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Improvement of the linear quadratic regulator control applied to a DC-DC boost converter driving a permanent magnet direct current motor

Adel Bouchahed[1,3], Mohamed Assabaa[2,3], Abdellah Draidi[3], Fateh Makhloufi[1,3], Ahmed Belhani[1]
[1]Laboratoire Satellites Intelligence Artificielle Cryptographie et Internet des Objets, Department of Electronics, Faculty of Science and Technology, University of Constantine 1, Constantine, Algeria
[2]Laboratoire de Traitement de Signal, Department of Electronics, Faculty of Science and Technology, University of Constantine 1, Constantine, Algeria
[3]Electromechanical Department, Institute of Applied Sciences and Techniques, University of Constantine 1, Constantine, Algeria

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ABSTRACT

This article discusses a new robust control technique that enables the DC-DC boost converter driving a permanent magnet direct current (PMDC) motor to operate in high static and dynamic performances. The new technique is based on the design of a both linear quadratic regulator (LQR) and linear quadratic regulator-proportional integral (LQR-PI) type controllers, which have the advantage of eliminating oscillations, overshoots and fluctuations on different characteristics in steady-state system operation. In order to increase the output voltage, the LQR regulator is combined with a first-order system represented in the form of a closed-loop transfer function, the latter raising the output voltage to 24 volts, this voltage is enough to drive the permanent magnet direct current motor. The contribution of this paper is the creation of a robust control system represented in the form of a hybrid corrector able to regulate steady-state and transient disturbances and oscillations as well as to increase DC-DC boost converter output voltage for the PMDC motor to operate at rated voltage. The results of the three control techniques are validated by MATLAB Simulink.

Corresponding Author:

Adel Bouchahed
Laboratoire Satellites Intelligence Artificielle Cryptographie et Internet des Objets, Department of Electronics, Faculty of Science and Technology, University of Constantine 1
Constantine, Algeria
Email: bouchahed.adel@umc.edu.dz

1. INTRODUCTION

DC-DC converters play a very important role in several technical areas such as: manufacturing industry, renewable energies, especially solar photovoltaic and hybrid systems (PV-wind). These converters facilitate the management of the direct current (DC) energy; therefore, it can supply DC electrical systems accurately. Several research have been carried out to control boost, Buck and mixed converters, including a robust-optimal control strategy allows to track and control DC-DC boost converter output voltage errors. The strategy used is based on the design of an optimized fractional-order proportional-integral (FoPI) controller that removes oscillations, overshoots, undershoots and steady-state fluctuations. In order to improve the error convergence rate during a transient response, the FoPI controller is supplemented by a pre-stage nonlinear error modulator, the latter combines the variations of the error and the error derivative via the signed distance method, the control system realized can reject external disturbances such as load transients and input fluctuations, which gives adequate operation to the DC-DC boost converter [1]. A linear quadratic integral

(LQI) controller is used for DC motors optimum speed regulation. It allows the motor to run without disturbances and fluctuations in steady-state for different responses, the LQI controller is complemented by a Lyapunov-based model reference adaptation system (MRAS) that modulates the controller gains adaptively while maintaining the asymptotic stability of the controller [2]. An adaptive and collaborative speed controller used to control a permanent magnet direct current (PMDC) motor; this controller is designed by a proportional-integral (PI) regulator and a linear-quadratic regulator (LQR), the adaptive combination of the two controllers brings an improvement on the transient and steady-state responses and the removal of the disturbances due to load-torque variations [3].

