Modeling and Control of an Electric Drive System with Continuously Variable Reference, Moment of Inertia and Load Disturbance

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***Abstract*—This paper presents applicative aspects concerning the modeling, simulation, analysis and design of control solutions for a direct current electric drive system with continuously variable reference input (speed), variable moment of inertia and variable load disturbance. Two variable control structures for speed control are treated. The structures employ the switching between three or more control algorithms, and their design is based on the detailed mathematical model of the plant and on the particular features of the drive system. Conventional and fuzzy control solutions are offered as they are advantageous with respect to the continuous parameter adaptation because of the simplicity in adaptation at representative operating points. The solutions are validated by a digitally simulated application with fixed parameters and tested on a strip winding system laboratory equipment as a representative mechatronics system application.**

Keywords*—*cascade control structures, PI controllers, PI-fuzzy controllers, strip winding systems, variable moment of inertia

I. INTRODUCTION

The development of industrial automation has led to the continuous performance improvement of electric drive systems and control solutions. The improvement concerns higher performance in terms of starting, speed control, braking, reversing and correlating management system, heavy operating regimes [1], [2]. Additional conditions may impose elastic torque drive shafts.

The application considered in this paper refers to electric drive systems with variable parameters which depend on the evolution of the plant, viz. variable moment of inertia (VMI) and variable disturbances. The design of conventional controllers with fixed parameter is possible in such cases by determining the variation of the operating conditions, but rather poor control system performance can be achieved. Due to the application involved, i.e., an electric drive system with Continuously Variable Reference, Moment of Inertia and Load Disturbance (C-VR-MI-LD), this paper focuses on modeling and development of control solutions with high performance.

Some representative particular cases of systems with C-VR-MI-LD are the electric drive systems with direct current motors (DC-ms) or with brushless direct current motors (BLDC-ms) [3]–[5] that wrap strip of various alloys as brass, aluminum, waxed paper, etc., on a drum (strip winding). The strip winding leads to the variation of the drum radius, actually the mass of the drum, and thus the variation of the moment of inertia, which obviously changes the plant parameters and the overall system behaviors. The basic idea of the control is to maintain a constant linear velocity of the wrapped strip by a continuously changing the angular velocity of the drum; that is the reason why the use of nonlinear controllers or controllers adapted to the operating point can represent a solution. Considering the plants with VMI, the linearized Mathematical Models (MMs) with time variant parameters can be used in the model-based design of controllers. Modern motion control solutions can employ robust algorithms, adapted to the variation of the plant parameters and load disturbances, algorithms with adaptive reference model, variable structure algorithms, fuzzy controllers, neural networks, etc.

A development method of a VMI reaction wheel system for spacecraft attitude control is presented in [6]. An adaptive speed control for drives with VMI based on a frequency-domain approach is proposed in [7]. The vibration control of two degrees of freedom system using variable inertia vibration absorbers is discussed in [8]. A design methodology for the flywheel with VMI is offered in [9]. Several approaches to the control designs for plants with VMI are also reported in many other fields. Many efficient design methods for classical PI(D) controllers have been reported recently as, for example, in [10] and [11]; they have been applied in various forms and techniques including fuzzy control, variable structure systems, control algorithms for electric drive motors, parameter

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estimation methods for linear time-invariant (LTI) systems, robust control applications, etc.

The paper is organized as follows. An overview on the mathematical modeling, MMs and block diagrams for the VMI drive system is presented in Section II. A general Cascade Control Structure (CCS) with point-adapted variable quasi-continuously operating control algorithms and implementation details are discussed in Section III. Section IV gives details regarding the speed control solutions with conventional PI and Takagi-Sugeno PI-fuzzy controllers. Section V presents the application, viz. a strip winding system with adjustable reference input. The conclusions are highlighted in Section VI.

