

ENERGETIC OPTIMAL CONTROL OF ADJUSTABLE DRIVE SYSTEMS

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Abstract: In the paper is developed a new control strategy for the adjustable speed drives. The strategy consists in the energetic optimal control of the dynamic regimes as starting, stopping and reversing. The main developed problems: formulation of energetic optimal problem, solution, experimental results via simulation and some considerations concerning the use of the control. The optimal developed solution can be applied for the both AC and DC drives, but only for linear systems.

Keywords: optimal control, adjustable drive systems.

1. INTRODUCTION

Actually variable speed drives with DC and AC induction machines are operated using different types of automation as: scalar, vectorial and direct torque control. This control provides a good dynamic response and stationary behavior, but it does not say anything about the conversion efficiency. It is very well-known that in the transient behavior, as starting, stopping or reversing, the efficiency of the energy conversion is diminished down to the value smaller than 70 percent, while in the stationary state it is greater. The objective of the research is to develop a new control, of optimal type. This optimal control must minimize the energy which will be consumed over the dynamic periods. The synthesis of the optimal control law is accomplished with the experimental results, via the simulation procedure.

2. DRIVES MODELS

A DC adjustable speed drive by armature voltage controlled, Fig. 1, is an invariant controllable dynamic system described by the differential equations

$$(1) \begin{bmatrix} \dot{\omega}_m \\ \dot{i}_A \end{bmatrix} = \begin{bmatrix} -\frac{F}{J} & -\frac{c}{J} \\ -\frac{c}{L_A} & -\frac{R_A}{L_A} \end{bmatrix} \cdot \begin{bmatrix} \omega_m \\ i_A \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{L_A} \end{bmatrix} \cdot u(t) + \begin{bmatrix} -\frac{1}{J} \\ 0 \end{bmatrix} \cdot m_s(t)$$

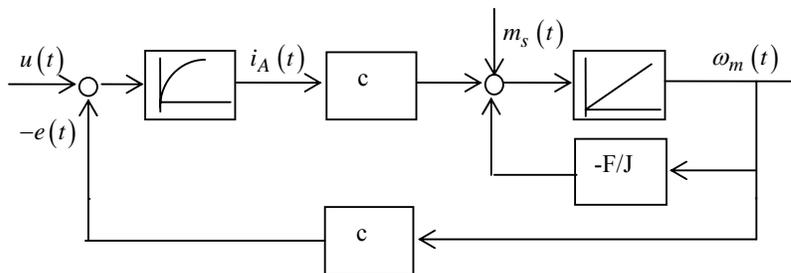


Fig.1. Mathematical model of DC drive

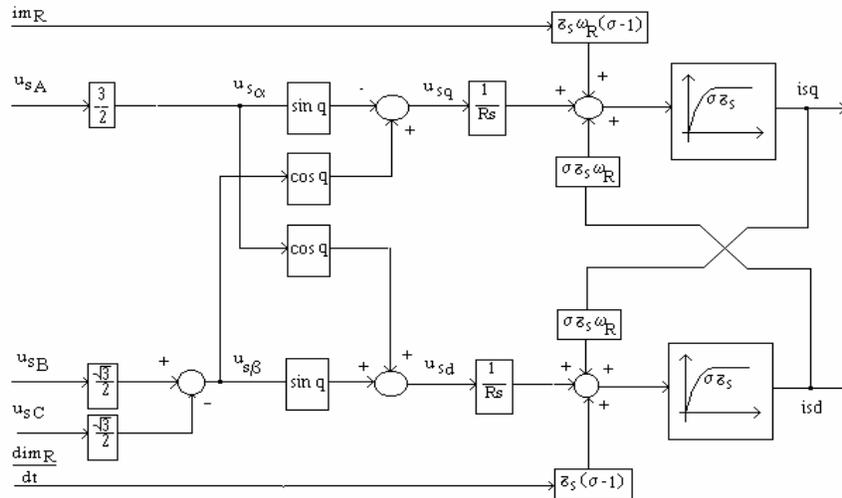


Fig.3. The mathematical model of the rotor oriented induction motor associated with VSI

3. PROBLEM FORMULATION

In order to improve the conversion efficiency, an optimal control law is proposed by using linear quadratic criteria. The objectives of the optimal control law are:

- smooth response ;
- no overshoot;
- the fast compensation of the load torque;
- the energies minimization.

