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Experimental results of controlling constrained DC-DC power converters

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***Abstract*— This paper deals with the problem of controlling a DC-DC buck converter. It proposes an optimal PI controller with anti wind up scheme in order to get best performances under any conditions and to ensure asymptotic stability of the closed loop system. It is shown using theoretical formalism simulation and experimental results that the controlled system satisfies the objectives.**

***Keywords*— Dc-dc buck power converter, PI controller, anti-windup, Digital control**

I. INTRODUCTION

In general, power electronic DC-DC converters are periodic time-variant systems due to their inherent switching operation. Static and dynamic characteristics of these converters have been widely discussed in the literature In order to obtain method that has the best performances under any conditions and to ensure their large signal stability, and also to improve their large signal dynamic response , a linear control based on a PI control is used .[2] In digital PI and PID controller for power converters, the main issue is the deterioration of the performances (when the system deviates from its nominal operation point) because of the presence of the control input limitation (the duty ration is constrained between 0 and 1). The presence of both input limitation [3] and an integrator in the controller make the closed-loop system suffer from what is commonly called 'windup effect'. This means that the system signals are likely to diverge if a disturbance affects the system.[1][2][3]

In this paper , the optimal PI controller with anti wind up scheme is proposed to ensure a tight regulation of DC voltage and asymptotic stability of the closed loop system in presence of load changes .It's shown using theoretical formalism simulation and experimental results that the controlled system satisfies the objectives . The rest of the paper is organized as follows. In Section 2, presentation and modeling of dc-dc buck power converter are described. A robust controller design and simulations results are presented in Section 3. Section 4 is devoted to the experimental results and discussion. A conclusion ends the paper.

II. DC-DC BUCK CONVERTER PRESENTATION AND MODELING

A. Dc-dc Buck power converter presentation

The DC-DC Buck converter is one of the basic power electronic circuits, and it has been widely used in the fields of DC power supplies and DC motor speed regulating systems[4].

Fig. 1 shows a typical pulse wide modulation (PWM)-based dc–dc buck power converter structure, where i_L is the inductance current and v_c the average output capacitor voltage, L the inductance of the circuit, C the capacitor of the circuit, R the load resistance of the circuit, E the voltage of the external source, u the binary input signal, and the duty ratio function $\mu\in$ [0,1] the control signal of PWM. In this model, all involved passive components are subject to linear laws.

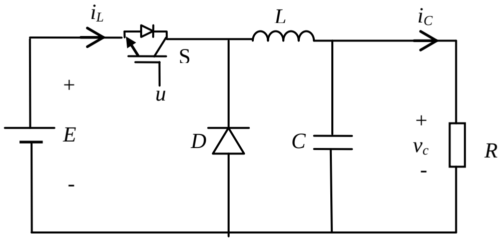

Fig. 1 Dc-dc Buck converter

B. Buck power converter modeling

From inspection of the circuit, shown in Figure.2, and taking into account that u can take the binary values 1 or 0, the following bilinear switching model can be obtained:

$$\frac{di_L}{dt} = -\frac{1}{L}v_c + u\frac{E}{L} \tag{1a}$$

$$\frac{dv_c}{dt} = -\frac{v_c}{RC} + \frac{i_L}{C} \tag{2b}$$

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For control design purpose, it is more convenient to consider the following averaged model, obtained by averaging the model (1) over one switching period

$$\frac{dx_1}{dt} = -\frac{1}{L} x_2 + \mu \frac{E}{L} \tag{1a}$$

$$\frac{dx_2}{dt} = -\frac{x_2}{RC} + \frac{x_1}{C} \tag{2b}$$

Where x_1 and x_2 denote the average input current (i_L) and the average output capacitor voltage (v_c), respectively. The control input for the above model is the duty ratio μ.

C. *Open loop system characteristics*

Using Laplace transform of the (2a-b), the following transfer function of dc-dc power converter is obtained

$$G(s) = \frac{x_2(s)}{\mu(s)} = \frac{G_0}{1 + 2\xi \frac{s}{\omega_0} + \left(\frac{s}{\omega_0}\right)^2} \tag{3}$$

where

$$G_0 = E \,,\ \omega_0 = \frac{1}{\sqrt{LC}} \ ,\ \xi = \frac{1}{R}\sqrt{\frac{L}{C}} \tag{4}$$

and s is Laplace operator.

The step response and bode diagram of the system (3) are illustrated by Fig.2 and Fig.3, respectively.

The figures are carried out using Matlab/Simulink software and with system parameters listed in Table1.

