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Modelling and Quadratic Dynamic Matrix Control of a DC Motor System with Non-linearities Consideration

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Abstract: DC motor models that have often been used to test and validate control algorithms, even the most robust ones, have usually been simplistic: limiting the generalization and applicability of the results obtained. This article presents a modeling approach for a DC motor system consisting of a Buck converter and driving a load at the end of the shaft, in which the nonlinearities of each of its sub-parts are taken into account in the model of the overall system. The model was simulated and its step responses were compared to those of the linear model and conventional nonlinear models with a significant difference (P-value<0.001). This model was then used to test the Fast Nonlinear Quadratic Dynamic Matrix Control (FNLQDMC). The later has demonstrated good performance in simulation in terms of setpoint tracking, constraint handling, and computational load savings during online optimization problem-solving.
Keywords: DC Motor, Nonlinearities, Modeling, control, FNLQDMC

I. INTRODUCTION

DC motors are widely used in industry due to their simple and miniaturized structure, wide and precise speed range, high torque for low input voltages, ease of reversing rotation direction while acting reversibly and returning energy to the line during braking and speed reduction times, even for large motors subjected to high loads [1]-[15]. In high-precision operations, the proven control performance of the DC motor is sought after [1], [4], [16]-[18]. However, its mechatronic nature and coupling to other devices with which it is required to operate often give rise to several sources of nonlinearities, making its modeling and hence its controllability complex, especially when they are not taken into consideration in the design of the model of the overall system on which it depends. These nonlinearities are mostly due to friction torque, converter, and the armature reaction [2], [3]. Therefore, the study of the nonlinear behavior of a DC motor constitutes a useful effort, first for obtaining a more representative model, and also for the design and validation of high-performance controllers. Indeed, DC Motors remains a good testing ground for advanced control algorithms due to its simple theory and extensibility to other disciplines [5], [7]-[9], [13], [14], [19]-[21]. In the modeling of DC Motors, the traditional approach is to limit oneself to electromechanical models (motor connected to a load) [22]. These models are generally linear. And in the contrary case, the usual tendency is to limit oneself only to the nonlinearities introduced by the friction torque of the load. To this end, several models have been proposed and used to accurately approximate the nonlinear behavior of the rotating mechanical load of the DC Motor in order to improve the performance of its control system [1], [10], [12], [15], [23]-[25]. However, Ibbini and Zakaria in [26] demonstrated that DC Motors are generally considered as linear systems by neglecting the effect of the induced magnetic reaction or by assuming that the compensating windings eliminate such an effect. Thus, they proposed a variable model of the mechanical constant of the motor to take into account the nonlinearities of the induced reaction in the DC Motor model. This model will be used in [9] for the validation of an adaptive control algorithm based on neural networks. However, in the model of [26], the nonlinearities of the friction torque are neglected.

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Lyshesvki in [26] later demonstrated that the static converter must be taken into account in the formulation of the DC Motor model and that its nonlinear dynamics cannot be neglected in practice. In industry, the DC Motor does not work alone, it is often coupled to a speed controller that serves as its control in the torque-speed plane. Thus, a new modeling approach for the DC motor while adding the converter to the classical electromechanical system has emerged [17], [27]. One of the major advantages of this model is the possibility of using the converter duty cycle to control the entire system directly. However, in the model of [17], the nonlinearities of the friction torque and those of the armature reaction are neglected.

This paper deals with the modeling of a DC Motor as a mechatronic system consisting of an electronic part, an electrical part, and a mechanical part, in which the nonlinearities of each of these sub-parts are explicitly taken into account in the formulation of the model of the overall system. A permanent magnet DC motor driving a mechanical load at the end of the shaft and coupled to a Buck converter is considered. The Fast Nonlinear Quadratic Dynamic Matrix Control (FNLQDMC) algorithm of [28] will be tested by this model. This paper is structured as follows: after the introduction in section 1, the system is modeled in section 2, section 3 briefly describes the FNLQDMC algorithm, results are presented and analyzed in section 4, and section 5 presents the conclusion.

