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An Optimal Control Scheme for a Class of Duty-Cycle Modulation Buck Choppers: Analog Design and Virtual Simulation

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Abstract – **This paper presents a design methodology and a virtual simulation framework, of the optimal feedback control scheme for DCM (duty-cycle modulation) Buck choppers. The transfer function of an open loop DCM chopper, is built from the numerical analysis of a virtual step response, with Ref = 2 volts as step control input. Then, the optimal PID controller for DCM Buck Choppers is formulated and synthetized as a LQR (Linear Quadratic Regulator) equivalent control, and the associated Riccati equations is easily solvable using Matlab/LQR tool. As a relevant implication, the parameters of the corresponding optimal PID, are straightforwardly obtained from the LQR gains according to a LQR/PID equivalence principle, which is proven for a relevant class of second order dynamic systems. In addition, in order to show the feasibility of the designed optimal PID control scheme, a whole prototyping DCM Buck chopper with given operating conditions (main DC supplied (12 V), load resistance (3.3 Ω), basic DCM frequency (30 kHz)), is virtually implemented and well tested using Multisim. The virtual simulation results obtained from numerous operating conditions (e.g., open loop, closed loop, load variations), are presented and discussed. Furthermore, relevant results and findings are reported, e.g., transient characteristics (i.e. controllability, stability, overshoot (4%), and time response (1.5 ms) and static performance levels (e.g. static error (0 %), high robustness under 50 % load variations). These results are a great challenge for the first virtual DCM Buck chopper, operating under a well-tested optimal PID-based control policy.**

Keywords - DCM Buck choppers; optimal PID controller; linear quadratic regulator; LQR/PID equivalence principle; analog design, Virtual simulation.

I. INTRODUCTION

The modern DCM (Duty-Cycle Modulation), developed and published since 2004 [1], has increasingly become a versatile modulation technique, offering minimum realization cost and optimal quality, in a wide variety of signal processing systems. A complete literature review about the DCM technique and its potential applications, are provided in a recent Review paper [2]. Indeed, the main relevant applications of DCM principles and related prototyping realization are: Analog-to-digital conversion [3-7], digital-to-analog conversion [7-12], electronic signal transmission [2, 13-14], and driving design for power electronics [6, 15-18].

As a scientific context, this paper falls into to the class of research works related to optimal control of power converters, with a Buck chopper architecture, equipped with low cost and high quality driver. However, it is worth nothing that a few optimal PID-based and LQR-based control schemes are encountered in the literature [19.22]. In addition the feasibility of DCM Buck choppers equipped with a standard PID controller, has been proven already in a pioneering work presented in [18]. However, according to our best knowledge, the optimization feedback control problem of DCM Buck converters, has not been formulated and solved in the literature.

Therefore, the scientific contribution of this paper, is to present a new design methodology and a well-tested *virtual realization*, of an optimal feedback control scheme for DCM *Buck choppers*. The relevant contribution of this paper has been to successfully design and implement a well-tested prototyping optimal PID-based control scheme, from a proven LQR/PID equivalence principle, for the sake of minimum virtual electronic realization, within *Multisim* Framework.

In Section II of this paper, a new design methodology of the optimal PID controller for DCM Buck choppers, from LQR synthesis, is presented. Then, in Section III, a virtual prototyping realization of the whole optimal PID-based control DCM system, is outlined. In addition, the main virtual simulation results, obtained when testing the complete feedback control system, are presented and discussed in Section IV, followed in Section V by the conclusion of the paper.

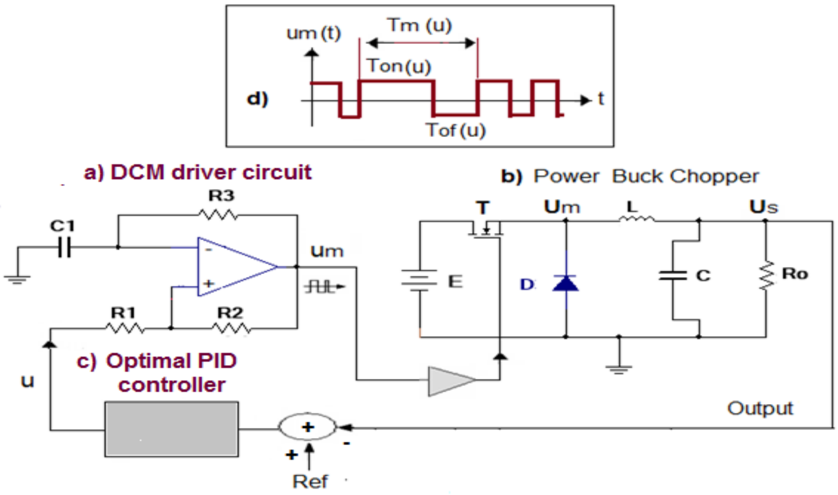


Figure 1. PID control scheme for DCM Buck choppers [18].