A theoretical study based on a mathematical model of the boost converter where the Lyapunov function has made closed loop current and the voltage control possible, nevertheless Lyapunov function does not give the boost converter an overall stability, the monodromy matrix which interfere on systems nonlinear dynamic behavior allows stability of the boost converter [4]. An adaptive controller proposed to improve the performance of the buck converter which presents a time-bound estimate of the unknown system uncertainties and the exogenous disturbances, moreover an online estimator is carried out to reconstruct the uncertainty incurred, the additive uncertainty estimated then passes to the nominal backstepping controller for further finite-time compensation [5]. An estimation based on the sliding mode controller, which is able to provide reference voltage tracking in the presence of uncertainties due to input voltage and reference voltage variations, this closed loop control gives a system stability [6]. A design of a robust control law based on pulse-width modulated (PWM) conditions; the strategy applied to a parallel interconnection of DC/DC converters [7]. A design of a dynamic sliding mode control based on an internal model for a DC-DC boost converter is proposed in order to reject system disturbances [8].

A design of a continuous signal generator used to control electrocardiographic (ECG) signals using a buck converter was proposed, it consists of the application of sliding mode controller on both current and voltage loops to impose the tracking of ECG voltage reference, this proposed controller is able to perform robustly regarding voltage input dynamics disturbances [9]. A novel DC-DC buck converter control technique based on generalized proportional integral observer (GPIO) is designed to estimate localized disturbance, improve anti-disturbance buck converter and transient performances. The PWM command is managed by the dynamic prescribed performance sliding mode control-GPIO (DPPSMC-GPIO) controller [10].

A finite control set model predictive control (FCS-MPC) method combined with a Kalman observer is designed to obtain the load variation and model correction, which can decrease the disturbance, moreover, it can estimate voltage error and its integration [11]. In order to solve the problem of regulating the buck converter output voltage under current constraint, a nonlinear algorithm is proposed so that the output voltage follows the reference voltage quickly in a finite time [12]. The speed control of PMDC motor by a buck converter using the adaptive backstepping controller and Legendre neural network allows to estimate the uncertainties online then to compensate them effectively during the robust control action. The stability of the closed-loop system under the action of the proposed controller and online adaptive learning laws are proved using Lyapunov's stability criterion [13]. A new fast learning neural network used for PMDC motor load torque estimation, angular rate control is generated by DC-DC buck converter which is linked to adaptive backstepping controller, the approach used in this system gives great stability using the Lyapunov criterion [14]. To increase the boost converter output voltage, a new improvement technique is based on output voltage closed-loop control which is designed by Simulink automatic code generation, the technology that makes the output voltage 170 V is the TMS320F2833 32-bit floating-point processor [15]. A new control technique highlights how nonlinear controllers based on reinforcement learning can improve the boost DC-DC converter dynamic performance compared to standard controllers [16].

The research work carried out in this article is based on the design of three LQR control techniques, which are LQR, LQR-PI and $LQR - \frac{K_c}{Ts+1}$. These techniques are applied to the DC-DC boost converter driving a PMDC. The controllers designed gave very efficient results in terms of voltage, current, power, angular speed and motor torque. Our contribution to the research works mentioned above is the design of a robust control system based on the linear quadratic regulator control theory $LQR - \frac{K_c}{Ts+1}$; this type of controllers removes oscillations, disturbances and fluctuations from the DC-DC boost converter outputs (voltage, current and power) therefore, this gives the PMDC motor a steady-state stable drive under load variation. The results obtained are simulated by MATLAB Simulink software.

2. SYSTEM DESCRIPTION

The PMDC motor is controlled by the boost converter where the variation of the speed is obtained by the output voltage of the boost converter using a closed servo loop, the circuit of Figure 1 represents an association of two assemblies, the first consists of a fixed DC source V_e, inductor L, load resistor R, diode D, a capacitor C, the current flowing through the coil L i_L, an output current I_{dc}, an output voltage V_{dc} and power electronics switch S_W , the second assembly represents the circuit of the PMDC motor which includes an armature inductance L_{ar}, armature resistance R_{ar}, motor inertia J, a viscous friction f and an angular velocity ω.