II. MODELING OF DC MOTOR SYSTEM

Unlike most of the DC motor systems available in the literature, whose studies are often limited to the individual DC motor without taking into account the effects of its interaction with other systems with which it is required to operate, this paper describes a system in which the DC motor is only a sub-part of a system consisting of a Buck converter and a mechanical load at its shaft as illustrated in Fig. 1.

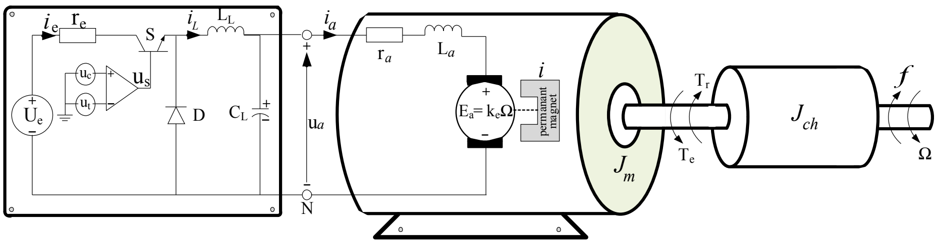

Fig. 1 DC Motor system

The system shown in Fig. 1 is a typical case of a mechatronic system consisting of three physical parts: the electronic part consisting of the Buck converter, the electrical part consisting of the DC motor itself, and the mechanical part consisting of the rotating load. The operating principle of such a mechanism is extensively detailed in [17]. The modeling method used in this work is based on the decomposition, analysis, and concise modeling of each sub-part of the system, taking into account their nonlinearities. The model of the overall system will be the average equivalent model of the three subsystems.

A. Formulation Of The Electronical Part Equations

The electronic part of the system shown in Fig. 1 can be isolated as depicted in Fig. 2.

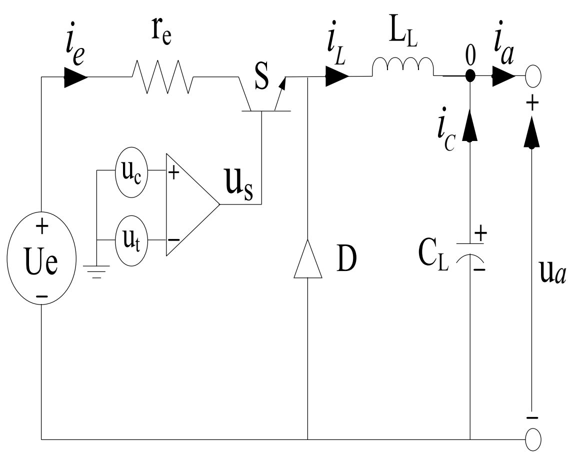

Fig. 2 Electronical part of DC motor system

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Fig. 2 shows the circuit of the Buck power static converter. This circuit consists of a DC voltage source U_e, a power switch S, a comparator that generates the switch control signal U_s by comparing the amplitude of the control voltage u_c with the corresponding triangular signal U_t, and a freewheeling diode D. S has an internal resistance r_e.

A low-pass filter with inductance L_L and capacitance C_L is used to ensure the output voltage u_a ripple. Equations (1) and (2) describe the dynamic behavior of the electronic circuit of the converter in steady-state as described in [14].

$$\frac{du_a}{dt} = \frac{1}{C_L}(i_L - i_a) \quad (1)$$

$$\frac{di_L}{dt} = \frac{1}{L_L}[(d_D(U_e - r_e i_L) - u_a)] \quad (2)$$

d_D is the duty cycle of the converter and its expression is $d_D = \frac{u_c}{u_{\text{tmax}}} \in [0\ 1]$, since $u_c \in [0\ u_{\text{cmax}}]$

$\Rightarrow u_{\text{tmax}} = u_{\text{cmax}}$. We can then write (3):

$$\frac{di_L}{dt} = \frac{1}{L_L}\left[\left(\frac{U_e}{u_{\text{tmax}}} - \frac{r_e}{u_{\text{tmax}}} i_L\right)u_c - u_a\right] \quad (3)$$

According to [14], the nonlinearity source of this subsystem is the internal resistance r_e of the transistor S when it is considered non-zero ($r_e \neq 0$).