II. Variable Inertia Drive Systems

A. Simplified Model of Drive System with DC Motor

The main hypotheses accepted in modeling imply that in normal operating regimes are taken into account [12]: the excitation flux is constant, the local nonlinear effects due to different constructive elements are neglected, the actuators and the measurement instrumentation are modeled by linear static characteristic, and the moment of inertia of the driven mechanism $J_{mech}(t)$ is time-variable but it can be considered quasi-constant for relatively slow variations of the drive parameters. Therefore, the moment of inertia is expressed as

$$J_{tot}(t) = J_m + J_{mech}(t)\,. \tag{1}$$

The well-known first principle equations that characterize the system are

$$\begin{aligned}
&L_a \cdot \dot{i}_a + R_a \cdot i_a = u_a - e,\\
&J_m \cdot \dot{\omega} = M_e - M_s - M_f,\\
&e = k_e \cdot \omega,\ \ u_\omega = k_{M\omega} \cdot \omega,\ \ u_i = k_{Mi} \cdot i_a,\\
&M_e = k_m \cdot i_a,\ \ M_f = k_f \cdot \omega,\\
&u_a = k_E \cdot u_c,\\
&T_a = L_a / R_a,
\end{aligned} \tag{2}$$

where: k_E - actuator gain, u_c - control voltage (signal) [V], u_a - armature voltage [V], i_a - armature current [A], R_a , L_a - electrical parameters [Ω, H], T_a - electrical time constant [s], M_e - electromagnetic torque [Nm], M_s - load torque [Nm], M_f - friction torque [Nm], e - counter electromotive force [V], k_e, k_m - electromagnetic- coefficients [V/rad/s, Nm/A], ω - angular (rotor) velocity [rad/s], J_m or $J_{tot}(t)$ - moment of inertia of DC-m [kgm^2] or of overall plant.

A state-space model of the DC-m can be expressed using (1) and (2). This model will be used, with further extensions, in the state feedback control solutions with variable parameters.

Since the MM of the BLDC-m in the symmetrical operating mode [3]–[5] is very close to the MM of the DC-m, this leads to some similarities of the control solutions and of their design. The controller design for the inner control loop makes use of the linearized equivalent second- or third-order benchmark-type transfer functions (t.f.s) connected to the operating points:

- in speed control applications:

$$H_P(s) = \frac{k_P}{(1 + s \cdot T_s)(1 + s \cdot T_1)},\ T_1 >> T_s, \tag{3}$$

$$H_P(s) = \frac{k_P}{(1 + s \cdot T_s)(1 + s \cdot T_1)(1 + s \cdot T_2)},\ T_1 > T_2 >> T_s, \tag{4}$$

- in position control applications:

$$H_P(s) = \frac{k_P}{s \cdot (1 + s \cdot T_s)}, \tag{5}$$

$$H_P(s) = \frac{k_P}{s \cdot (1 + s \cdot T_s)(1 + s \cdot T_1)},\ T_1 >> T_s, \tag{6}$$

where k_P is the process gain, T_1 and T_2 are the large time constants and T_s is the small time constant. The parameters k_P and T_1 are time variant.

B. Model of Strip Winding System

The application is focused on control systems for which the reference input is constantly changing, the load disturbance input is permanently variable and the system has variable parameters (mainly the moment of inertia). The electric drive system with variable moment of inertia refers to a DC-m [13], but it can also be a BLDC-m, with rigid coupling (the elastic case is discussed separately) with a rolling drum, which wraps a strip with the thickness h and the density ρ.

