of speed for suboptimal control

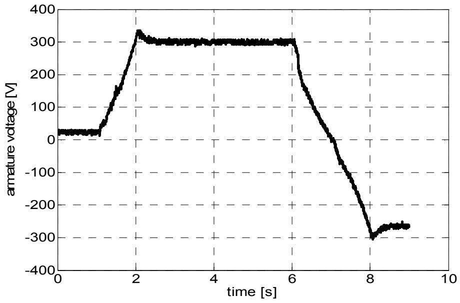

Fig.20 Armature voltage acquisition for suboptimal control

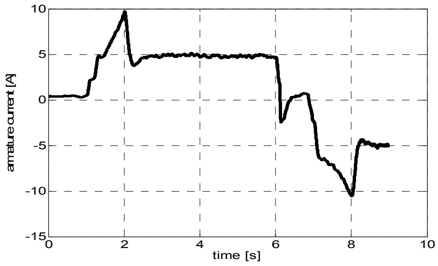

Fig.21 Armature current acquisition for suboptimal control

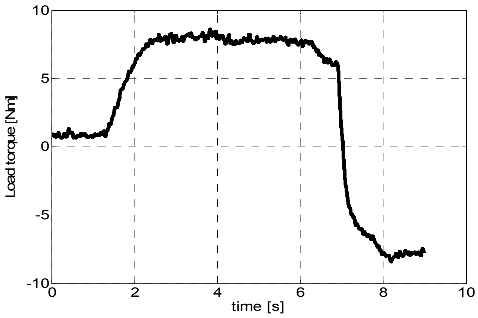

Fig.22 Load torque acquisition for suboptimal control

The experimental results for suboptimal control are presented in Figs. 15, 16, 17, 18, 19, 20, 21 and 22. The conditions of simulation are the same with conventional controls. There are more differences between the two controls. The variations of the current and speed are different, but both are in the admissible limits. Also the dynamic behaviors of the drive system are normal.

For the experiment purpose, a cascade current and speed controllers are used. The optimal trajectory is fed as external speed reference, while for the conventional one a ramp is used. The dynamic regimes are similar as time length, for the two types of control. The energies calculation is taking into consideration only during on the dynamic regime, from the starting point of reference to the stationary state.

The energy components are presented in Table 2 for a starting and reversing at 8 [Nm] load torque. The drawn energy, W_I, is smaller in the case of suboptimal control, from 5.93% to 10.38%, while the output energy, W_O, with 13.52% to 16.43%. As far as W_{RA}, the copper armature losses energy, the reducing was 3.96% for starting, but on reversing an 3.96% increasing was obtained. For the last value, which does not correspond to the other determinations, does not exist a plausible explanation.

Less one exception the experimental results confirm the numerical simulations. Therefore the optimal control approach proposed in the paper is an energy one, aiming at a reduction of the energy consumption, which increases significantly the conversion efficiency of the drive system.

There are insignificant differences between simulation and experimental results. The differences are generated by the different experimental conditions: the simulation is made for a minimum final time, physically feasible, and with the online input calculation; the experimental results, from the laboratory system limitations were made for a longer final time, one second for starting and 2 seconds for reversing. These results lead to the conclusion that the new control structure, Fig. 12, is more favourable from the point of view of system efficiency.

Conclusions

In order to enhance the conversion efficiency of the DC drive systems a new optimal control law, which minimizes the drawn energy, was developed. In this paper the validation of optimal control was made. The solution properties have been tested via simulation, using MATLAB-SIMULINK, and experimentally validated using laboratory facilities. With respect to conventional control, the optimal proposed control for a DC drive system minimizes the drawn energy to perform a given trajectory. The reduction in the drawn energy leads to the decreasing of the energy expenditure.

The main features of the proposed optimal control law are: the solution of control is an analytical one; high dynamic performances, without overshoots and good robustness to the load variation; decreasing the drawn energy with about 6% to 10% for a dynamic regime as starting, stopping and reversing; the optimal control is linear and unconstrained being applicable only for linear drive systems; voltage, current and speed limits can be maintained within strict limits by adequate choice of the weighting matrices; the optimal control can be mixed with conventional control in the aim to assure the works, dynamic and steady state regimes.

An implementation variant, for laboratory testing, named integrated control, is proposed. The proposal is a suboptimal one which uses the conventional control and the calculus of the optimal speed reference as input for the system.

Table 2 Energetic analysis

Type of regime	Torque [Nm]	Control	W_I [Ws]	W_O [Ws]	W_{RA} [Ws]
Starting	8	Conventional	1680.40	720.78	516.31
		suboptimal	1506.00	602.42	495.87
		$\frac{\text{suboptimal}}{\text{conventional}}$[%]	89.62	83.57	96.04
Reversing	8	conventional	2752.60	1826.60	883.87
		suboptimal	2589.50	1579.80	918.94
		$\frac{\text{suboptimal}}{\text{conventional}}$[%]	94.07	86.48	103.96

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***Authors**:*

Traian MUNTEANU - phd.student - traian.munteanu@ugal.ro, Romeo PADURARU - phd. student - romeo.paduraru@ugal.ro, Emil ROSU - professor - emil.rosu@ugal.ro, Marian GAICEANU - assistant professor - marian.gaiceanu@ugal.ro, Teodor DUMITRIU - assistant professor - teodor.dumitriu@ugal.ro , Cristian DACHE - phd student - cristian.dache@ugal.ro,
University of "Dunarea de Jos" Galati,Faculty of Automatic Control, Computers, Electrical and Electronics Engineering