B. Formulation Of The Electrical Part Equations

The electrical part of the system shown in Fig. 1, isolated in Fig. 3, essentially contains the motor armature circuit and its excitation. This circuit consists of the armature resistance and inductance r_a and L_a, respectively, an electromotive force E_a, and an electromagnet.

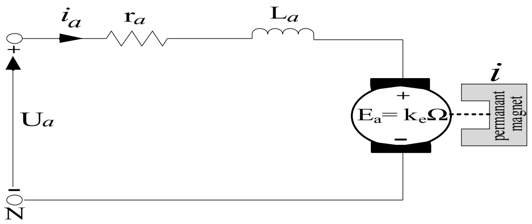

Fig. 3 Electrical part of DC motor system

Since the motor excitation is provided by an electromagnet, its excitation current is assumed to be constant ($i \approx$ cst). Applying Kirchhoff's second law to the circuit in Fig. 3 yields equation (4), which governs the dynamic behavior of the current flowing in the electrical part of the DC motor [17].

$$\frac{di_a}{dt} = \frac{1}{L_a}(u_a - r_a i_a - k_e \Omega) \quad (4)$$

Where k_e is the electrical constant, i_a and u_a are the output variables of the converter described in (2.2).

To account for the effect of the armature reaction of the motor armature, equation (5) from [26] is considered.

$$k_e = A + Bi_a \quad (5)$$

Where A is the machine constant at no-load, and B is a small negative number representing the effect of the induced current on the machine constant. Thus, (5) in (4) yields equation (6), representing the nonlinear dynamics of the electrical part of the DC motor [26].

$$\frac{di_a}{dt} = \frac{1}{L_a}[u_a - r_a i_a - (A + Bi_a)\Omega] \quad (6)$$

II.3. Formulation of the mechanical part equations

Fig. 4 shows the mechanical part of the system consisting of the frame, motor shaft, and rotating load.

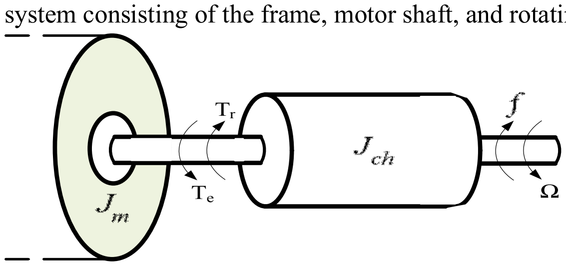

Fig. 4 Mechanical part of DC motor system

Considering the fact that the electromechanical torque of the motor is a function of its armature current ($T_e = k_m i_a$), and applying the first fundamental law of dynamics, we obtain the expression for the angular velocity variation of the motor (equation (7)).

$$\frac{d\Omega}{dt} = \frac{1}{J_t}(k_m i_a - f\Omega - T_r) \quad (7)$$

Where $J_t = (J_m + J_{ch})/2$ represents the equivalent inertia of the system, with J_m and J_{ch} being the moments of inertia of the motor and load, respectively, k_m is the torque or mechanical constant, T_r is the resisting torque imposed on the motor by the load, also known as the Coulomb friction torque, and f is the viscous friction coefficient. One nonlinearity of this subsystem is obtained by taking into account the effect of the armature reaction (5) from [26] in (7), with $k_m = k_e$, yielding equation (8).

$$\frac{d\Omega}{dt} = \frac{1}{J_t}(A i_a + B {i_a}^2 - f\Omega - T_r) \quad (8)$$

Another nonlinearity is obtained by considering the variable model of the resisting torque (9) from [1], [16], [25], [28].

$$T_r(\Omega) = T_c\, sgn(\Omega) + (T_s - T_c) e^{-\alpha|\Omega|} sgn(\Omega) \quad (9)$$

Where T_c represents the Coulomb friction torque, T_s the static friction torque, and α the mechanical time constant. With $sgn(\Omega) = \begin{cases} 1 & \Omega > 0 \\ 0 & \Omega = 0 \\ -1 & \Omega < 0 \end{cases}$, et $\alpha \in R^+$.