Taking into account the minimizing of the energy dissipation in the motor for dynamic regimes the functional

$$J = \frac{1}{2} [\mathbf{x}(t_1) - \mathbf{x}_1]^T \mathbf{S} [\mathbf{x}(t_1) - \mathbf{x}_1] + \frac{1}{2} \int_0^{t_1} [\mathbf{x}^T(t) \mathbf{Q} \mathbf{x}(t) + \mathbf{u}^T(t) \mathbf{R} \mathbf{u}(t)] dt \quad (8)$$

is considered, where \mathbf{S} and \mathbf{Q} are a 2x2 positive semidefinite matrices, \mathbf{R} is a 1x1 positive definite matrix and t_1 is the specified terminal time, corresponding to an actual duration of the dynamic regime.

3.1. DC drives

The first term of the cost functional (8) is often called the terminal cost and its purpose is to guarantee that the square error between the final free state $\mathbf{x}(t_1)$ and the desired final state

$$(9) \mathbf{x}_1 = \begin{bmatrix} \omega^* \\ 0 \end{bmatrix}$$

is small.

Thus, by setting

$$(10) \mathbf{S} = \begin{bmatrix} s & 0 \\ 0 & 0 \end{bmatrix}$$

the terminal cost is given by

$$(11) \lambda(t_1) = \frac{1}{2} \cdot s \cdot [\mathbf{x}(t_1) - \mathbf{x}_1]^2 = \frac{1}{2} \cdot s \cdot [\omega_m(t_1) - \omega^*]^2$$

In the same way, by setting

$$(12) \mathbf{Q} = \begin{bmatrix} 0 & 0 \\ 0 & R_A \end{bmatrix}$$

the second term of (8) is related by equation

$$(13) \frac{1}{2} \int_0^{t_1} [\mathbf{x}^T(t) \mathbf{Q} \mathbf{x}(t)] dt = \frac{1}{2} R_A \int_0^{t_1} [i_A^2(t)] dt$$

and it minimizes the energy expended in the armature winding, which signifies the most important constituent part of the drive dissipation energies.

The third term of (8) given by

$$(14) \frac{1}{2} \int_0^{t_1} [\mathbf{u}^T(t) \mathbf{R} \mathbf{u}(t)] dt = \frac{1}{2} r \int_0^{t_1} [u^2(t)] dt$$

where

$$(15) r = \mathbf{R}$$

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

3.2. AC drives

In the same way, for the case of IM, by setting

$$(16) \mathbf{Q} = \begin{bmatrix} q_1 & 0 \\ 0 & q_2 \end{bmatrix}$$

the second term of (8) is related by equation

$$(17) \frac{1}{2} \int_0^{t_1} [\mathbf{x}^T(t) \mathbf{Q} \mathbf{x}(t)] dt = \frac{1}{2} q_1 \int_0^{t_1} [\omega_m^2(t)] dt + \frac{1}{2} q_2 \int_0^{t_1} [q^2(t)] dt$$

and it minimizes the oscillations of rotor field spatial angle.

The third term of (8) is given by

$$(18) \frac{1}{2} \int_0^{t_1} [\mathbf{u}^T(t) \mathbf{R} \mathbf{u}(t)] dt = \frac{1}{2} r \int_0^{t_1} [i_{sq}^2(t)] dt$$

where $\mathbf{R} = r$. This term weights the cost of the control i_{sq} and, in the same time, minimizes the energy expended in the motor windings.

Therefore, the optimal control problem is with free end point, specified terminal time and without constraints. The magnitude constraints for the control and state can be solved by adequate choice of the weighting matrices \mathbf{S} , \mathbf{Q} and \mathbf{R} . Finally, the quadratic linear problem consists of finding the optimal control $\mathbf{u}(t)$, $t \in [0, t_1]$ which minimizes the functional (8) corresponding to the dynamic system (1) or (5), with initial $\mathbf{x}(0)$ state, such as the transition from initial phase $(0, \mathbf{x}(t_0))$ be closed to the final phase $(t_1, \mathbf{x}(t_1))$.