II. DESIGN METHODOLOGY OF THE OPTIMAL CONTROLLER FOR DCM BUCK CHOPPERS

A. *Recall on PID control for DCM Buck Choppers*

The PID control scheme for DCM Buck Choppers is shown in Fig.1. It consists of many main parts including a DCM circuit (Fig. 1a), a power Buck Chopper (Fig. 1b) where the notation E, L-C, Ro, Us, u and u_m, stands for main DC source, power filter, load resistance and output voltage, control and DCM wave respectively); and a standard PID controller (Fig. 1c). It is obvious that the DCM circuit shown in Fig. 1a, offers exceptional visual qualities, including a single state hardware architecture, an embedded clock, and both positive and negative feedback loops for the sake of better operating robustness under infected modulating waves.

The general shape of the DCM wave shown in Fig. 1d, is a switching aperiodic wave, where over a DCM period $T_m(u) = T_{on}(u) + T_{of}(u)$, the notations $T_{on}(u)$ and $T_{of}(u)$ stand for ON pulse width and OF pulse width respectively. Given $\alpha 1 = R_1/(R_1+R_2)$, and $\alpha 2 = 1- \alpha 1$, then the duty-cycle $R_m(u)$ of the DCM signal u_m as proven and reported in the literature [1, 9], is given by equation (1), given (2).

$$R_m(u) = \frac{Ton(u)}{Tm(u)} = \frac{\ln\left(\dfrac{\alpha_2 u - (1+\alpha_1)E}{\alpha_2 u + (\alpha_1 - 1)E}\right)}{\ln\left(\dfrac{(\alpha_2 u)^2 - ((1+\alpha_1)E)^2}{(\alpha_2 u)^2 - ((\alpha_1 - 1)E)^2}\right)} \approx p_m u + \frac{1}{2} \qquad (1)$$

where,

$$p_m = \left(\frac{\dfrac{\alpha_1 \alpha_2}{E(1-\alpha_1^2)}}{\log\left(\dfrac{1+\alpha_1}{1-\alpha_1}\right)} \right) \qquad (2)$$

The validity of the linear approximation used in (1), will be justified later in section 3, from numerical analysis fundamentals. In addition, it has been shown also in the literature [1, 9], that the DCM frequency $f_m(u)$ and its maximum $f_m(0)$ are given by (4)

$$f_m(x) = \frac{1}{R3\ C1\ Log\left(\dfrac{(\alpha_2 x)^2 - ((1+\alpha_1)\ E)^2}{(\alpha_2 x)^2 - ((\alpha_1 - 1)\ E)^2}\right)}, \qquad (3)$$

$$f_m(0) = \frac{1}{2\ R3\ C1\ Log\left(\dfrac{1+\alpha_1}{1-\alpha_1}\right)} \qquad (4)$$

Unlike the well known PWM (Pulse Width Modulation) technique, for which the modulating signal is encapsulated in $T_{on}(u)$ under a constant $T_m(u)$, the DCM period $T_m(u)$ and pulse width $T_{on}(u)$ simultaneous vary, the modulating signal being encapsulated into $R_m(u)$. In this paper, we resort to the same power DCM Buck Chopper used in [18], with open loop transfer function given by,

$$G(s) = \frac{Y(s)}{U(s)} = \frac{K_s \omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \qquad (5)$$

where $Y(s) = Uo(s)$, and Ks, ω_n^2 and ξ could be obtained according to relationships (6-8) from those of the step response of a virtual realization, i.e., Ref (step control input), $Y(\infty)$, D (overshoot), Tr (setting time), and *r* (% of setting time).

$$K_S = \frac{Y_S(\infty)}{E_0} \text{ (Static gain)} \qquad (6)$$

$$\xi = \frac{\log(D)}{\sqrt{\pi^2 + (\log(D))^2}} \text{ (Damping coefficient)} \qquad (7)$$

$$\omega_n = \frac{\log(\dfrac{100}{r})}{\xi Tr} \text{ (Natural frequency} \qquad (8)$$