Substituting (9) into (8) in its expression yields the expression of the rotational dynamics behavior of the mechanical part of the system (10).

$$\frac{d\Omega}{dt} = \frac{1}{J_t}(A i_a + B {i_a}^2 - f\Omega - T_c\, sgn(\Omega) - (T_s - T_c) e^{-\alpha|\Omega|} sgn(\Omega)) \quad (10)$$

By combining the different models of each of the subparts of the system found in sections (2.1), (2.2), and (2.3) (equations (1), (3), (6) and (10)), the average equivalent nonlinear state-space model of the DC motor system described in fig.1, taking into account the nonlinearities of the converter, of the armature reaction, and that of the friction torque is obtained with equation (11).

$$\begin{cases} \frac{di_a}{dt} = -\frac{r_a}{L_a} i_a - \frac{B}{L_a} i_a \Omega - \frac{A}{L_a}\Omega + \frac{1}{L_a} u_a \\ \frac{d\Omega}{dt} = \frac{B}{J_t} i_a^2 + \frac{A}{J_t} i_a - \frac{f}{J_t}\Omega - \frac{T_c}{J_t} sgn(\Omega) - \frac{(T_s - T_c)}{J_t} e^{-\alpha|\Omega|} sgn(\Omega) \\ \frac{di_L}{dt} = -\frac{1}{L_L} u_a + \left(\frac{U_e}{L_L u_{\mathrm{tmax}}} - \frac{r_e}{L_L u_{\mathrm{tmax}}} i_L\right) u_c \\ \frac{du_a}{dt} = -\frac{1}{C_L} i_a + \frac{1}{C_L} i_L \\ \text{with } u_c \in [0\ u_{\mathrm{cmax}}] \end{cases} \quad (11)$$

III. FNLQDMC ALGORITHM

Consider any process described by a continuous nonlinear model (12):

$$\begin{cases} \dot{x}(t) = f(x(t), u(t)) \\ y(t) = h(x(t), u(t)) \end{cases} \quad (12)$$

where x, u, and y are the state, input, and output vector, respectively.

The Fast Nonlinear Quadratic Dynamic Matrix Control (FNLQDMC) algorithm is described by the flowchart in Fig.5. This algorithm was developed in [29] to solve the computation time problem of classical NLQDMC.

The FNLQDMC is based on the idea that a constrained optimization problem in some cases gives the same solutions as the associated problem without constraints, which can be solved faster. This is particularly interesting when the problem without constraint admits an explicit solution, as in the case of quadratic problems. In the FNLQDMC algorithm, the scheme is similar to that of the conventional NLQDMC.

The major difference is that the optimization problem is first solved analytically without constraints and a constraint violation test is performed on each sample. Then, the constrained optimization problem is solved only in cases where at least one constraint has been violated. The details on the definition and determination of the variables presented in fig. 5 relating to the construction of the FNLQDMC predictive controller algorithm are clearly explained in [29].

