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# Synthesis of A Digital PID/LQR Control System for Duty-Cycle Modulation Buck Converters

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**ABSTRACT**

This research paper presents a synthesis approach of a digital optimal PID/LQR control system for DCM (duty-cycle cycle modulation) Buck converters. The step response of the DCM Buck converter is obtained under Multisim virtual simulation framework. The related data file is saved as *.SCP format, and imported into EditPad Lite7 editor, then exported as Matlab file to be processed. The transfer function of the DCM Buck converter is computed from the imported step response data. Then, using the zoh (zero order holder) discretization method with 100 ms resampling period, the z-transfer function of the DCM Buck converter is computed, and that of the analog optimal PID/LQR(linear quadratic regulator) controller is calculated using Tustin's discretization technique. Furthermore, the step response of the related closed loop digital PID control system is simulated and compared to that of the original analog PID/LQR control system. The simulation results obtained are presented in order to show the high precision as well as the reliability of Matlab-based synthesis of digital optimal PID/LQR control systems for DCM Buck converters.

**Keywords :** Buck converters, duty-cycle modulation, z-transfer functions, PID/LQR control systems

## I. INTRODUCTION

The Buck converters remains an active and growing application area of optimal controllers [1], [2], e.g., optimal PID (proportional, integral and derivative) and LQR (Linear quadratic regulators) controllers.

However, in a classical context of automation engineering practice, the design methodologies of optimal PID and LQR control systems are different and independent, with a lack of straightforward relationship between the two. In fact, while a PID control system is usually synthetized in the frequency domain given the transfer function of an open loop dynamic process, conversely, the design of LQR control systems is conventionally conducted in an n-dimensional state model associated with a dynamic process.

Fortunately, in modern control engineering literature, a direct relationship has been established and proven.

Between optimal PID controller and LQR configuration, at least for the class of second order dynamic processes. Here, the resulting optimal control strategy is named PID/LQR. On the other hand, it is worth noting that most published papers on optimal PID/LQR control of power converters, are limited to the class of PWM (Pulse Width Modulation) Buck choppers [3], [4].

On the order hand, the optimal PID/LQR control scheme for a DCM (duty-cycle modulation) Buck converter, with electronic diagram presented in Fig. 1, has been recently studied in the analog domain in [5]. It consists of a main power supply (number 1), a power Buck converter (number 2), a load (number 3), a DCM circuit (number 4), and an analog PID/LQR controller (number 5). The aforementioned DCM circuit belongs to the class of switching analog modulating circuits developed since 2005 in [6]. Obviously, following most further pioneering research works, e.g. [7]-[12], the DCM is technically more beneficial, architecturally lower cost, and offers more versatile application opportunities, than a traditional analog PWM circuit. The DCM architecture owes its better and relevant properties to its dual positive/negative feedback loop topology. These relevant properties have been well tested in numerous application areas (e.g., optical signal transmission systems [9], ECG signal acquisition systems [10], and power DCM inverters [11]), this paper presents the synthesis of a digital PID/LQR control scheme for DCM Buck converters. In the analog electronic scheme (Fig. 1), it is assumed that the function G(p) = Uo(s)/Uc(s) of the DCM Buck converter, and that of the analog PID/LQR controller Dc(s) = Uc(s)/(Uo(s)) are known. The set of descriptive variables is defined as follows: {Uo = load voltage, Ref = set point, Uc = modulating control signal, and Ucm = swiching modulated DCM wave}. Equations (1) shows the structures of Gc(s) with parameters Ks (static gain), ω in rd/s (natural frequency), and ξ (damping coefficient). Therefore, the purpose of this paper, is to synthetize and validate a digital optimal PID/LQR control system of a DCM Buck converter.

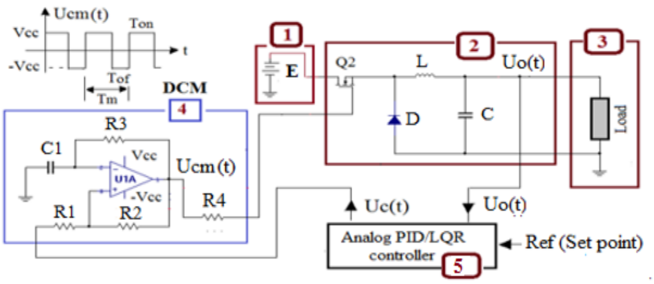


Figure 1. Analog PID/LQR control system for DCM buck converters [5]

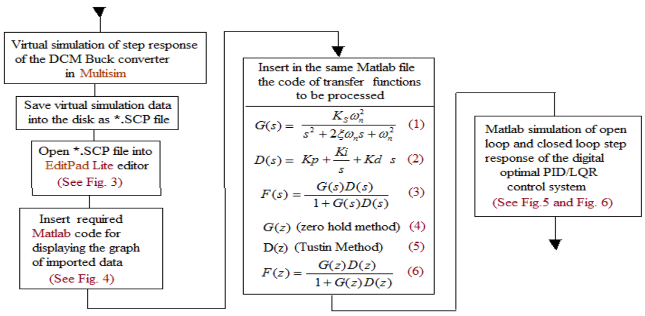


Figure 2. Building scheme of a digital optimal PID/LQR control system for DCM Buck converters

In section 2, the research methodology and tools for the synthesis of the digital optimal PID/LQR control system for Buck converter are outlined. In section 3, relevant simulation results are presented and discussed, and the paper is concluded in Section 4.