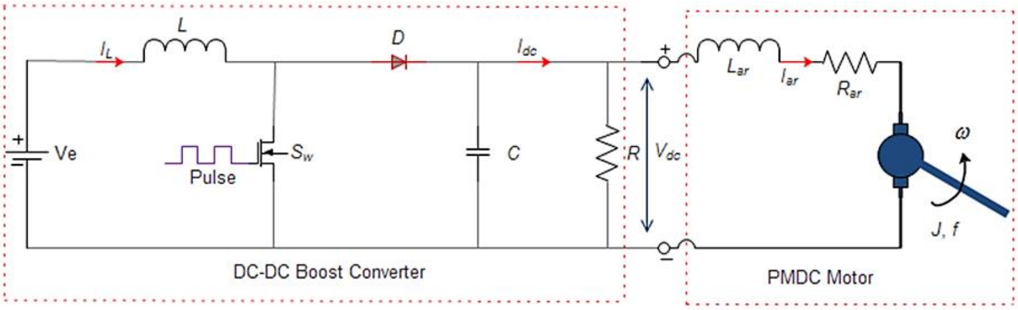

Figure 1. PMDC motor drive by boost converter

From the diagram of Figure 1 we can get the mathematical models of the PMDC and the boost converter. The equations governing the operation of the PMDC motor are [17]–[21]:

$$V_{ar}(t) = L_{ar}\frac{di_{ar}}{dt} + R_{ar}i_{ar}(t) + e_b(t) \tag{1}$$

$$T_e(t) = J\frac{d\omega(t)}{dt} + f\omega(t) + T_l(t) \tag{2}$$

$$T_e(t) = K_t i_{ar}(t) \tag{3}$$

$$e_b(t) = \omega(t)K_b \tag{4}$$

with $V_{ar}(t)$ armature voltage of PMDC motor, $i_{ar}(t)$ armature current, $T_e(t)$ motor torque, $T_l(t)$ load torque, K_t torque constant, K_b electromotive force (EMF) constant and $e_b(t)$ the EMF.

The equations governing the boost converter operation are as follows [22]–[24]. The switch S_w is closed, the diode D is blocked therefore, $t_0 \le t \le t_0 + dT$, we will have the (5) to (7),

$$L\frac{di_l}{dt} = V_e \tag{5}$$

$$C\frac{dv_{dc}}{dt} = -\frac{v_{dc}}{R} \tag{6}$$

$$i_c + i_{dc} = 0 \tag{7}$$

The switch S_w is open, then the diode D is on therefore, $t_0 + dT \le t \le t_0 + T$, we obtain the (8) to (10),

$$L\frac{di_l}{dt} = V_e - V_{dc} \tag{8}$$

$$C\frac{dv_{dc}}{dt} = i_l - \frac{v_{dc}}{R} \tag{9}$$

$$i_c + i_{dc} = i_l \tag{10}$$

The dynamic equations of the boost converter in continuous conduction regime are given as (11) and (12),

$$L\frac{di_L}{dt} = V_e - V_{dc}(1-u) \tag{11}$$

$$C\frac{dV_{dc}}{dt} = i_L\,(1-u) - \frac{V_{dc}}{R} \tag{12}$$

with u is the Mosfet control signal. We put: $x_1 = i_L$ et $x_2 = V_{dc}$ the (11) and (12) become:

$$\dot{x}_1 = \frac{V_e}{L} - \frac{x_2(1-u)}{L} \tag{13}$$

$$\dot{x}_2 = \frac{x_1\,(1-u)}{C} - \frac{x_2}{RC} \tag{14}$$

The system parameters are the inductance of the coil L in [H], the capacitance of the capacitor (C) in [F] and the load resistance R in [Ω]. The state variables are the current in the coil and the voltage across the capacitor. The control signal u is between {0;1} and it indicates the state of the switch S_w: open for 0 and closed for 1. It can be replaced by its average value over a chopping period d which represents the duty cycle $d = T_{on}/T_s$ where T_{on} is the conduction time and T_s is the chopping period.