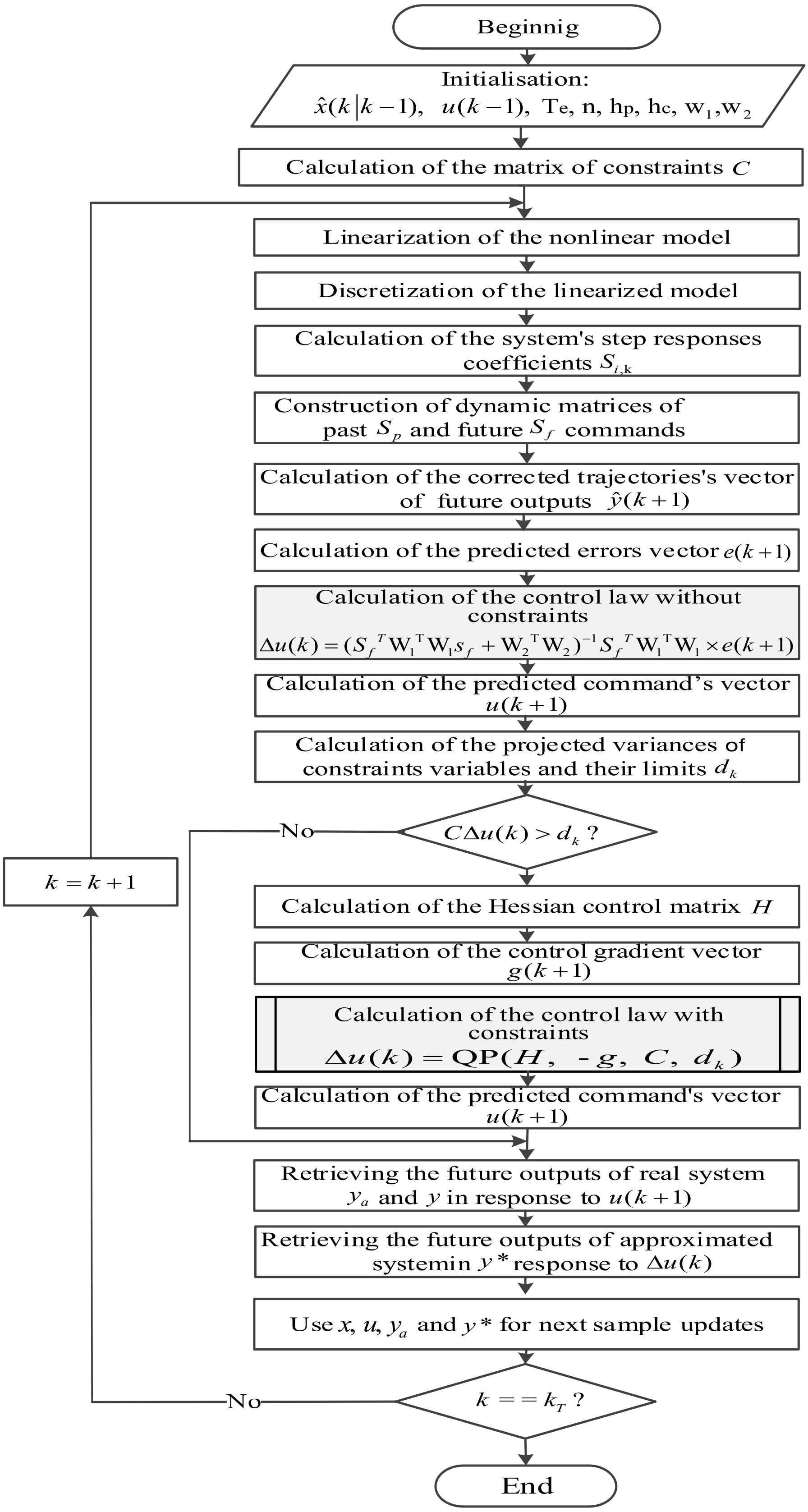

Fig. 5 Flowchart of the FNLQDMC algorithm

IV. RESULTS AND ANALYSES

The obtained model of the system (11) was simulated in the Matlab environment using the ode45 solver for 0.2s. In addition, four other simplified models, including the linear model, the one considering only the nonlinearity of the converter, the one considering only the nonlinearity of the armature reaction, and the one considering only the nonlinearity of the friction torque of the same system were also simulated under the same conditions. Table 1 provides the values of the system settings. Most of these values were taken from [17, 26].

TABLE I
SYSTEM SETTINGS

Settings	Designation	Value
U_e	Supply voltage	24 V
r_e	converter internal resistance	0.05 Ω
u_c	Comparator input voltage	[0 5 V]
L_L	Filter inductance	0.007 H
C_L	Fiter capacitance	0.008 F
r_a	Armature resistance	1 Ω
L_a	Armature inductance	0.005 H
k_e	Voltage constant	0.1 V.s/rad
k_m	Torque constants	0.1 N.m/A
A	No load machine constant	0.57
B	Armature current effet constant	-0.1
f	Viscous friction coefficient	0.2 N.m.s
J_t	Equivalent moment of inertia	0.02 Kg.m2
T_c	Coulomb friction torque	0.5 N.m
T_s	Static friction torque	0.5044552 N.m
α	Time constant	0.2
A= *Amp,* V=*Volt,* Ω=*Ohm,* H=*Henri,* F= *Farad,* s=*second,* rad=*radian,* N=*Newton,* kg=*kilogram,* m=*meter*		

Fig. 6 shows the comparative step responses of the complete DC motor system model and those of the conventional simplified models, respectively, the armature currents i_a (A) (Fig.6a), and the angular velocities Ω (rad/s) (Fig.6b).