4. THE SOLUTION OF THE OPTIMAL CONTROL PROBLEM

The solution of the problem, such as formulated above, exists and is unique if the system is controllable and completely observable and matrices \mathbf{Q} , $\mathbf{S} \geq 0$ and $\mathbf{R} > 0$. Via variational calculus, the

Hamiltonian of the optimal control problem is given by

$$(19) \mathbf{H}(\mathbf{p}, \mathbf{x}, \mathbf{u}, t) = \frac{1}{2} [\mathbf{x}^T(t) \mathbf{Q} \mathbf{x}(t) + \mathbf{u}^T(t) \mathbf{R} \mathbf{u}(t)] + \langle \mathbf{p}(t)^T, \mathbf{A} \mathbf{x}(t) + \mathbf{B} \mathbf{u}(t) + \mathbf{G} \mathbf{w}(t) \rangle$$

in which $\mathbf{p}(t) \in \mathfrak{R}^2$ is the costate vector.

The optimal control minimizing the cost functional (8) is given by

$$(20) \frac{\partial \mathbf{H}}{\partial \mathbf{u}} = \mathbf{R} \mathbf{u}(t) + \mathbf{B}^T \mathbf{p}(t) = 0$$

From equation (20) optimal control $\mathbf{u}^*(t)$ can be written in the form

$$(21) \mathbf{u}^*(t) = -\mathbf{R}^{-1} \mathbf{B}^T \mathbf{p}(t)$$

The state and costate vectors are the solutions of the canonical system

$$(22) \begin{bmatrix} \dot{\mathbf{x}}(t) \\ \dot{\mathbf{p}}(t) \end{bmatrix} = \begin{bmatrix} \mathbf{A} & -\mathbf{B} \mathbf{R}^{-1} \mathbf{B}^T \\ -\mathbf{Q} & -\mathbf{A}^T \end{bmatrix} \begin{bmatrix} \mathbf{x}(t) \\ \mathbf{p}(t) \end{bmatrix} + \begin{bmatrix} \mathbf{G} \\ 0 \end{bmatrix} \mathbf{w}(t)$$

with boundary conditions:

- the initial state $\mathbf{x}(0) = \mathbf{x}_0$;

- the transversality of the costate vector

$$(23) \mathbf{p}(t_1) = \left. \frac{\partial \lambda(t)}{\partial \mathbf{x}} \right|_{t=t_1} = \mathbf{S} [\mathbf{x}(t_1) - \mathbf{x}_1]$$

The integration of the canonical system leads to the well-known matrix differential equation, Riccati type, and the associate vectorial equation. The integration of these two equations is a very difficult work because the Riccati equation is nonlinear, its solution is recursive one that can be calculated only backward in time. Moreover, the backward computation needs to know a priori the variation of the perturbation vector $\mathbf{w}(t)$ on the duration of the dynamic rating t_1 . The last condition is too strong and it can not be accomplished.

In order to avoid these difficulties is developed a nonrecursive solution of the Riccati equation using two linear transformations. The first transformation changes actual time t into $t_1 - t$, time remaining until the end of the optimal process. Thus by setting

$$(24) \tau = t_1 - t$$

and new state, costate and perturbation vectors

$$(25) \begin{bmatrix} \mathbf{m}(\tau) \\ \mathbf{n}(\tau) \end{bmatrix} = \begin{bmatrix} \mathbf{x}(t) \\ \mathbf{p}(t) \end{bmatrix}$$

$$(26) |\mathbf{l}(\tau)| = |\mathbf{w}(t)|$$

the canonical system (22) becomes

$$(27) \begin{bmatrix} \dot{\mathbf{m}}(\tau) \\ \dot{\mathbf{n}}(\tau) \end{bmatrix} = \begin{bmatrix} -\mathbf{A} & \mathbf{B}\mathbf{R}^{-1}\mathbf{B}^T \\ \mathbf{Q} & \mathbf{A}^T \end{bmatrix} \begin{bmatrix} \mathbf{m}(\tau) \\ \mathbf{n}(\tau) \end{bmatrix} + \begin{bmatrix} -\mathbf{G} \\ 0 \end{bmatrix} \mathbf{l}(\tau)$$