At the equilibrium point the derivatives of the average states are zero and the average order of u_m is equal to a constant value $\bar{u}_m$,

$$0 = V_e - \bar{V}_{dc}(1 - \bar{u}_m) \tag{15}$$

$$0 = \bar{i}_l\,(1 - \bar{u}_m) - \frac{\bar{V}_{dc}}{R} \tag{16}$$

from (11) and (12) we can get the average states at equilibrium of the boost converter:

$$\bar{V}_{dc} = \frac{V_e}{(1-\bar{u}_m)} \tag{17}$$

$$\bar{i}_l = \frac{1}{(1-\bar{u}_m)} \cdot \frac{V_e}{R} \tag{18}$$

The normalized static characteristic of the boost converter is given as (19),

$$\frac{\bar{V}_{dc}}{V_e} = \frac{1}{(1-\bar{u}_m)} \tag{19}$$

The linearized model of the boost converter based on the average equilibrium voltage which is (20) to (22),

$$u = d.V_e \tag{20}$$

$$\bar{u}_m = \frac{d-1}{d} \tag{21}$$

$$\bar{i}_l = d^2 \cdot \frac{V_e}{R} \tag{22}$$

The average model of the boost converter as a state is as (23),

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}0 & -\frac{1}{dL}\\ \frac{1}{dC} & -\frac{1}{RC}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} + \begin{bmatrix}d\frac{V_e}{L}\\ d^2\frac{V_e}{RC}\end{bmatrix}u_m \tag{23}$$

The linearization of the average model around the equilibrium point is (24),

$$[\dot{e}] = \begin{bmatrix}0 & -\frac{1}{dL}\\ \frac{1}{dC} & -\frac{1}{RC}\end{bmatrix}[e] + \begin{bmatrix}d\frac{V_e}{L}\\ d^2\frac{V_e}{RC}\end{bmatrix}e_u \tag{24}$$

with:

$$e = \begin{bmatrix}i_l & \bar{i}_l\\ V_{dc} & \bar{V}_{dc}\end{bmatrix} \tag{25}$$

$$e_u = u_m - \bar{u}_m \tag{26}$$

2.1. LQR control of boost converter

From the boost converter equations, we can design the control law based on LQR, linear quadratic regulator-proportional integral (LQR-PI) and the hybrid control $LQR - \frac{K_c}{Ts+1}$ methods in the form of state (27),

$$\dot{x} = Ax(t) + Bu(t)$$
$$y = Cx(t) \quad (27)$$

with x is the state vector, u the input vector, y the output vector, *A* the state matrix, *B* the control matrix, and *C* the output matrix.

To control the boost converter with high static and dynamic performances, we represent the system of state (23) in the form of a closed loop. From this state equation we designed a control system based on the linear quadratic regulator technique which allows the DC-DC converter to operate without disturbances and oscillations and which gives great stability for different characteristics (current and voltage). The Figure 2 represents an LQR type corrector applied to the DC-DC boost converter:

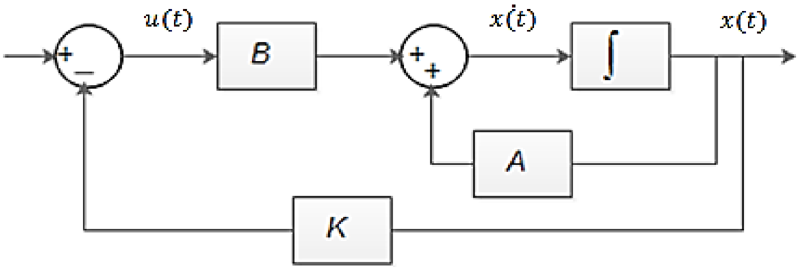

Figure 2. Main structure of the LQR corrector

where K is the gain matrix, so the control vector equals (28).

$$u(t) = -K.x(t) \quad (28)$$

To improve the performance of the boost converter control, we apply the infinite horizon *LQR* theory where the criterion used is as (29) [25]–[28]:

$$J = \frac{1}{2}\int_0^{\infty}(x^T(t)Qx(t) + u^T(t)Ru(t))dt \quad (29)$$

If the control is linear with invariant time, it becomes a constant state feedback control where the gain matrix *K* is expressed by (24) and *P* expressed in the algebraic Riccati (30).