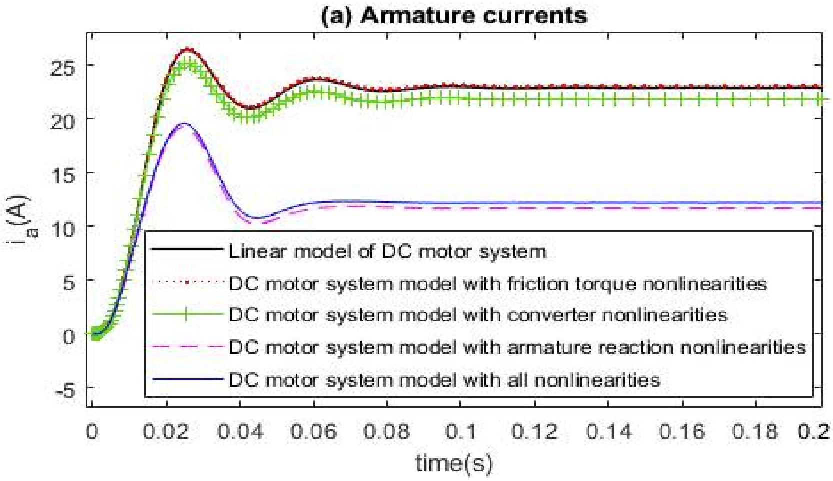

Fig. 6a Comparative step responses of models: currents

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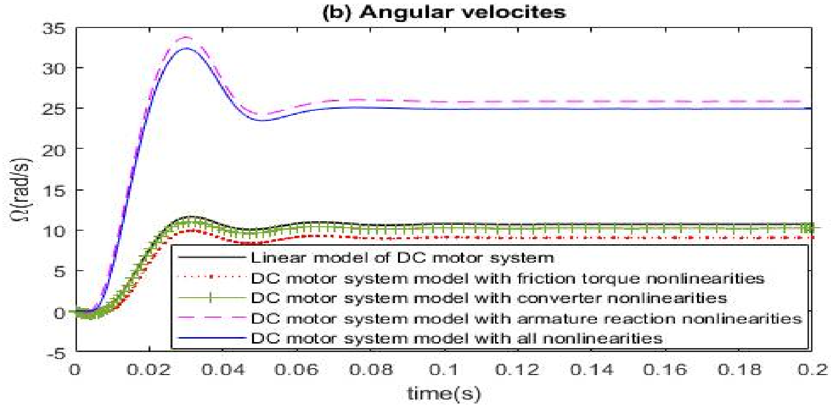

Fig. 6b Comparative step responses of models: velocities

Table 2 shows the Mean Square Errors (MSE) of the different models (MSEc for currents, and MSEv for velocities). They are determined for N samples defined for i elements of the step response of a model j with respect to the linear model considered here as the reference.

$$MSE_{(j)} = \frac{1}{N}\sum_{i=1}^{N}[y_{\mathrm{LM}}(i) - y_j(i)]^2 \quad (13)$$

From Fig.6, one can already observe the difference in the step response trajectories of the different models, which is confirmed by the P-values of the MSEs of the step responses of these models.

TABLE II
DEVIATION BETWEEN MODELS (MSE)

Obtain models	(MSE)	
	MSEc	MSEv
DC motor system model with friction torque nonlinearities	0.0121	0.3327
DC motor system model with converter nonlinearities	1.0550	0.2277
DC motor system model with armature reaction nonlinearities	86.7893	269.6492
DC motor system model with all nonlinearities	86,7325	215,9047
	P-valus	
	Pc<0.001	Pv<0.001

Indeed, the P-value of the MSEc (Pc) and that of the MSEv (Pv), both less than 0.001 in Table 2, show that there is a significant difference between the different models, proving that the obtained DC motor system model is significantly different from those that completely or partially neglect the nonlinearities of other subsystems of the DC motor system. It is also observed that the model incorporating the nonlinearity of the armature reaction is the one that deviates the most from the linear model due to its higher MSEs (MSEc=86.7325 and MSEv=269.6492), indicating that the nonlinearities of the armature reaction have the greatest influence on the complete DC motor system model. The obtained nonlinear DC motor system model is used here to test the FNLQDMC algorithm in simulation, so the system is not physical. From a control point of view, this is a 1x2 MIMO nonlinear system with a hard constraint on the manipulated variable u_c (converter control voltage).