The basic idea is that the strip is wrapped on a rolling drum with a velocity which should be synchronized with the strip linear velocity. The functional diagram of the electric drive system with VMI connected with a strip rolling mill is presented in Fig. 1, where: a - transmission parameter which characterizes the speed reduction unit, ω_f - angular velocity (rolling drum) [rad/s], v_T - linear velocity (rolling drum) [m/s], v_S - linear velocity of the strip imposed by the pressing rollers [m/s], J_T - moment of inertia of the (rolling) drum, $J_{tot}(t)$ - moment of inertia of overall system, [kgm^2], $r(t)$ - drum radius with strip wrapped [m], f_h - resistance force of the strip [N]. The variation of the angular velocity of the drum and also the total inertia of the system can be described by

$$a = \omega_f / \omega,\ J_{tot}(t) = J_m + a^2 \cdot J_T(t). \tag{7}$$

Accepting the condition that h is sufficiently small, the drum radius variation and the variation of the moment of inertia of the drum can be approximated as (l - drum width):

$$\begin{aligned}
&\frac{dr(t)}{dt} = (h/(2\cdot\pi))\cdot\omega_f(t) = (h/(2\cdot\pi))\cdot a\cdot\omega(t),\\
&J_T(t) = \rho\cdot\pi\cdot l\cdot r^4(t)/2.
\end{aligned} \tag{8}$$

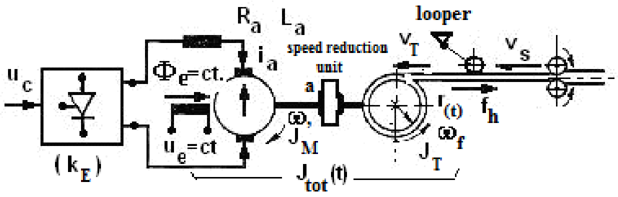


Fig. 1. Functional diagram of a DC electric drive system with VMI.

This leads to the following extended MM of the electric drive system with VMI:

$$
\begin{aligned}
\frac{di_a(t)}{dt} &= -\frac{R_a}{T_a}\cdot i_a(t) - \frac{k_e}{L_a}\cdot \omega(t) + \frac{k_E}{L_a}\cdot u_c(t),\\
\frac{d\omega(t)}{dt} &= \frac{k_m}{J_{tot}(t)}\cdot i_a(t) - \frac{1}{J_{tot}(t)}\cdot\left[\frac{dJ_{tot}(t)}{dt}\right]\cdot\omega(t),\\
&\quad -\frac{a\cdot r(t)}{J_{tot}(t)}\cdot f_h(t) - \frac{k_f}{J_{tot}(t)}\cdot\omega(t),\\
\frac{df_h(t)}{dt} &= C\cdot a\cdot r(t)\cdot\omega(t) - C\cdot v_s(t),
\end{aligned}
\tag{9}
$$

where C is the elasticity constant of the strip material.

The model (9) is nonlinear considering the change of the system parameters over time, viz. the drum radius changes with the wrapping of the strip and therefore changes the moment of inertia of the drum (J_T). The applications of such electric drive systems usually involve the linear velocity of the strip imposed by the pressing rollers such that to be kept constant and the resistance force of the strip, f_h, as well:

$$
v_S(t) \approx \text{const}, \quad f_h(t) = \text{const}\,. \tag{10}
$$

Accepting various simplifying assumptions – valid but only in well defined situations – and using the classical linearization technique around fixed steady state points or trajectories, simplified mathematical models can be obtained, for example, in forms of benchmark-type t.f.s; based on these, speed control structures and controller designs can be used. The verification of the obtained results will be made on detailed (nonlinear) MMs that are the nearest to the real behavior of the system.

III. Speed Control Solutions for Strip Winding Systems with Variable Inertia

The stability of the closed-loop system is necessary. This is especially important because in case of plants with VMI the changing of the operating point modifies the plant dynamics and because the control law depends on the plant. Building upon previous results given in [1] and [2], this paper proposes the switching between three control algorithms.

The CCS according to Fig. 2 is considered for the winding system with VMI, with the speed controller in two possible versions. The CCS offers additional benefits such as the ability to address multiple disturbances to the process and to improve variable set-point response performance.