TABLE I
PARAMETERS OF THE CONTROLLED SYSTEM

Parameter	**Value**
Inductance L	4mH
Inductance ESR, R_L	0.2 Ω
Capacitor, C	680µF
Load resistance, R	20 Ω
Input voltage E	12V
Switching frequency, f_s	15kHz

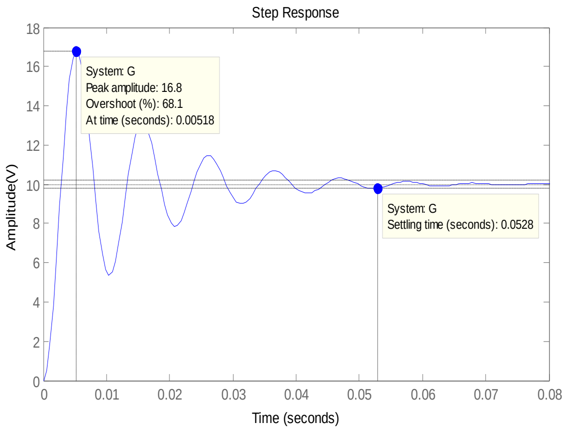


Fig. 2 System step response in open loop

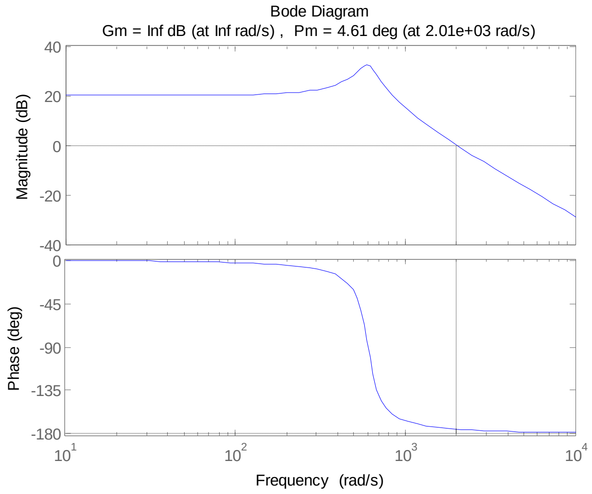


Fig. 3 System bode diagram in open loop

As can be seen from the figures, the system in open loop control presents the following characteristics:

- An overshoot of 70%
- A settling time of 52ms
- A phase margin (PM) of 4.6 degrees.

All these characteristics are not satisfactory. The next Section is then devoted to the controller design which allows better performances.

III. CONTROLLER DESIGN AND SIMULATION RESULTS

The objective now is to design a controller that regulating the output voltage of dc-dc buck power converter and which meets the following requirements

a) an overshoot lower than 10%,
b) a zero steady-state error,
c) a phase margin greater than 35 degrees.

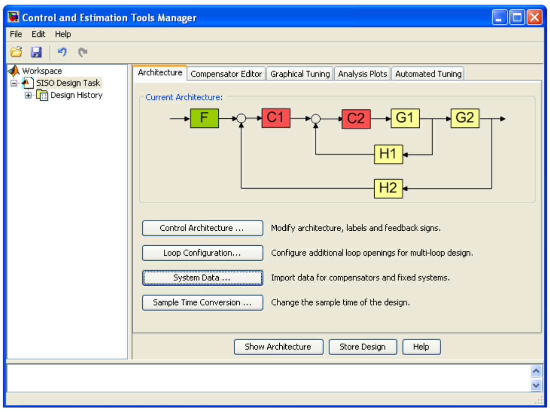
In order to meet all the control objectives, the following PI controller is proposed

$$C(s) = K_P\left(1 + \frac{1}{T_p s}\right) \tag{5}$$

The controller optimal parameters K_p and T_p are tuned using the Sisotool® software integrated in Matlab® (see Fig.4). Accordingly, the regulators C(s) is optimized in order to satisfy some design requirements such as phase margin (PM), gain margin (GM), settling time. Doing so, the following parameter values have been retained

$$K_p = 37.6 \times 10^{-3} \ \ ,\ \ T_p = 10ms \tag{6}$$

The performances of the linear control are illustrated by Fig.5 and Fig.6. The simulations show clearly that the linear PI-based control strategy performs well. The phase margin of the compensated system is PM = 37.5deg which allows a high level of robustness against uncertainties.



Control Architecture ... Modify architecture, labels and feedback signs.
Loop Configuration... Configure additional loop openings for multi-loop design.
System Data ... Import data for compensators and fixed systems.
Sample Time Conversion ... Change the sample time of the design.