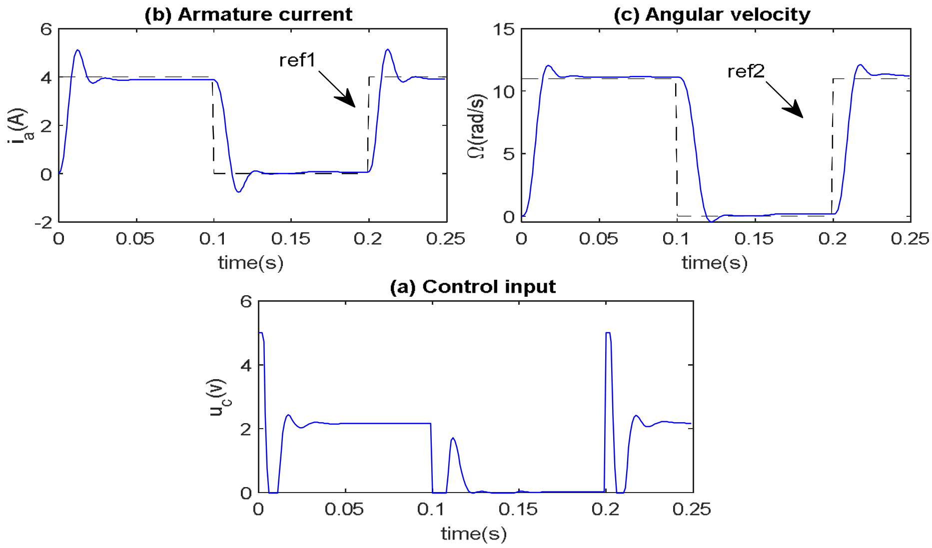

Fig. 7 Results of FNLQDMC control of the DC motor system: (a)-Control input, (b)-Armature current, (c)-angular velocity

The controlled outputs are the armature current i_a and the motor angular velocity Ω. The objective is to control the motor angular velocity and armature current by manipulating the chopper duty cycle via the comparator control voltage. According to [30], the effective parameter tuning values of the controller are chosen as follows: $T_e = 1\ ms$, $n = 150$, $h_p = 9$, $h_c = 1$, W_1 and $W_2 = 1$ respectively the sampling period, model horizon, prediction horizon, control horizon, control and error weighting matrices. Figure 6 shows the results of the FNLQDMC control of the system.
These results show that the control actions delivered by the control (Fig.7(a)) remain within the allowed constraints, while the controlled outputs Fig.7(b) and (c) remain around their respective setpoints with very little deviation. In addition, for the chosen setpoint profile, the constrained optimization problem was only solved 41 times out of $k_T = 250$ samples, resulting in an economy of 209 times that the quadratic program (QP) would have been called if conventional NLQDMC was used. These results support those of [29] and once again confirm the performance of FNLQDMC.

V. CONCLUSION

In this work, a modeling approach for the DC motor has been presented. A permanent magnet DC motor system, consisting of an electronic part, an electrical part, and a mechanical part, has been considered. This approach is based on the decomposition and consideration of the nonlinearities of each of these functional subparts of the motor in formulating the complete model of the system. At the end of the process, the obtained model was compared to the simplistic models of the same system with the simplifying assumptions of the conventional models. The simulation results obtained show a significant difference between the models and dominance of the nonlinearities of the armature reaction on the complete system model. Used to execute the FNLQDMC algorithm, the latter presented good simulation performance in terms of setpoint tracking, constraint handling, and calculation load economy during online optimization problem-solving. These results encourage the use of the proposed complete nonlinear model of the DC motor system for the implementation and validation of high-performance control algorithms. However, it should be noted that the results presented in this work are based on simulations, and further experimental validation is necessary to confirm the effectiveness of the proposed approach in practical applications. Furthermore, the modeling approach presented in this work can be extended to other types of motors and systems with nonlinearities, offering a promising research direction for control engineers and researchers in the field of nonlinear control systems.