$$P(t)A + A^TP(t) - P(t)BR^{-1}B^TP(t) + Q = 0 \quad (30)$$

with $Q \geq 0$ and $R > 0$, symmetric matrices

To stabilize the system, we apply the theory of the state feedback looped system induced by the optimal control (31).

$$u(t) = -R^{-1}B^TPx(t) \quad (31)$$

where P is the solution of Riccati's algebraic equation, it is asymptotically stable if: The $\{A, B\}$ pair is controllable and the $\{A, \sqrt{Q}\}$ pair is detectable. Thus, the matrix *P* is positive definite if and only if $\{A, \sqrt{Q}\}$ is completely observable. The eigenvalues of the matrix $[A - BR^{-1}B^TP]$ are then all with negative real part. The transfer function of the PI corrector is (32),

$$F_{PI}(s) = K_P + K_I\frac{1}{s} \quad (32)$$

From (11), (12) and (24) we will design the transfer function of the boost converter:

$$F_{Boost}(s) = \frac{V_{dc} - \frac{V_{dc} \cdot L}{R(1-d)^2} s}{-\frac{dLC}{(1-d)^2} S^2 - \frac{dL}{(1-d)^2} S + 1} \quad (33)$$

The closed loop transfer function of the full system is (34).

$$F_{CLT} = \frac{F_{PI}(s).F_{Boost}(s)}{1 + F_{PI}(s).F_{Boost}(s)} \quad (34)$$

By calculating the numerator and denominator of the closed-loop transfer function, then comparing the denominator with the third-order characteristic equation represented as (35).

$$(S + a)^3 = S^3 + 3aS^2 + 3a^2S + a^3 \quad (35)$$

From the characteristic (35) and the denominator of the (34) we deduce the gains of the proportional integral corrector (PI), with: K_P is the proportional gain and K_I the integral gain. The *LQR*, *LQR-PI* and $LQR - \frac{K_c}{Ts+1}$ control system is represented by Figure 3.

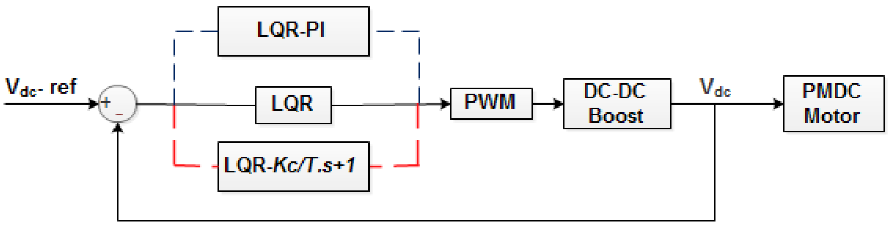

Figure 3. Control of the boost converter driving a PMDC motor

3. SIMULATION RESULTS

To obtain different results, the parameters of the DC-DC boost converter and of the PMDC motor are given in Tables 1 and 2. Table 1 gives an estimated parameter of PMDC motor like armature resistance and inductance, back electromotive force constant, torque constant, moment of inertia and viscous friction coefficient. Whereas Table 2 gives an estimated parameters of DC-DC boost converter like input DC voltage, switching frequency, resistor load, boost inductor, boost capacitor, output DC voltage, *Kc* constant, time constant, proportional gain and integral gain. From these parameters the simulation results using MATLAB are as shown in Figures 4 to 7.