The system (27) can be integrated via the fundamental matrix. The solution is given by

$$(28) \begin{bmatrix} \mathbf{m}(\tau) \\ \mathbf{n}(\tau) \end{bmatrix} = \Phi(\tau, 0) \left\{ \begin{bmatrix} \mathbf{m}(0) \\ \mathbf{n}(0) \end{bmatrix} + \int_0^\tau \Phi^{-1}(\beta, 0) \begin{bmatrix} \mathbf{l}_1(\beta) \\ 0 \end{bmatrix} d\beta \right\}$$

where

$$(29) \Phi(\tau) = e^{\mathbf{M}\tau}$$

$$(30) \mathbf{l}_1(\beta) = -\mathbf{G}\mathbf{l}(\beta)$$

and

$$(31) \mathbf{M} = \begin{bmatrix} -\mathbf{A} & \mathbf{B}\mathbf{R}^{-1}\mathbf{B}^T \\ \mathbf{Q} & \mathbf{A}^T \end{bmatrix}$$

The solution (28) has a certain advantage because it can be calculated at the actual time t . Thus, using (24), the fundamental matrix becomes

$$(32) \Phi(\tau, 0) = \Phi(t_1 - t, t_1)$$

On the other hand, the solution needs only the value of the perturbation vector $\mathbf{w}(t)$ at any time t . This condition can be achieved by using a torque observer.

The main difficulty is the calculus of the fundamental matrix $\Phi(\tau)$ because the matrix \mathbf{M} contains both types of the eigenvalues, positive and negative. Thus, the fundamental matrix has two types of terms:

- $e^{\mathbf{A}(t_1-t)}$, which has a large value;
- $e^{-\mathbf{A}(t_1-t)}$, which has a small value.

The manipulation of these values for the period $[0, t_1]$ becomes too difficult, if not impossible.

The second transformation is made in order to use only the negative eigenvalues of the matrix \mathbf{M} . Let be a new state vector defined by

$$(33) \begin{bmatrix} \mathbf{c}(\tau) \\ \mathbf{d}(\tau) \end{bmatrix} = \mathbf{W}^{-1} \begin{bmatrix} \mathbf{m}(\tau) \\ \mathbf{n}(\tau) \end{bmatrix}$$

where

$$(34) \mathbf{W} = \begin{bmatrix} \mathbf{W}_{11} & \mathbf{W}_{12} \\ \mathbf{W}_{21} & \mathbf{W}_{22} \end{bmatrix}$$

is the matrix of the eigenvectors corresponding to eigenvalues of the matrix \mathbf{M} .

The canonical system (27) with (33) becomes

$$(35) \begin{bmatrix} \dot{\mathbf{c}}(\tau) \\ \dot{\mathbf{d}}(\tau) \end{bmatrix} = \begin{bmatrix} \mathbf{A} & 0 \\ 0 & -\mathbf{A} \end{bmatrix} \begin{bmatrix} \mathbf{c}(\tau) \\ \mathbf{d}(\tau) \end{bmatrix} + \mathbf{W}^{-1} \begin{bmatrix} -\mathbf{G} \\ 0 \end{bmatrix} \mathbf{l}(\tau)$$

where

$$(36) \mathbf{A} = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix}$$

is the matrix of the positive eigenvalues of matrix \mathbf{M} .

After the algebraic manipulations, the solution of the system (35) becomes

$$(37) \begin{bmatrix} \mathbf{c}(0) \\ \mathbf{d}(\tau) \end{bmatrix} = \begin{bmatrix} e^{-\mathbf{A}\tau} & 0 \\ 0 & e^{-\mathbf{A}\tau} \end{bmatrix} \begin{bmatrix} \mathbf{c}(\tau) \\ \mathbf{d}(0) \end{bmatrix} + \begin{bmatrix} \mathbf{I} - e^{-\mathbf{A}\tau} & 0 \\ 0 & \mathbf{I} - e^{-\mathbf{A}\tau} \end{bmatrix} \begin{bmatrix} \mathbf{H}_1 \\ \mathbf{H}_2 \end{bmatrix} \mathbf{l}(\tau)$$