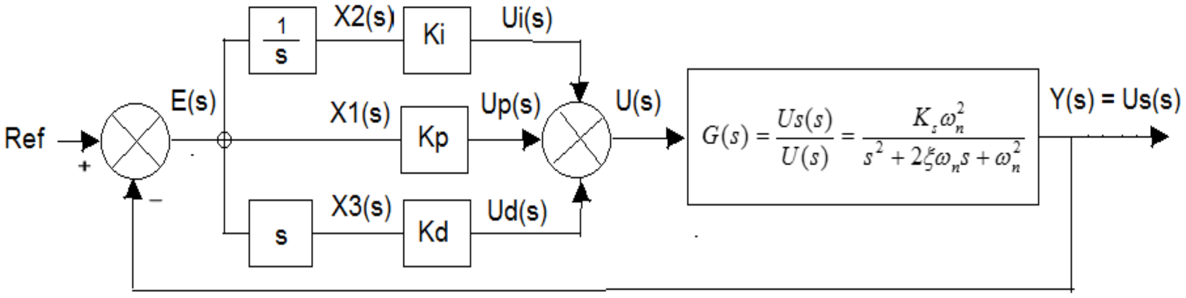


Figure 2. PID control scheme for DCM Buck choppers

$$F(s) = \frac{Y(s)}{\mathrm{Re}\,f(s)} = \frac{K_s\omega_n^2(K_d\,s^2 + K_p\,s + K_i)}{s^3 + (2\xi\omega_n + K_s K_d\,\omega_n^2)\,s^2 + \omega_n^2(1 + K_s K_p)s + K_s K_i\,\omega_n^2} \tag{9}$$

B. DESIGN OF OPTIMAL PID CONTROLLER

A PID control scheme for DCM Buck choppers, with transfer function (5), is presented in figure 2. After straightforward algebraic developments from Fig. 2, the closed loop transfer function of the resulting PID control system, is given by (9).

It is clear that formulating and solving an optimal control problem from (8), in order to find optimal PID gains Kp, Ki and Kd, is both an intractable and tedious work. Fortunately, this optimization control problem could be easily formulated and solved from a suitable state space representation, as it is proven next.

The optimal feedback control for DCM Buck choppers, is formulated as an optimal LQR control problem for a suitable choice of state variables x1, x2 and x3 as outlined in Fig. 2.

In a time domain, let consider the 2nd order ODE (ordinary differential equation) described by (10), associated with the transfer function (5), and the choice of state variable x1, x2 and x3 given by (11), as located in Fig. 2.

$$\frac{d^2y(t)}{dt} = -2\xi\omega_n\frac{dy}{dt} - \omega_n^2\,y + K_s\,\omega_n^2\,u(t) \tag{10}$$

$$x_1 = e = \mathrm{Re}\,f - y,\quad x_2 = \int e\,dt,\quad x_3 = \frac{de}{dt} \tag{11}$$

For a constant set voltage denoted Ref, the ODE (10) given (11) leads to (12), which can be organized into matrix form (13) or (14) equivalently.

$$\begin{cases} \dfrac{dx_1}{dt} = \dfrac{de}{dt} = -\dfrac{dy}{dt} = x_3 \\ \dfrac{dx_2}{dt} = e = x_1 \\ \dfrac{dx_3}{dt} = \omega_n^2\,(\mathrm{Re}\,f - x_1) - 2\xi\omega_n x_3 - K_s\,\omega_n^2\,u(t) \end{cases} \tag{12}$$

$$\begin{cases} \dfrac{dx(t)}{dt} = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ -\omega_n^2 & 0 & -2\xi\omega_n \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 0 \\ -K_s\,\omega_n^2 \end{bmatrix} u(t) + \begin{bmatrix} 0 \\ 0 \\ \omega_n^2 \end{bmatrix} \mathrm{Ref} \\ y(t) = [\,-1 \quad 0 \quad 0\,]\,x(t) + \mathrm{Ref} \end{cases} \tag{13}$$

$$\begin{cases} \dfrac{dx(t)}{dt} = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ -\omega_n^2 & 0 & -2\xi\omega_n \end{bmatrix} x(t) + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -K_s\,\omega_n^2 & \omega_n^2 \end{bmatrix} \begin{bmatrix} u(t) \\ \mathrm{Re}\,f \end{bmatrix} \\ y(t) = [\,-1 \quad 0 \quad 0\,]\,x(t) + [\,0 \quad 1\,] \begin{bmatrix} u(t) \\ \mathrm{Re}\,f \end{bmatrix} \end{cases} \tag{14}$$

As a fundamental result, any arbitrary state feedback control u(t), applied to (14), is given by (15), from which it becomes obvious that, (15) is a pure PID control policy, with gains given by (16).

$$\begin{aligned} \mathrm{u} &= -\mathrm{K}_1\,x_1 - K_2\,x_2 - K_3\,x_3 \\ &= \mathrm{K}_p\,e + K_i\int e\,dt + K_d\,\frac{de}{dt} \end{aligned} \tag{15}$$

$$\begin{cases} Kp = -K_1 \quad \text{(Proportional gain)} \\ Ki = -K_2 \quad \text{(Integral gain)} \\ Kd = -K_3 \quad \text{(Derivative gain)} \end{cases} \tag{16}$$

Therefore, for the same dynamic system (5), an optimal PID controller and the LQR with optimization criterion (17), have equivalent feedback control gains.

$$J = \int_0^\infty (x^T(t)Q_c\,\mathrm{x(t)} + u^T(t)R_c\,\mathrm{u(t)})\,dt \tag{17}$$