Table 1. Estimated parameters of PMDC motor [29]

Parameters	Estimated parameters
Armature resistance	0.157378 Ω
Armature inductance	0.0003137 H
Back-electromotive force constant	0.0492 $Volts/(rad/sec)$
Torque constant	0.0501 $Nm/Amps$
Moment of inertia	0.000466 $kg - m^2$
Viscous friction coefficient	0.0002546 $Nm/(rad/sec)$

Table 2. Estimated parameters of DC-DC boost converter

Parameters	Estimated parameters
Input DC voltage $\boldsymbol{Ve}$	12 V
Switching frequency $\boldsymbol{fs}$	20 kHz
Resistor load $\boldsymbol{R}$	35 Ω
Boost inductor $\boldsymbol{L}$	0.01 H
Boost capacitor $\boldsymbol{C}$	0.0000299 F
Output DC voltage $\boldsymbol{V_{dc}}$	24 V
Constant $\boldsymbol{Kc}$	46.16
Time constant $\boldsymbol{T}$	0.001993 s
proportional gain $\boldsymbol{K_P}$	0.020
integral gain $\boldsymbol{K_I}$	0.010

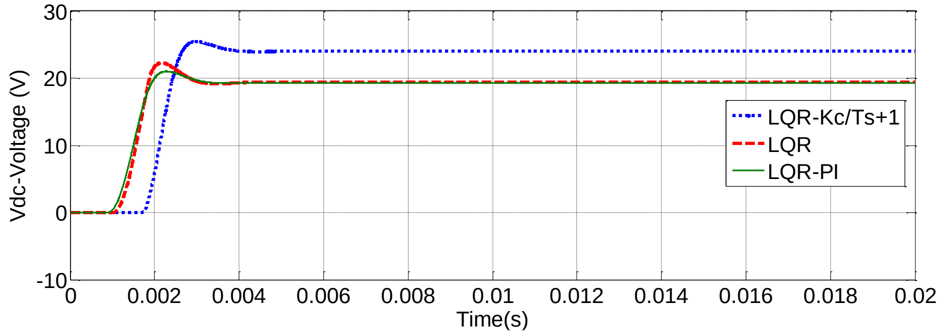

Figure 4. DC-DC converter output voltage for a reference of 20 to 24 volts

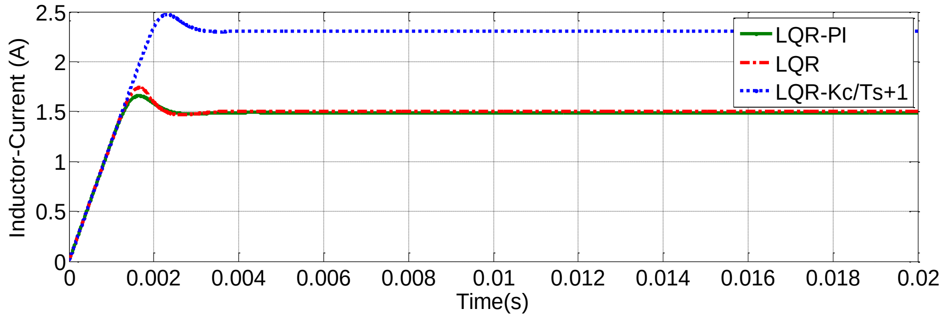

Figure 5. Current at the output of the inductor for a reference of 20 to 24 volts