where \mathbf{H}_1 and \mathbf{H}_2 result from (35) and

$$(38) \mathbf{I} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

The transversality condition (23) becomes

$$(39) \mathbf{d}(0) = \mathbf{E}\mathbf{c}(0) + \mathbf{F}\mathbf{x}_1$$

where

$$(40) \mathbf{E} = [\mathbf{S}\mathbf{W}_{12} - \mathbf{W}_{22}]^{-1} [\mathbf{W}_{21} - \mathbf{S}\mathbf{W}_{11}]$$

and

$$(41) \mathbf{F} = [\mathbf{S}\mathbf{W}_{12} - \mathbf{W}_{22}]^{-1} \mathbf{S}$$

Now, with the condition (39) we can write a relation between $c(\tau)$ and $d(\tau)$ in the form

$$(42) \quad c(\tau) = Z(\tau)d(\tau) + e^{-A\tau} E(I - e^{-A\tau})H_1 l(\tau) + Fx_1 + (I - e^{-A\tau})H_2 l(\tau)$$

where

$$(43) \quad Z(\tau) = e^{-A\tau} E e^{-A\tau}$$

Coming back to the system (22) via transformations (25) and (33), the optimal control law, at any moment t , is given by

$$(44) \quad u^*(t) = -R^{-1}B^T P(t_1 - t)x(t) + R^{-1}B^T K_1(t_1 - t)x_1 + R^{-1}B^T K_2(t_1 - t)w(t)$$

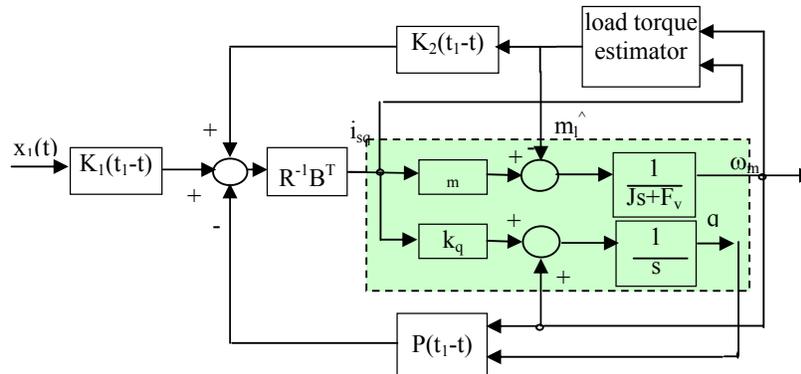


Fig.4. The structure of the optimal control law

in which $P(t_1 - t)$ is the solution of the differential matrix Riccati equation and the matrices K_1 and K_2 are calculated via $P(t_1 - t)$.

Obviously, the solution (44) is analytical and supposes the knowledge of the perturbation $w(t)=m_l(t)$ at any time t . Now, because the solution is nonrecursive, the perturbation $m_l(t)$ can be estimated by using a torque observer.

The structure of the optimal control law is presented in Fig.4 for the case of IM.

The optimal control law has three components: the state feedback, the input component to achieve the desired state x_1 and the compensating feed-forward of the perturbation $w(t)$.

5. ANALYSIS OF THE OPTIMAL SOLUTION

The simulation results are presented for the AC drive.

5.1. Starting process

The optimal control law (44) and the model (5) were numerically simulated by discretization using Z - transform and zero order hold for a starting of a 0.75 [kW], 3000 [r.p.m.] induction motor under a rated load torque of 2.38 [Nm].