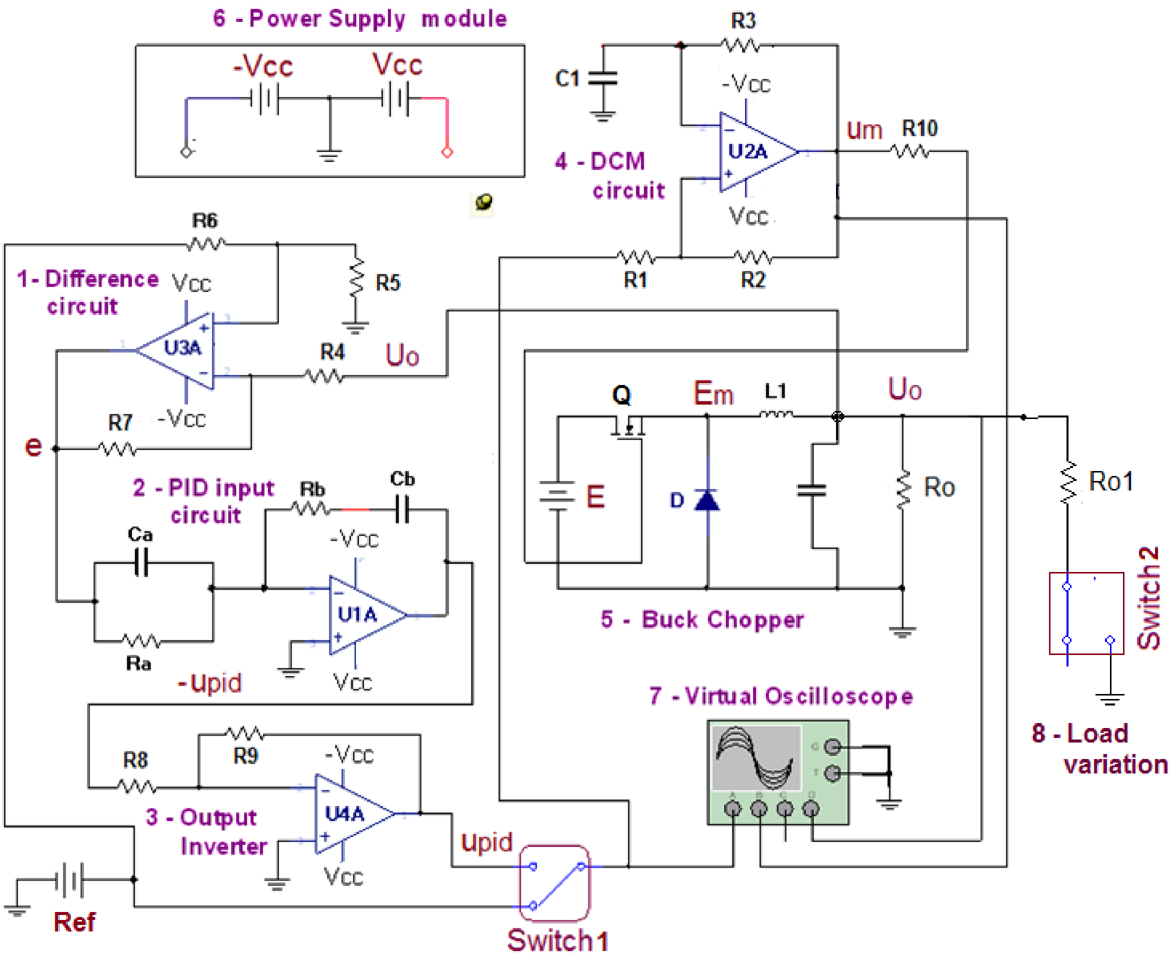


Figure 3. Multisim schematic diagram of a DCM Buck chopper under optimal PID control.

Subsequently, the optimal gain vector K = [$K_1 = K_p$ $K_2 = K_i$ $K_3 = K_d$] can be obtained by solving the Riccati Equation (18) [23-24]:

$$Q + A_c^T K + K A_c - K B_c R^{-1} B_c^T K = 0 \qquad (18)$$

Fortunately, solving (18) in a practical context, is easy using Matlab/LQR command. As a result, the optimal LQR state feedback, which is equivalent to an optimal PID control is given by (19).

$$\begin{cases} \dfrac{dx(t)}{dt} = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ -\omega_n^2 \text{-} K1\,\mathrm{Ks}\,\omega_n^2 & K2\,\mathrm{Ks}\,\omega_n^2 & -2\xi\omega_n - K3\,\mathrm{Ks}\,\omega_n^2 \end{bmatrix} x(t) \\ \qquad + \begin{bmatrix} 0 \\ 0 \\ \mathrm{Ks}\,\omega_n^2 + \omega_n^2 \end{bmatrix} \mathrm{Ref} \\ y(t) = [\ \text{-}1 \quad 0 \quad 0\ ]\ x(t) + \mathrm{Ref} \end{cases} \qquad (19)$$