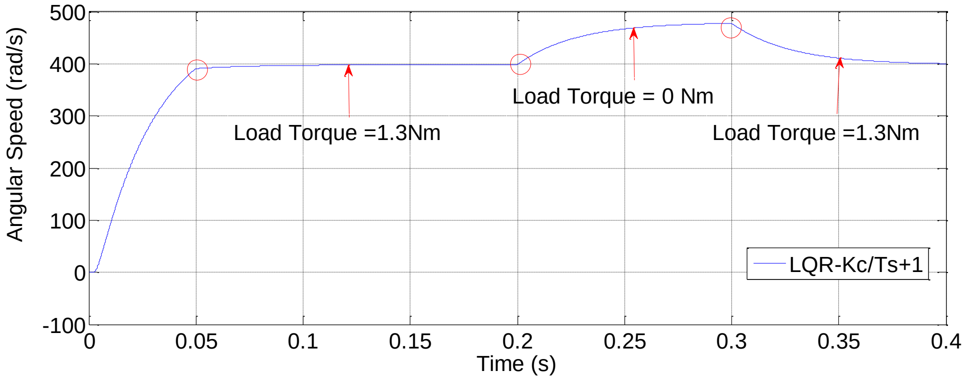

Figure 6. Speed shape during the introduction of a 1.3 N.m load torque

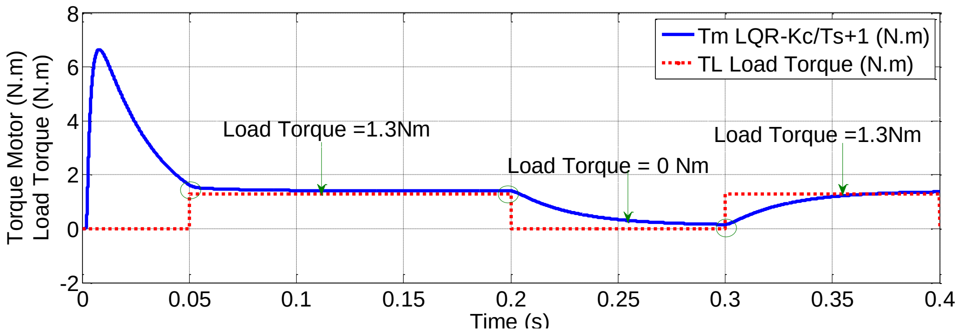

Figure 7. Motor torque curve when introducing a load torque equal to 1.3 N.m

4. RESULTS AND DISCUSSION

After the establishment of various mathematical laws of the DC-DC boost converter associated with the PMDC motor system and the design of a control law based on the *LQR*, *LQR-PI* and the hybrid control $LQR - \frac{K_c}{Ts+1}$, the DC-DC boost converter is subject to a voltage amplitude between 20 and 24 volts. The results in Figure 4 represent the output voltage of the boost converter using the three control methods *LQR*, *LQR-PI* and $LQR - \frac{K_c}{Ts+1}$), it is observed that the voltage obtained by the LQR method (19 V) equals that obtained by the *LQR-PI* controller in steady state but the performances (response time and oscillations) of the *LQR-PI* are better than the LQR control. For driving the PMDC motor, the $LQR - \frac{K_c}{Ts+1}$ controller gives a continuous output voltage equal to 24 Volts which is sufficient for the operation of the motor in steady state without disturbances and oscillations, but the response time is less than those *LQR* and *LQR-PI* control methods. Figure 5 represents the currents at the output of the inductor, we note that the current obtained by the *LQR* and *LQR-PI* method are lower than that obtained by the $LQR - \frac{K_c}{Ts+1}$ method nevertheless, for the static and dynamic performance we note that the overshoot obtained by the *LQR-PI* method is smaller compared to the *LQR* and $LQR - \frac{K_c}{Ts+1}$ methods.

Figure 6 represents the angular speed of the PMDC motor driven by the DC-DC boost converter. The speed follows well its applied reference, at the instant [0.05 to 0.2] second the angular speed has decreased during the introduction of the resistive torque which equals 1.3 Nm but at the instant of [0.2 to 0.3] second the angular speed increases up to the rated speed (no-load running) and for the instant of [0.3 to 0.4] second the angular speed has decreased down to 400 rad/s because of the load torque applied and stabilizes at this value in steady state until the end of the 0.4 second period. The motor torque of Figure 7 follows the variation of the load torque applied, we notice at the instant [0.05 to 0.2] second that the motor torque takes the value of the resistive torque which is equal to 1.3 Nm and stabilizes in this value in steady state then this motor torque decreases in the period of [0.2 to 0.3] second during no-load running and in the period of [0.3 to 0.4] the motor torque increases up to the value of the load torque applied (1.3 Nm) and stabilizes at this value until the end of the period. The various simulation tests applied to the system (DC-DC boost converter-PMDC motor) make it possible to confirm the robustness of the *LQR*, *LQR-PI* control and the $LQR - \frac{K_c}{Ts+1}$ hybrid control. These three control techniques allowed the system to operate at high dynamic and static performance during the introduction of disturbances.