## II. METHODS AND MATERIAL

Building an optimal digital PID/LQR control system for a DCM Buck converter from a known analog scheme, requires a rigorous design methodology, i.e., with lossless static and dynamic properties. For the sake of better understanding, the building scheme defined in this paper is graphically shown in Fig. 2.

As reported earlier in Fig. 2, the building scheme of a digital optimal PID/LQR control system for DCM Buck converters, involves many software tools including:

- Multisim for virtual simulation processes
- EditPad Lite for the importation from Multisim of *.SCP data file as a readable text format), to be saved as a raw *.m Matlab file as in Fig. 3.
- Matlab for advanced numerical computing and simulation, of the behavior of numerous dynamic models of objects.

The set of involved analog transfer functions {G(s), D(s) F(s)} as defined in equations {(1), (2), (3)} respectively, are used here for numerically computing the corresponding set of z-transfer functions {G(z), D(z) F(z)} according to {(4), (5), (6)} (see [5] and [13] for development details).

$$G(s) = \frac{U_0(s)}{Uc(s)} = \frac{K_S\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \qquad (1)$$

$$D(s) = \frac{Uc(s)}{\mathrm{Re}f(s) - U_0(s)} = Kp + \frac{Ki}{s} + Kd\ s \qquad (2)$$

$$F(s) = \frac{Y(s)}{\mathrm{Re}f(s)} = \frac{G(s)D(s)}{1+G(s)D's)}$$
$$= \frac{K_s\omega_n^2\left(K_d s^2 + K_p s + K_i\right)}{s^3 + \left(2\xi\omega_n + K_S K_d\omega_n^2\right)s^2 + \omega_n^2\left(1 + K_s K_p\right)s + K_s K_i\omega_n^2} \qquad (3)$$

$$G(z) = \frac{Y(z)}{U(z)} = \left(\frac{z-1}{z}\right) Z\left(\frac{G(s)}{s}\right) \qquad (4)$$

(zero order holder discretization method)

$$D(z) = D\left(s \rightarrow \left(\frac{2}{T}\right)\left(\frac{z-1}{z+1}\right)\right) \qquad (5)$$

(Tustin discretization method)

$$F(z) = \frac{Uo(z)}{\mathrm{Re}f(z)} = \frac{G(z)D(z)}{1+G(z)D(z)} \qquad (6)$$