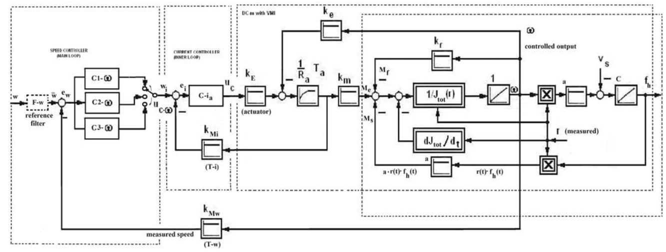


Fig. 2. Cascade Control Structure for a DC-m drive with VMI and variable load disturbance.

The first version of CCS is characterized by an I or a PI current controller C-i_a, and the speed controller consists of three conventional quasi-continuously operating PI controllers, C1-ω, C2-ω and C3-ω. All controllers can be designed using classical design methods, the Modulus Optimum (MO) method for C-i_a [14], and the Extended Symmetrical Optimum (ESO) method in its different versions [15] for C1-ω, C2-ω and C3-ω.

The second version of CCS (to be described in Section IV) is also characterized by an I or a PI current controller C-i_a, but the speed controllers C1-ω, C2-ω and C3-ω are Takagi-Sugeno PI-Fuzzy Controllers (TS-PI-FCs). The main advantage is that our fuzzy control solutions can ensure good control system performance and compensation for plant nonlinearities.

As mentioned in Section I, the same control solutions can be used in BLDC-m applications. The current controller for BLDC-ms is an on-off (with hysteresys) or a sliding mode controller (for each phase), and this solution can be also used in induction motor control [4], [14], [16].

The bumpless switching of the control algorithm (c.a.) needs the re-updating of tuning parameters, q_v^i with $v = 0$ or 1 (in case of a PI controller $p_1 = -1$) and $i = 1 \ldots m$ (m – the number of c.a.s, here m=3) and the past values in the c.a.s. If the controller operates on the basis of c.a. (1) and it switches to c.a. (2), next c.a. (2) switches to c.a. (3), the algorithms are

$$
\begin{aligned}
&u_{mk} = q_1^{(m)}\cdot x_{1k}^{(m)} + q_0^{(m)}\cdot x_{2k}^{(m)}, \quad m = 1,2,3, \quad \text{c.a.}\,(m)\\
&e_k^{(m)} = e_k,
\end{aligned}
\tag{11}
$$

$x_{1k}^{(m)} = x_{2,k-1}^{(m)}$, with values which must be calculated. Since

$$
x_{2k}^{(m)} = e_k - p_1^{(m)}\cdot x_{1k}^{(m)}, \quad m = 1,2,3, \tag{12}
$$

the relations for c.a. (1), c.a. (2) and c.a. (3) given in (11) are transformed into:

$$
u_{mk} = q_1^{(m)}\cdot x_{1k}^{(m)} + q_0^{(m)}\cdot e_k - q_0^{(m)}\cdot p_1^{(m)}\cdot x_{1k}^{(m)}\,. \tag{13}
$$

Imposing the bumpless switching condition $u_{2k} = u_{1k}$ and next $u_{3k} = u_{2k}$, this leads to

$$
\begin{aligned}
&x_{1k\,nec}^{(n+1)} = \{q_1^{(n)} x_{1k}^{(n)} + q_0^{(n)} x\ [q_0/(q_1 - q_0 p_1)] x_{2k}^{(n)}\}\\
&/(q_1^{(n+1)} - q_0^{(n+1)} p_1^{(n+1)}) - [q_0^{(n+1)}/(q_1^{(n+1)} - q_0^{(n+1)} p_1^{(n+1)})] e_k,\\
&x_{2,k-1\,nec}^{(n+1)} = x_{1k\,nec}^{(n+1)}, \quad n = 1, 2.
\end{aligned}
\tag{14}
$$

The switching structure presented in Fig. 3 is applicable without difficulties to both mentioned versions of c.a.s.