The initial state condition for the starting process is the null state

$$(45) \quad \begin{bmatrix} \omega(0) \\ q(0) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

The final value is

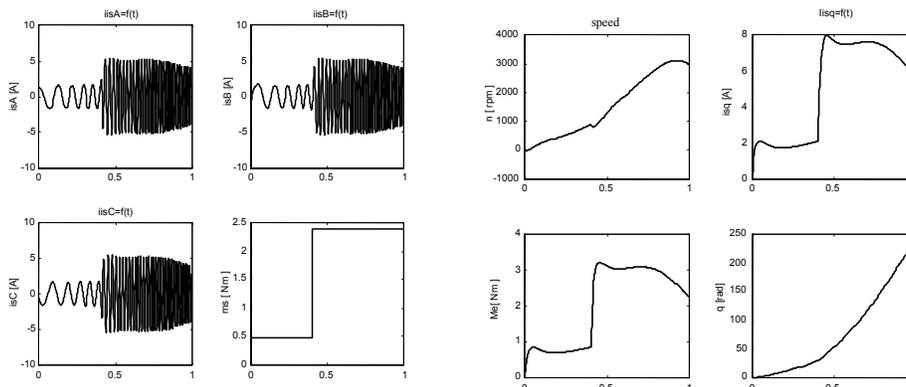


Fig.5-12. The experimental results

$$(46) \begin{bmatrix} \omega(t_1) \\ q(t_1) \end{bmatrix} = \begin{bmatrix} \omega_n \\ 0 \end{bmatrix}$$

- i_{sA}, i_{sB}, i_{sC} are the phase currents;
- i_{sq} the torque component current;
- n_m the speed of the rotor;
- m_e electromagnetic torque of the induction motor;

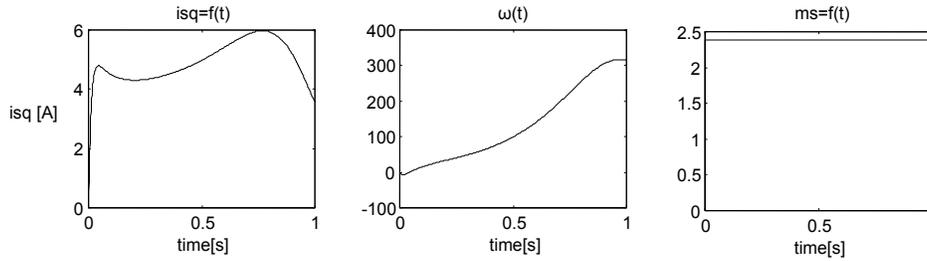


Fig.13-15. The starting process at rated torque

where ω_n is nominal angular velocity and the q angle is free.

The experimental results are presented in Fig. 5-12 where:

In the fig.16 the comparative energies of both control methods (classical U/f - optimal control) is depicted, in which W_{p1} the input energy, W_u the output energy,

From energetic point of view it could be noticed that the output energy is the same in both controls while the input energy decreases significantly, about 27%, in optimal control case. The decline of stator copper losses, W_{cu1} , is less significant, about 6%. The decline of the input energy can be explained only by the change of the speed rising form and, obviously, decreasing of the mechanical losses, Fig. 9 and 14.

- m_s load torque, initial 0.5 Nm and a step of 2.38 Nm at 0.4 second;
- q the angular position of the rotor field.

In Fig.13-15 is presented the same starting process under the rated load torque, 2.38 Nm value.

W_{cu1} the energy expended in the stator windings, W_{cu2} the energy expended in the rotor windings and W_{fv} the viscous friction energy.

5.2. Breaking process

The initial state condition for the breaking process is the nominal angular velocity and the q angle (the rotor magnetizing flux angle) value at the nominal torque ($m_s=M_N$), corresponding with the final value for a starting process i.e.

$$(47) \begin{bmatrix} \omega(0) \\ q(0) \end{bmatrix} = \begin{bmatrix} \omega_N \\ q_N \end{bmatrix}$$