B. PROTOTYPING SYSTEM

The prototyping DCM Buck chopper studied in this section has been implemented in Multisim platform. Its electronic schematic diagram presented in Fig. 3. The analog PID control part consists of a few simple operational amplifier circuits, numbered as follows: 1 (difference circuit with output e = Ref – Uo; 2 (PID input circuit); and 3 (Output inverter). Additional relevant parts are numbered also: 4 (DCM driver circuit); 5 (Power Buck chopper; 6 (Main power supply), 7 (Virtual multichannel oscilloscope); and 5 (Load variation unit). Following circuit analysis techniques, it is easy to show that the transfer function of the PID controller is given by (20),

$$\frac{Upid\ (s)}{E(s)} = \frac{R_b}{R_a} + \frac{C_a}{C_b} + \frac{1}{R_a C_b}\,\frac{1}{s} + R_b C_a\ \mathrm{s} \qquad (20)$$

then, the parameters of the optimal PID controller are given in terms of those of electronic building components, as follows:

$$K_p = \frac{R_b}{R_a} + \frac{C_a}{C_b}, \quad K_i = \frac{1}{R_a C_b}, \quad K_d = R_b C_a \qquad (21)$$

Table 1 : Technical information and data for the prototyping control system

Part	Name	Symbols	Valeurs
Power Buck chopper	Main Power supply	E	12 V
	Control power suply	± Vcc	±12 V
	Resistive loads	Ro, Ro1	3.3Ω
	Power MOSFET	Q	IRLZ14
	Diode	D	HFAD04TB60
Difference circuit	Resistance	R4	100 kΩ
	Resistance	R5	100 kΩ
	Resistance	R6	100 kΩ
	Resistance	R7	100 kΩ
Optimal PID/LQR	State matrix cost	Diag(q1, q2, q3)	q1=80; q2=1e04; q3=1e-3
	Control cost	r	0.4
	Proportional gain	Kp	14.3316
	Integral gain	Ki	158.114
	Derivative gain	Kd	0.0499
Optimal PID circuit	Operational amplifiers	U1j, j = 1, 2, 3, 4	TL082CD
	Resistance	Ra	120 kΩ
	Capacitance	Ca	0.725 uF
	Resistance	Rb	1.65 MΩ
	Capacitance	Cb	0.53 nF
DCM circuit	Resistance	R1	1.2 kΩ
	Resistance	R2	10 kΩ
	Resistance	R3	2.32 kΩ
	Capacitance	C1	33 nF
	Resistance	R10	1 kΩ

Indeed, the numerical values of parameters Ra, Ca, Rb and Cb, can be computed according to a simple algorithm (22).

$$\begin{cases} R_a = \text{ Given value, e.g, } \quad \text{Ra} = 120 \text{ k}\Omega \\ C_b = \dfrac{1}{K_i \, R_a} \\ R_b = R_a C_b K_p \pm \dfrac{\sqrt{(R_a C_b K_p)^2 - 4\, C_b \, R_a \, K_d}}{2\, C_b} \\ C_a = \dfrac{K_d}{R_b} \end{cases} \tag{22}$$

III. VIRTUAL SIMULATION

A. TECHNICAL INFORMATION AND DATA

The technical information and data used for the prototyping optimal PID-based control system, are summarized in Table 1 provided above. Using the open loop step response (Ref = 2 volts step input) of the virtual prototyping DCM Buck chopper (see Fig. 4), the set of parameters {Ks = 2.7494, ωn = 2116.7 rad/s, ξ = 0.3626} of the transfer function (23) have been identified according to (6), (7) and (8). It is worth noting the main characteristics of the open loop control are: overshoot (17 %), time response (3.66 ms), and static error (64%).

$$G(s) = \frac{Y(s)}{U(s)} = \frac{K_s \omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} = 2.7494 \, \frac{(4480400)}{s^2 + 1535\, s + 4480400} \tag{23}$$

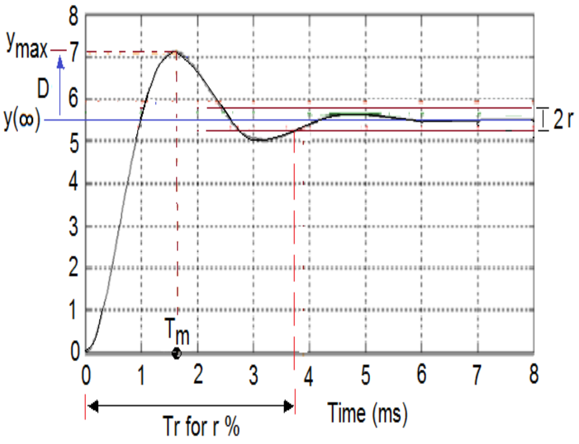


Figure 4. Open loop step response in Matlab

Then, using Matlab *ctrb* and *rank* commands, it has been rapidly check, that the controllability matrix extracted from (14), has full rank. As an implication, *the prototyping state model, is fully controllable*. In addition, the value of the basic DCM frequency given by (4) is fm(0) = 30 kHz.