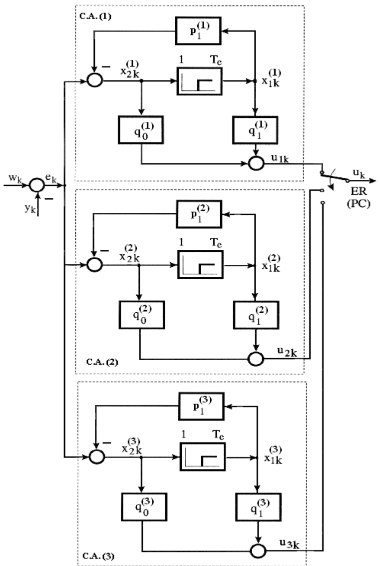


Fig. 3. Detailed block diagram of controller switching.

IV. PI and Takagi-Sugeno PI-Fuzzy Speed Control Solutions for Strip Winding Systems

Our first version of CCS uses the switching between three discrete-time PI c.a.s with the following generic t.f. of the continuous-time PI c.a.s:

$$H_C(s) = k_C \cdot (1 + s \cdot T_i)/(s \cdot T_i), \quad (15)$$

where the controller gain is k_C and the integral time constant is T_i. The discretized c.a.s are referred to as c.a. (1), c.a. (2) and c.a. (3) as shown in Fig. 3 with $u_k=\{u_{c\text{-}\omega}\}$. The c.a.s are designed and tuned on the basis of the linearized models of the plant in terms of the ESO method [15]. Using Tustin's method, the continuous-time PI controller is discretized resulting in

$$\begin{aligned} &q_0 = k_c + k_c \cdot T_e/(2 \cdot T_i),\ q_1 = -[k_c - k_c \cdot T_e/(2 \cdot T_i)], \\ &p_0 = 1,\ p_1 = -1, \end{aligned} \quad (16)$$

where T_e is the sampling period.

Our second version of CCS uses TS-PI-FCs based on the continuous-time PI controllers, where k_C and T_i are tuned by the MO method [14]. Tustin's method is next applied to discretize these PI controllers yielding the PI quasi-continuous digital controller with output integration (OI) [12], [17]

$$\begin{aligned} &\Delta u_k = K_p \cdot \Delta e_k + K_i \cdot e_k = K_p \cdot (\Delta e_k + \alpha \cdot e_k), \\ &K_p = k_C \cdot [1 - T_e/(2 \cdot T_i],\ K_i = k_C \cdot T_e / T_i, \\ &\alpha = K_i / K_p = 2 \cdot T_e/(2 \cdot T_i - T_e), \end{aligned} \quad (17)$$

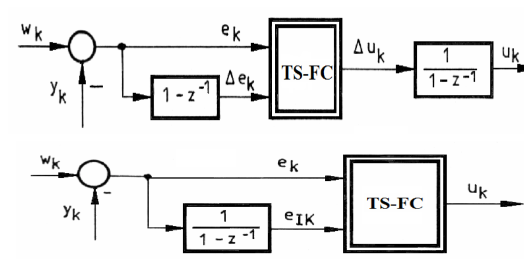
and the PI quasi-continuous digital controller with input integration (II) [12], [17]

$$\begin{aligned} &u_k = K_i \cdot e_{Ik} + K_p \cdot e_k = K^*_p e_{Ik} + K^*_i \cdot e_k = K^*_p \cdot (e_{Ik} + \alpha^* \cdot e_k), \\ &K^*_P = K_i = k_C \cdot T_e / T_i, K^*_i = K_p = k_C \cdot [1 - T_e/(2 \cdot T_i)], \\ &\alpha^* = K^*_i / K^*_p = (2 \cdot T_i - T_e)/(2 \cdot T_e). \end{aligned} \quad (18)$$