5. CONCLUSION

The work presented in this article is to carry out three control techniques: the linear quadratic regulator (*LQR)* control technique, the *LQR-PI* control as well as the hybrid control $LQR - \frac{K_c}{Ts+1}$, these controls are applied to the boost DC-DC converter. To test the efficiency and robustness of the controls used, MATLAB environment gives different curves. In order to improve the dynamic performance of the system, the *LQR*, *LQR-PI* and $LQR - \frac{K_c}{Ts+1}$ correctors participate in a considerable way to the elimination of oscillations and fluctuations on different characteristics. The most effective control strategy for driving the PMDC motor is the hybrid control which allows DC-DC boost converter output voltage to increase up to 24 V, this allows the PMDC motor to operate under rated conditions without oscillations, disturbances, overshoot and fluctuations. The simulation results of the applied tests demonstrated the efficiency and robustness of the control techniques applied to the boost DC-DC converter driving the PMDC motor.

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BIOGRAPHIES OF AUTHORS

Adel Bouchahed was born in GUELMA (Algeria) on April 10, 1980**.** The High Education is achieved in Heliopolis City Algeria graduated with Bachelor of Electrotechnics in 2000. Postgraduate diplomas in electromechanical engineering received from Annaba University, in 2006. The electromechanical magister degree was received from Annaba University, in 2009. The electromechanical doctorate degree received in 2017 from Annaba University. He is a lecturer at the Institute of Science and Applied Technics of Constantine 1 University. Present research interests are electrical vehicle, renewable energy, power electronics, and industrial automation. He can be contacted at email bouchahed.adel@umc.edu.dz.

Mohamed Assabaa received the Engineer degree in Electronics (systems control) from University of Constantine 1, Algeria, in 2002 and the Magister and Doctorate degrees in electronics (systems control) in 2006 and 2015 respectively from the Department of Electronics, University of Constantine 1, Algeria. Currently, he is a lecturer in the Electromechanical department at the institute of applied sciences and techniques, University of Constantine 1, Algeria. His research interests include fractional order control, adaptive control, robust control, fractional order systems, renewable energy, industrial automation. He can be contacted at email mohamed.assabaa@umc.edu.dz.

Abdellah Draidi received the Engineer degree in Electrotechnics from University of Constantine 1, Algeria, in 2006 and the Magister and Doctorate degrees in electrotechnics in 2010 and 2016 respectively from the Department of Electrotechnics, University of Constantine 1, Algeria. Currently, he is a lecturer and Head of the Electromechanical department at the institute of applied sciences and techniques (Institut des Sciences et Techniques Appliquées-ISTA), University of Constantine 1, Algeria. His research interests include renewable energy, power systems, load flow control, economic dispatch, artificial intelligence techniques and industrial automation. He can be contacted at email: draidi_abdellh@umc.edu.dz or Abdellah.draidi@gmail.com.

Fateh Makhloufi was born in SETIF (Algeria) on January 27, 1986. The High Education is achieved in ANNABA City Algeria graduated with Bachelor of Science degree in mechanical fabrication in 2004. The master's degree in mechatronics received from the Annaba University, in 2009. The PhD degree in mechanical engineering from Annaba University, in 2015. He is a lecturer at Institut of Science and applied technics of Constantine 1 University. Present research interests are robotics, mechatronics, renewable energy, artificial intelligence. He can be contacted at email: fateh.makhloufi@umc.edu.dz.

Ahmed Belhani has received an engineer degree, master's degree and PhD degree in control engineering from the University of Constantine, Algeria. Recently, he is a professor at Constantine University. His research interests include nonlinear control, IA, renewable energy, hybrid system, optimization, FPGA and embedded systems. He can be contacted at email: ahmed.belhani@umc.edu.dz.