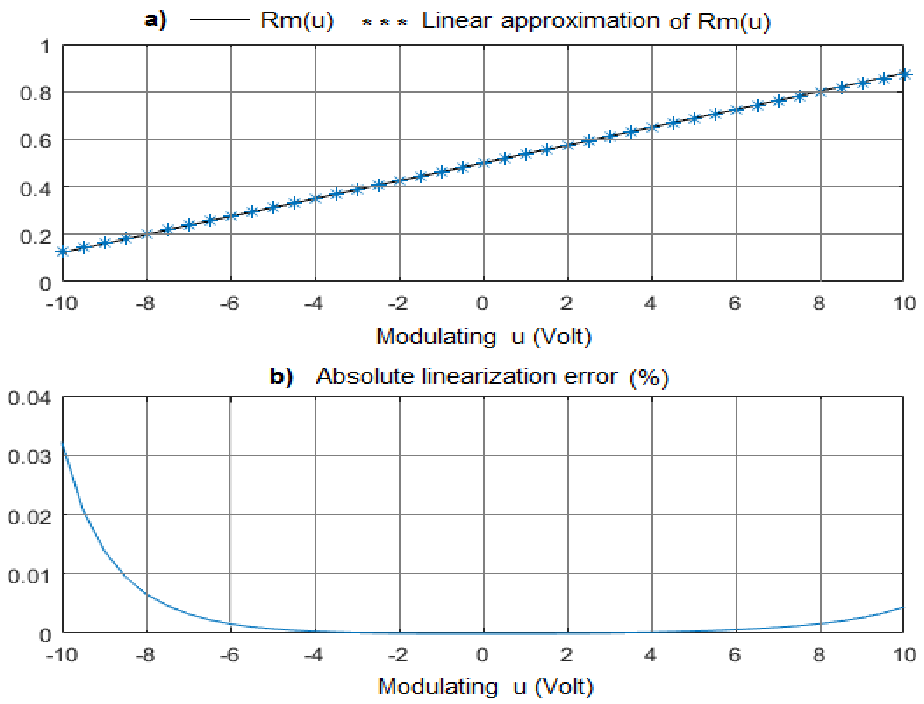
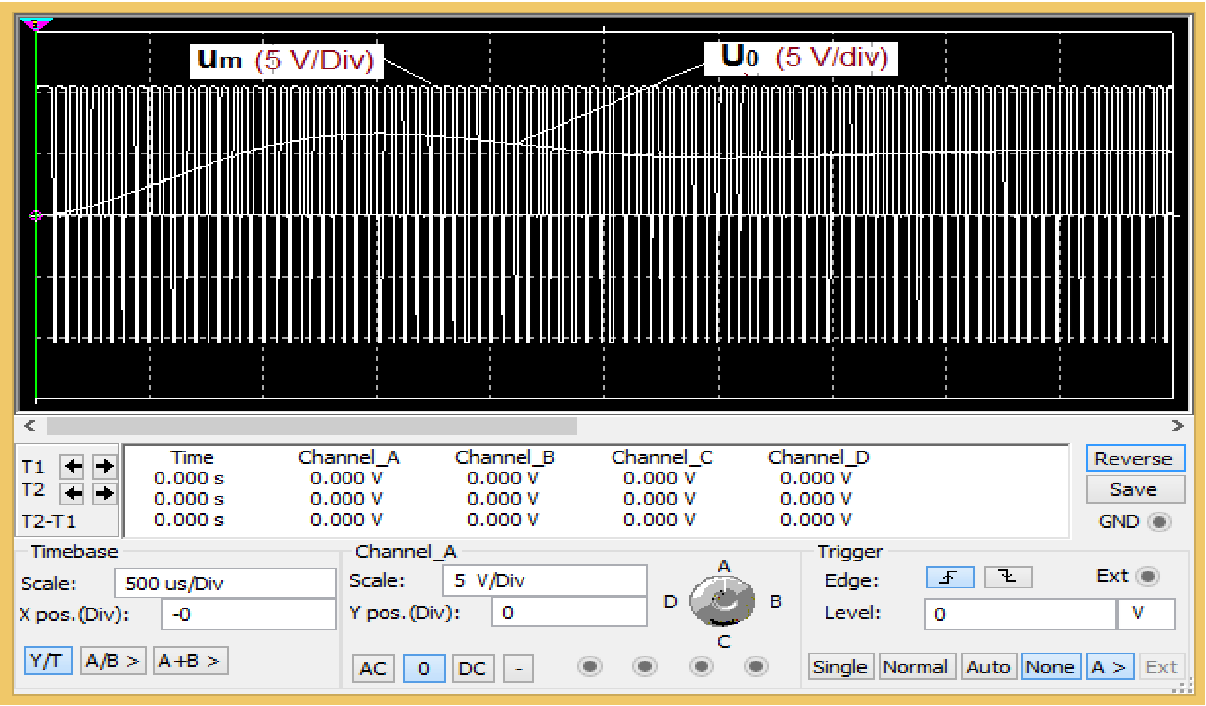