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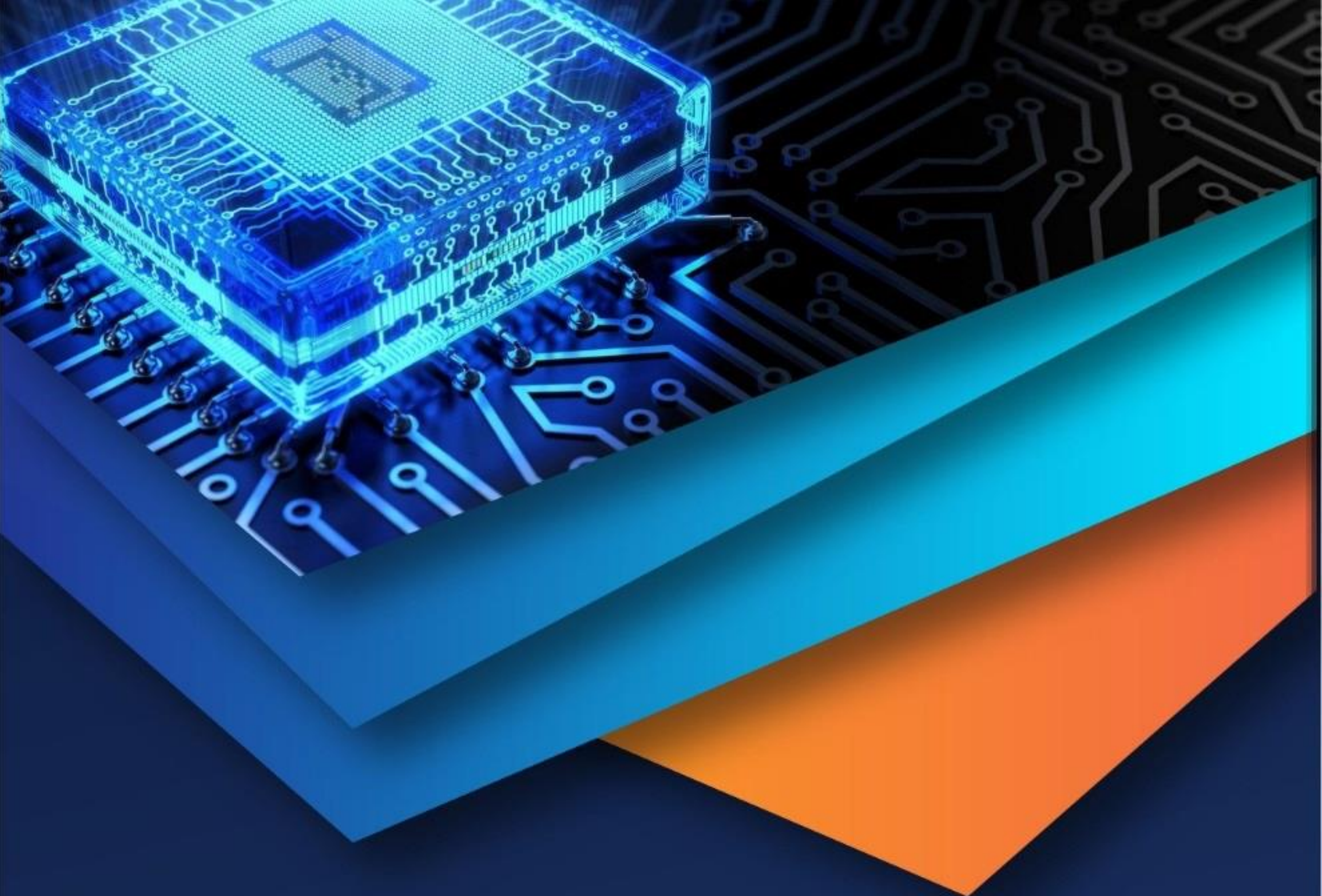

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