The structures of the TS-PI-FCs with OI and with II are given in Fig. 4 (a) and in Fig. 4 (b), respectively. The parameters of these TS-PI-FCs are $\{B_e, B_{\Delta e}, B_{\Delta u}\}$ for OI and $\{B_e, B_{eI}, B_u\}$ for II, and the tuning relations are obtained from the modal equivalence principle:

$$\begin{aligned} &B_{\Delta e} = (K_I / K_P) \cdot B_e,\ B_{\Delta e} = \alpha \cdot B_e,\ B_{\Delta u} = K_i \cdot B_e, \\ &B_{eI} = (K^*_i / K^*_p) \cdot B_e,\ B_{eI} = \alpha^* \cdot B_e,\ B_u = K^*_i \cdot B_e. \end{aligned} \quad (19)$$

Fig. 4 uses e_k - control error, Δe_k - increment of control error, e_{Ik} - integral of control error, Δu_k - increment of control signal, and u_k - control signal.



(a)

(b)

Fig. 4. TS-PI-FC structure with output integration (a) and TS-PI-FC structure with input integration (b).

The fuzzification uses five linguistic terms with triangular and trapezoidal membership functions for each input, LTe, LTde for the TS-PI-FC with OI, LTe and LTeI for the TS-PI-FC with II)∈ {NB, NS, ZE, PS, PB}. The rule base consists of 25 rules expressed in terms of

- *IF* (e_k *IS LTe AND* Δe_k *IS LTde*) *THEN* $\Delta u_k = \Delta u^i_k$ for the TS-PI-FC OI,
- *IF* (e_k *IS LTe AND* e_{Ik} *IS LTeI*) *THEN* $u_k = u^i_k$ for the TS-PI-FC with II.

The MAX and MIN operators are involved in the inference engine and the weighted average defuzzification method is used in both TS-PI-FCs.

V. Simulation Results

The speed control in strip winding systems can be carried out using a CCS with an inner (current) PI (or I) controller as a current controller and with one of our two versions of controllers in the external (speed) loop. The application is a strip winding system (Fig. 1), where the desired linear speed v_{ref} (reference input) must be converted in angular sped reference input, ω_{ref}, correlated to the actual value of the radius, $r(t)$ and measured angular speed $\omega(t)$. An additional correction of ω_{ref} is also necessary.

Two main aspects must be solved: the measurement or estimation of the actual value of the radius $r(t)$, and the calculation or estimation of the VMI (J_{tot}). The CCS design is next conducted and assisted by the speed controller parameter tuning and retuning. The tuning is connected to the fixed value of radius (e.g., for three points, r_{01}, r_{02}, r_{03}) for which linear benchmark-type t.f.s and fixed tuning parameters can be calculated. The modification of ω_{ref} is done in terms of

$$v_T(t) = v_S = \text{const}, \quad \omega_{ref}(t) = v_{ref} / r(t). \tag{20}$$

The presented application is a drive system with DC-m with VMI characterized by the following parameters: rated voltage $u_{an} = 24\,\text{V}$, rated current $i_{an} = 3.1\,\text{A}$, rated speed $\omega = 3000\,\text{rpm}$, rated torque $M_{en} = 0.15\,\text{Nm}$, rotor inertia $J_M = 0.18 \cdot 10^{-4}\,\text{kg m}^2$, terminal resistance $R_s = 2\,\Omega$, initial value of mechanical time constant $T_m = 0.013 s$, electrical time constant $T_a = 0.001\,\text{s}$, torque constant $k_m = 0.056\,\text{N m/A}$.