Figure 5. Rm(u) and its linear approximation



	Time	Channel_A	Channel_B	Channel_C	Channel_D
T1	0.000 s	0.000 V	0.000 V	0.000 V	0.000 V
T2	0.000 s	0.000 V	0.000 V	0.000 V	0.000 V
T2-T1	0.000 s	0.000 V	0.000 V	0.000 V	0.000 V

Timebase
Scale: 500 us/Div
X pos.(Div): -0

Channel_A
Scale: 5 V/Div
Y pos.(Div): 0

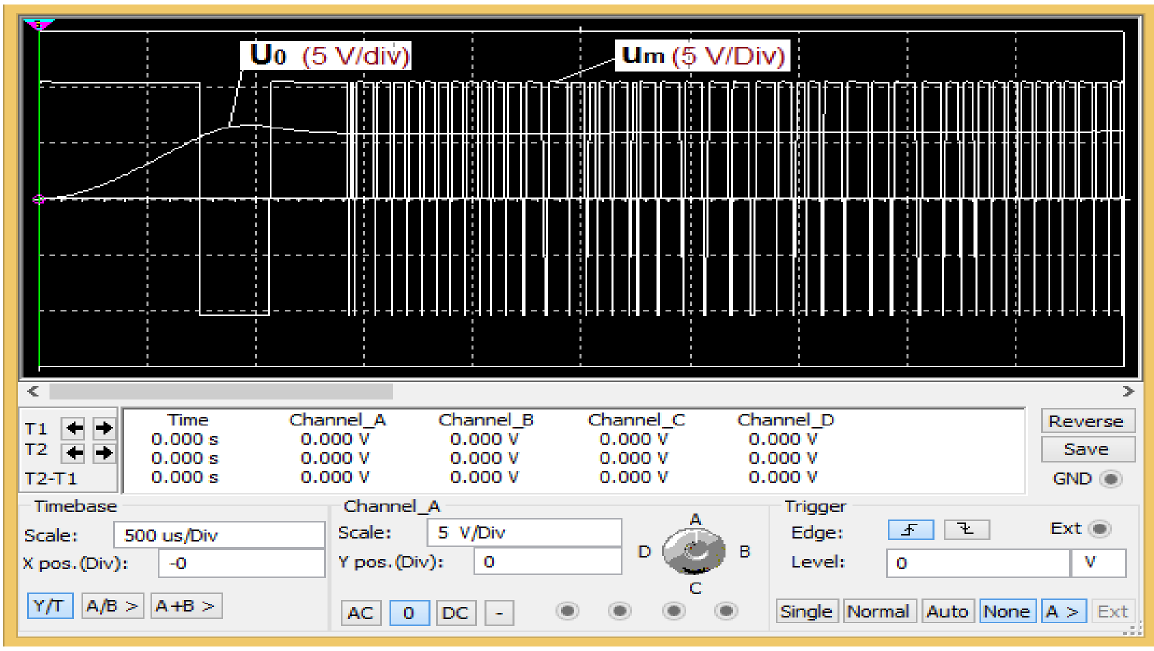
Trigger
Level: 0 V

Figure 6. Virtual simulation of the open loop control systems for Ref = 2 volts

Furthermore, as predicted earlier in (3), Fig. 5 shows a piecewise perfect closeness between the exact nonlinear duty-cycle Rm(u) and its linear approximation. It is a challenge to discover from Fig. 5 that the absolute error incurred when using the linear approximation of the duty-cycle function Rm(u), is less than 3% within the modulating range [-10 10], while it becomes piecewise zero when the modulating control falls into the range of [-4 4] volts. As a relevant conclusion, the feasibility of the prototyping DCM Buck chopper is outlined.

B. VISUAL SIMULATION ANS RESULTS

Fig. 6 shows the shape of waveforms Um and Uo for an open loop step response.