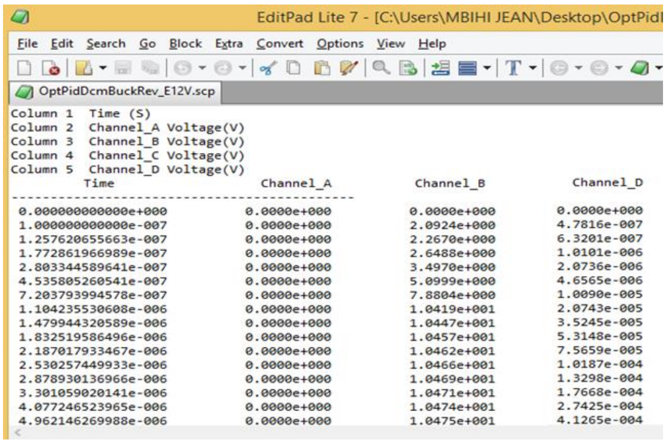


**Figure 3.** Data (*.SCP format) imported from Multisim into EditePad Lite Editor

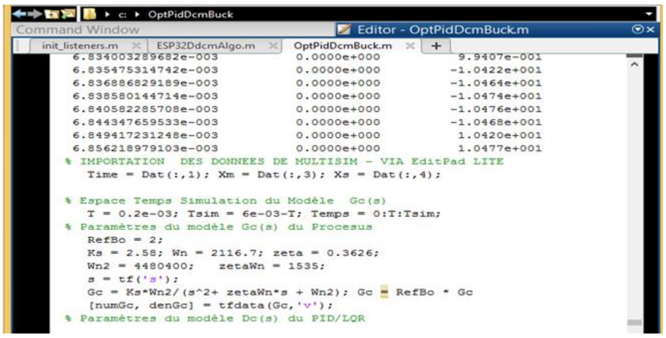


**Figure 4.** A part of Matlab file created and extended by powerful numerical simulation and plotting commands

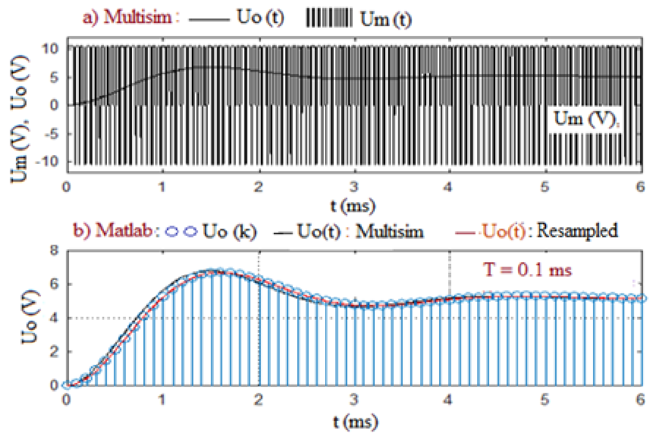


**Figure 5.** Comparison of open loop step responses of both analog and digital dynamic models of the DCM Buck converter.

Fig. 4 shows the content of a part of Matlab file, created and extended by powerful simulation and plotting commands, which have been used for rapid synthesis of the proposed Digital optimal PID/LQR control scheme of DCM Buck power converters. As relevant examples, (1) and (2) is analytically defined using *tf*('s') object, while (3) being automatically computed using the *feedback* command. On the other hand, (4), (5) and (6) are instantaneously computed using *zoh*, *Tustin* and *feedback* commands respectively, with appropriate input arguments in each case.

## III. RESULTS AND DISCUSSION

The relevant results obtained when simulating analog and digital models of PID/LQR control systems for DCM Buck converters, are plotted on Fig. 5 and Fig. 6.

In Fig. 5a, the steps response of a DCM Buck converter resulting from Simulink simulation is provided. Then, it is compared in Fig. 5b with the digital step response simulated under Matlab, under a resampling period T = 0.1 ms. On the other hand, the closed loop step response of both analog and digital control systems, are compared also in Fig. 6. Fig. 6a stands for virtual simulation under Simulink as reported in [5], while Fig. 6b shows the corresponding results obtained when implementing and well testing our proposed methodological as earlier predicted in Fig. 2.

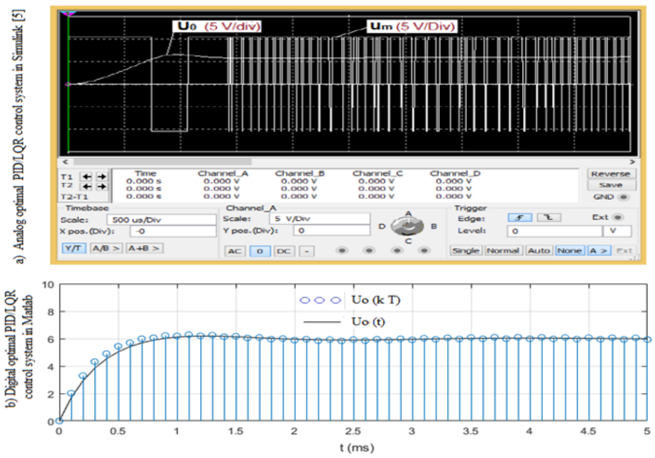


**Figure 6.** Comparison of open loop step responses with Ref = 6 volts of analog and digital PID/LQR control system for a DCM Buck converter

It is worth noting in all cases that the dynamic behaviour of the digital PID/LQR control scheme is highly closed to that of the equivalent analog versions, even using resampled digital models of involved transfer functions, with resampling period T = 0.1 ms. The mayor relevant finding arising from these results is that, the digital optimal PID/LQR control systems for DCM Buck converters as synthetized in this paper from its equivalent analog processing scheme, is quite safe and reliable, as well as valid for real time implementation in future research works.

## IV.CONCLUSION

This is a lossless valuable extension of the analog PID/LQR control scheme for DCM Buck converters, into digital signal and system processing world. Beside the collection of relevant analytical models to be processed, the use of suitable software tools, e.g., Multisim, EdidPad Lite and Matlab, has greatly facilitated planning and processing as well as simulation tasks. At this point where the content of this has demonstrated that the proposed digital optimal PID/LQR control system for DCM Buck converters is highly reliable, it would be beneficial to implement in future research works, a first pioneering optimal PID/LQR controller for power DCM Buck controllers, into a SOC (system-on-chip) device. Finally, the proposed digital scheme as developed and well tested in this paper, could be extended to other types of power DC-DC and DC-AC converters.

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