The parameters of the digital PI speed controllers were calculated for a constant T_e considering three radius values:

$$\begin{aligned} & T_e = T_a / 4 = 0.00025, p_0^{(i)} = p_0^{(m)} = 1, p_1^{(i)} = p_1^{(m)} = -1, \\ & C1-\omega:\ q_0^{(1)} = 0.0151, q_1^{(1)} = -0.0149, \\ & C2-\omega:\ q_0^{(2)} = 0.0551,\ q_1^{(2)} = -0.0549, \\ & C3-\omega:\ q_0^{(3)} = 0.026,\ q_1^{(3)} = -0.0024, \\ & C-i_a:\ q_0^{(i)} = 1.5344,\ q_1^{(i)} = -1.4656. \end{aligned} \tag{21}$$

The CCS with PI current controller and three PI speed controllers was first tested by simulation. Figs. 5 and 6 show the response of the system for a DC-m-based electric drive system with VMI for a properly modification of the reference input which will result in a corresponding increase of the drum radius and the variation of the moment of inertia.

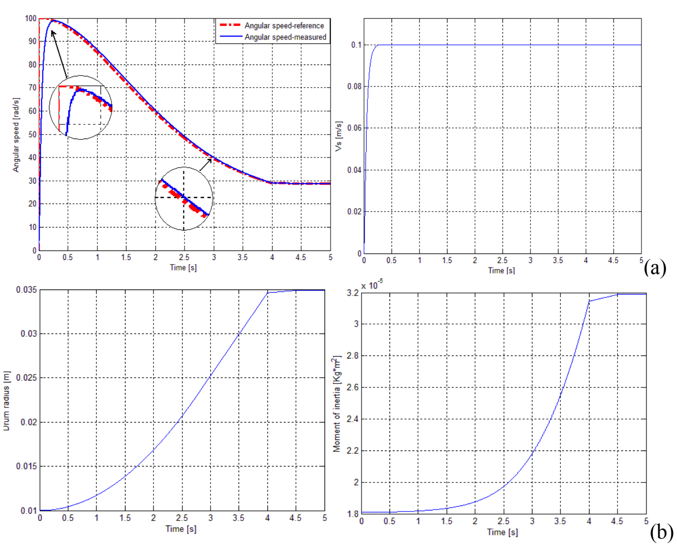


Fig. 5. Simulation results for linear control system: angular speed (reference and measured) and linear speed versus time (a), drum radius and moment of inertia versus time (b).

The use of fuzzy controllers is justified by the presence of nonlinearities and by the variable $J_{tot}(t)$. The TS-PI-FCs with OI and the TS-PI-FC with II were next tested. The values of the parameters result from: C1-ω: $T_e = 0.00025$, $k_{C1} = 26$, $T_{i1} = 0.06333$, C2-ω: $k_{C2} = 29$, $T_{i2} = 0.07433$, and C3-ω: $k_{C3} = 33$, $T_{i3} = 0.085$. The results for the two fuzzy control systems with TS-PI-FCs are presented in Figs. 7 and 8.

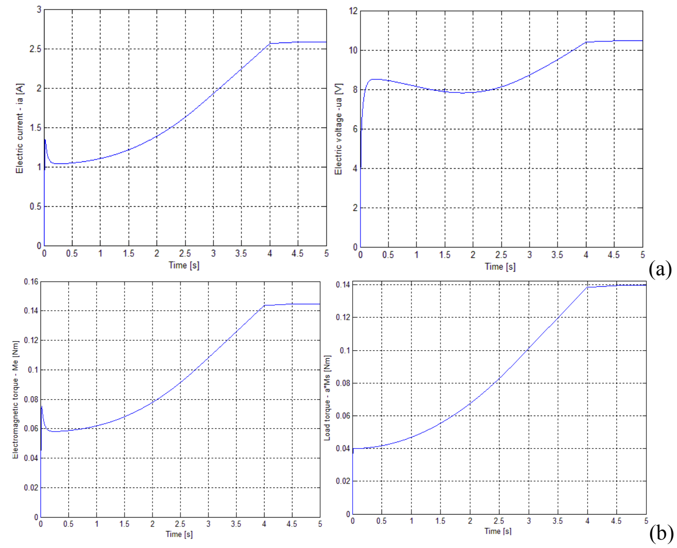


Fig. 6. Simulation results for linear control system: electric current and electric voltage versus time (a), electromagnetic torque and load torque versus time (b).