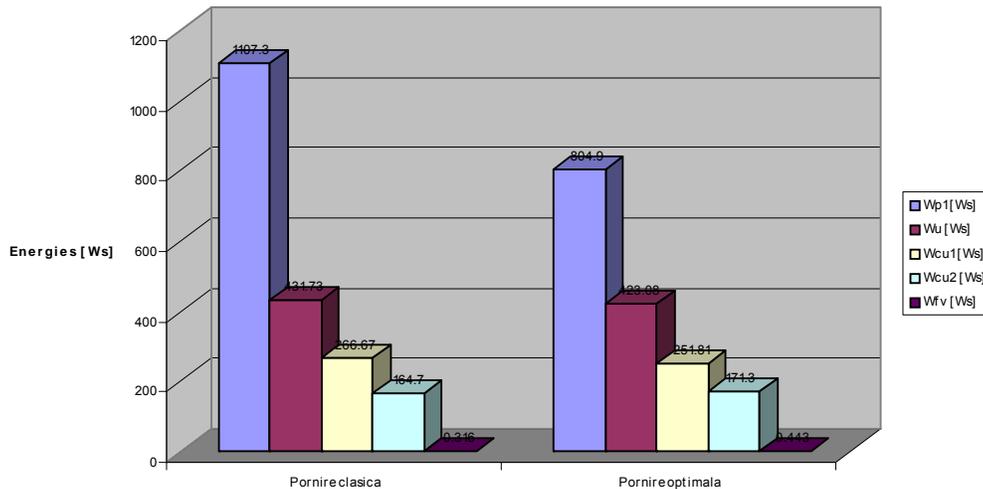


Fig. 16 The comparative energies of both control methods (classical U/f - optimal control)

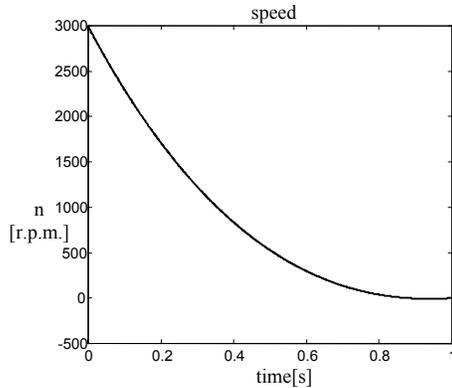


Fig.17. Breaking process

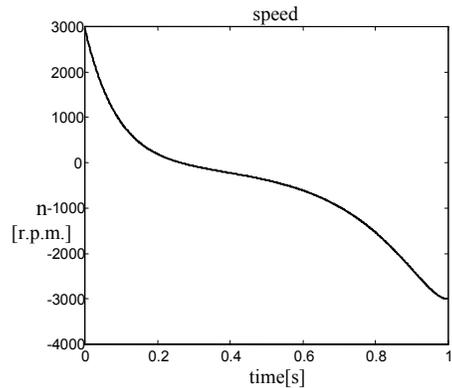


Fig.18. Reversing process

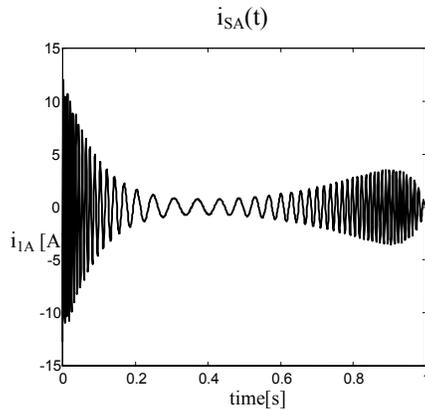


Fig.19. Current i_{sA}

The final values are null state

$$(48) \begin{bmatrix} \omega(t_1) \\ q(t_1) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

The experimental results are presented in Fig. 17 at the level of speed [rpm].

5.3. The reversing process

The initial condition for the reversing process is the final condition for the starting process, equation (47). The final state condition is

$$(49) \begin{bmatrix} \omega(t_1) \\ q(t_1) \end{bmatrix} = \begin{bmatrix} -\omega_N \\ 0 \end{bmatrix}$$

in which the final value of rotor current magnetizing flux angle is free. The variations of the speed and the phase current i_{sA} are depicted in Fig.18 and 19. The comparative energies of both control methods (classical U/f - optimal control) presented in Fig.20, where the notations are the same as in Fig.16.

From energetic point of view it could be noticed that the conclusions are the same as in the case of a starting. Thus the output energy is the same in both controls while the input energy decreases significantly, about 29%, in optimal control case. The decline of stator copper losses, W_{cu1} , is less significant, about 6%. The decline of the input energy can be explain in the same way, by the different form of the speed variation than in the case of classical U/f.