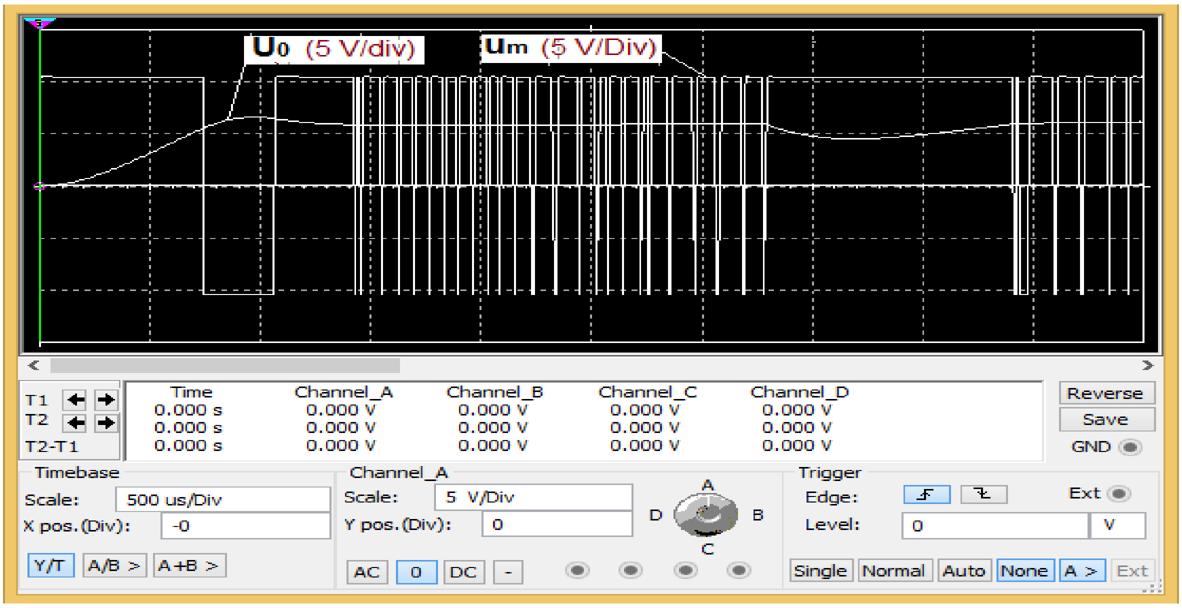
	Time	Channel_A	Channel_B	Channel_C	Channel_D
T1	0.000 s	0.000 V	0.000 V	0.000 V	0.000 V
T2	0.000 s	0.000 V	0.000 V	0.000 V	0.000 V
T2-T1	0.000 s	0.000 V	0.000 V	0.000 V	0.000 V

Timebase
Scale: 500 us/Div
X pos.(Div): -0

Channel_A
Scale: 5 V/Div
Y pos.(Div): 0

Trigger
Edge:
Level: 0 V

Figure 7. Step response of the nominal optimal control system (Ref = 6 volts)



	Time	Channel_A	Channel_B	Channel_C	Channel_D
T1	0.000 s	0.000 V	0.000 V	0.000 V	0.000 V
T2	0.000 s	0.000 V	0.000 V	0.000 V	0.000 V
T2-T1	0.000 s	0.000 V	0.000 V	0.000 V	0.000 V

Timebase
Scale: 500 us/Div
X pos.(Div): -0

Channel_A
Scale: 5 V/Div
Y pos.(Div): 0

Trigger
Edge:
Level: 0 V

Figure 8. Robustness under a permanent disturbance (50 % load variation)

Fig. 7 presents the visual waveforms of DCM signal u_m and output voltage Uo delivered to the nominal load Rs = 3.3 Ω. In this case, the optimal characteristics provided are as follows: Overshoot (D = 4 %), time response (Tr = 1.5 ms), static error (0 V). These characteristics are a challenge compared to those of the open loop control. Fig. 8 shows the behavior of the optimal feedback control system, under a permanent disturbance (50 % load variation), applied in steady operating state from time = 3.28 ms. It is worth noting that, the undesired deviation of the output Uo due to the permanent disturbance, is cancelled before 1.23 ms time interval. These performance levels and associated findings, are a great challenge for the first virtual prototyping DCM Buck chopper, operating under optimal PID-based control policy.

IV. CONCLUSION

This paper has presented new achievements, on both the design methodology of optimal PID-based control for DCM Buck choppers. High quality results and potential findings, have been reported from a well-tested virtual workbench. It would be interesting to study in depth the behavior of the optimal PID-based control DCM Buck choppers under active DC loads, e.g., DC motors, in order to appreciate their possible use in fixed or mobile robotic control systems. Furthermore, a digital implementation of the proposed optimal PID-based controllers for DCM Buck power choppers, using microchip board technology, will be also a new contribution for future research works

AUTHORS CONTRIBUTIONS

Paul Owoundi Etouke contributed to the dynamic modelling of buck choppers, and to the development of the well tested virtual workbench, used to produces relevant results presented in the paper.

Leandre Nneme Nneme contributed to the synthesis of the LQR, from which the equivalent optimal PID controller has been synthetized. He also reinforced the results by the robustness analysis.

Jean Mbihi contributed to the edition of the abstract, as well as the introduction and conclusion of the paper. He also contributed to the technical specification of the prototyping buck chopper to be simulated.

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