Figs. 5 to 8 show that the system responds very well in both cases. It exhibits very good control system performance expressed as reduced overshoots and settling times. Since the application has VMI, frequency domain conclusions can be drawn using the sensitivity analysis of the DC-m drive.

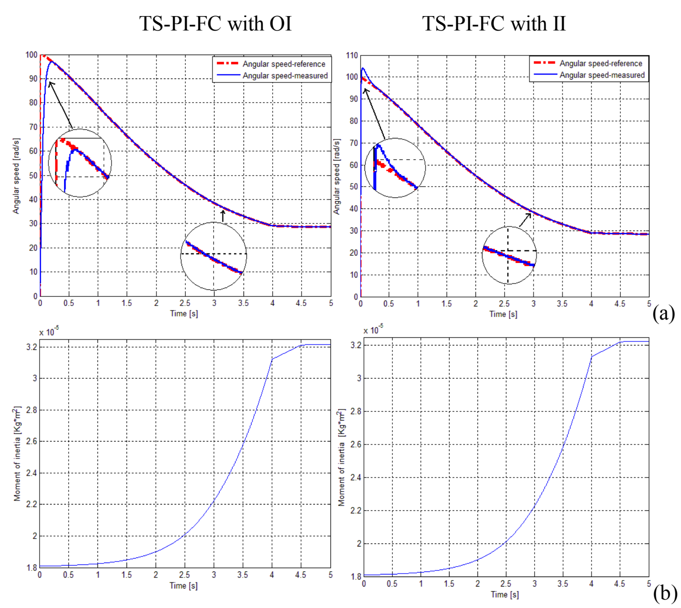


Fig. 7. Simulation results for fuzzy control systems: angular speed (reference and measured) versus time (a), moment of inertia versus time (b).

VI. Conclusion

The paper has given results concerning the design of conventional and fuzzy control solutions meant for electric drive systems with C-VR-MI-LD. Original variable structure control solutions have been proposed and embedded in two cascade control structures which involve the switching between three separately designed digital control algorithms.

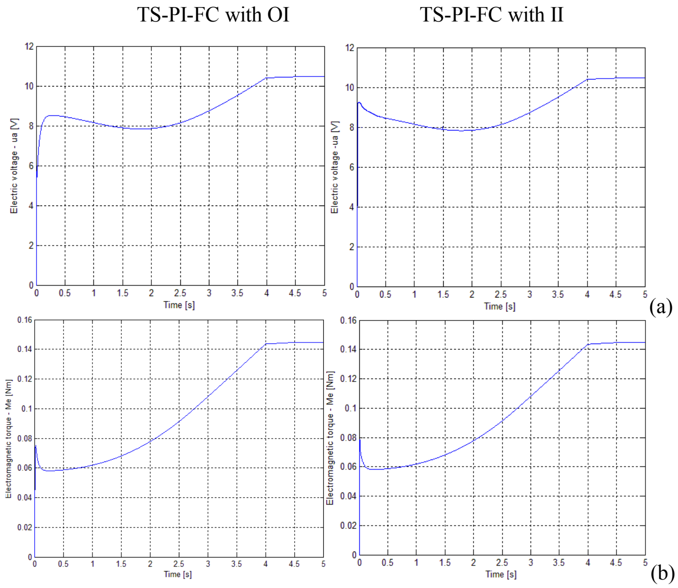


Fig. 8. Simulation results for fuzzy control systems: electric voltage versus time (a), electromagnetic torque versus time (b).

Our control solutions and design methods enlarge the areas of industrial application of the DC-m and BLDC-m drives. They can be also implemented in other control applications. Future research will be focused on the improvement of CS performance based on the treatment of load disturbance inputs by advanced control techniques [18] and structures [19]–[26].

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