5.4. The weighting matrices

The optimal control is with free end point and without constraints. The magnitude constraints for the state and control were solved by adequate choice of the weighting matrices. For example in Fig. 21 is presented the influence of the \mathbf{R} matrix value on the component torque current i_{sq} and speed for a starting process. The influences of the \mathbf{S} and \mathbf{Q} matrices are studied in the same way.

6. CONCLUSIONS

- 1) The solution of the optimal control exists for the both cases, DC and AC drives. It is a feasible solution and the saved energy is significant, between 7-28%.
- 2) The copper losses reductions are based on the improving of the transversal stator current profile.
- 3) It could be noticed a major influence of the speed dynamic to input energy. Therefore, an additional energy reduction could be obtained by speed reference imposing.
- 4) By realizing the energy reduction the thermal regime is improve such that either could obtain the overload permission or increasing the motor life.
- 5) By motor energy reduction, due to the transversal stator current form, the energy in transformer, converter and in cables is decreasing.

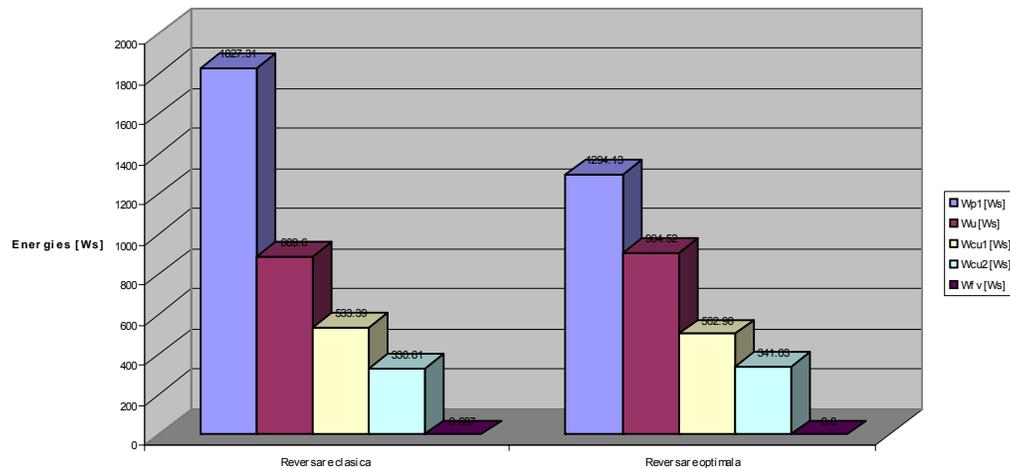


Fig.20. The comparative energies of both control methods (classical U/f - optimal control) for a reversing process

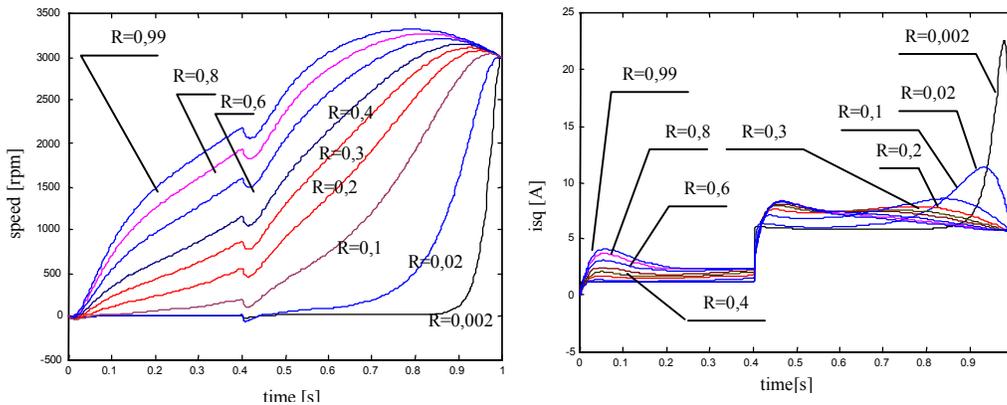


Fig.21. The influence of R matrix

6) By obtain the optimal control solution in one sample time, the load torque oscillations are eliminated, the number of power semiconductor devices switching is minimizing.

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