Fig. 4 Sisotool software of Matlab

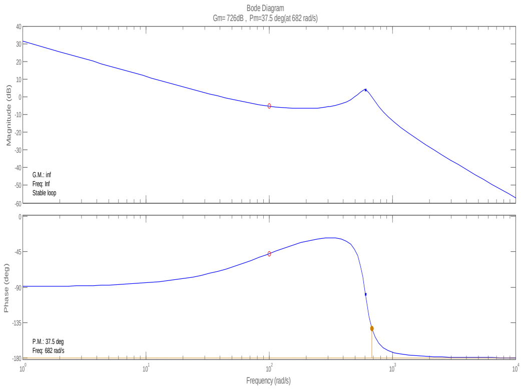


Fig. 5 Bode diagram of compensated system

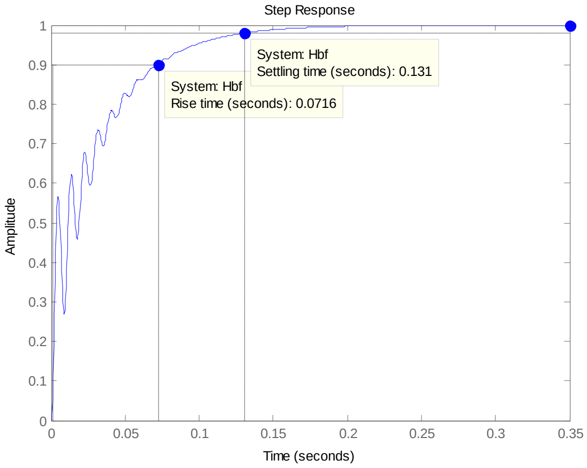


Fig. 6 System step response in closed loop

IV. EXPERIMENTAL RESULTS

A. *Experimental test bench*

To implement the proposed control system, an experimental test bench was developed. It consists essentially of (see Fig. 9):

- A 300W Programmable DC Electronic Load from BK Precision operated under multiple modes such as constant current (CC), constant voltage (CV), constant power (CW), and constant resistance (CR).
- A power supply from BK Precision.
- Hall Effect voltage and current sensors.
- A digital oscilloscope.
- A dc-dc buck power converter.
- A dspace DS1104 with Control Desk software plugged in a Pentium 4 personal computer.[9]

Fig.7 . View of the experimental test bench

B. *Windup phenomena*

Although many aspects of a control system can be understood based on linear theory, some nonlinear effects must be accounted for in practice. The "Windup" phenomena is such an aspect that is encountered in our first experiments. The output takes a long time to converge to its desired value. The system is also unstable in presence of the load step changes.

The deterioration of the controller performances (when the system deviates from its nominal operation point) is presently worsened by the presence of the control input limitation (the duty ratio is constrained between 0 and 1). The presence of both input limitation and an integrator in the controller make the closed-loop system suffer from what is commonly called "windup effect". This means that the system signals are likely to diverge if a disturbance affects the system. Presently, the disturbance is produced by the modeling error resulting from the load resistance uncertainty.

To overcoming this issue, a PI controller with "anti windup" is used (see Fig. 8). Integrator windup is avoided thanks to back-calculation which works as follows: when the output saturates, the integral term in the controller is recomputed so that its new value gives an output at the saturation limit. It is advantageous not to reset the integrator instantaneously but dynamically with a time constant T_i. The time constant T_i determines how quickly the integrator of the PI controller is reset[5][6][7][8].

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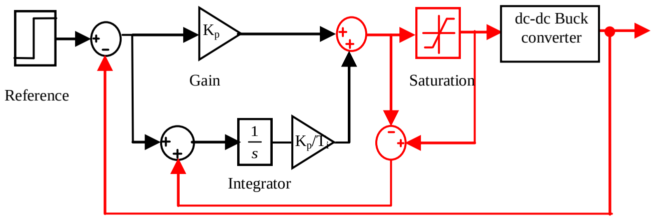

Fig . 8 Anti windup scheme for PI controller.

C. Controller performance evaluation

The control system with anti windup scheme (Fig.8) has been implemented in the dSPACE DS1104 R&D Controller Board. Used with Real-Time Interface (RTI), the DS1104 R&D Controller Board is fully programmable from the Simulink® block diagram environment and all I/O are configured graphically. The experiment results are illustrated by Fig.9 to Fig.11.

Fig.9 and Fig. 10 illustrate the output voltage v_c and the inductor current i_L in presence of load current step changes between 4A and 6A. The changes are performed using Programmable DC Electronic Load. The figures clearly show that the output voltage is regulated to its desired V_d=10V value whatever the load changes.

Fig. 11 shows the binary control input u applied to the gate of IGBT switch.

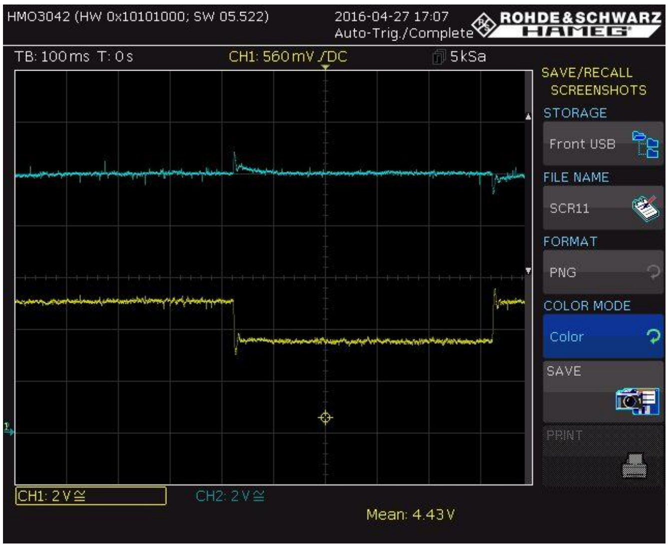

Fig. 9 Output voltage V_C and inductor current i_L in presence of load step changes between 4A and 6A

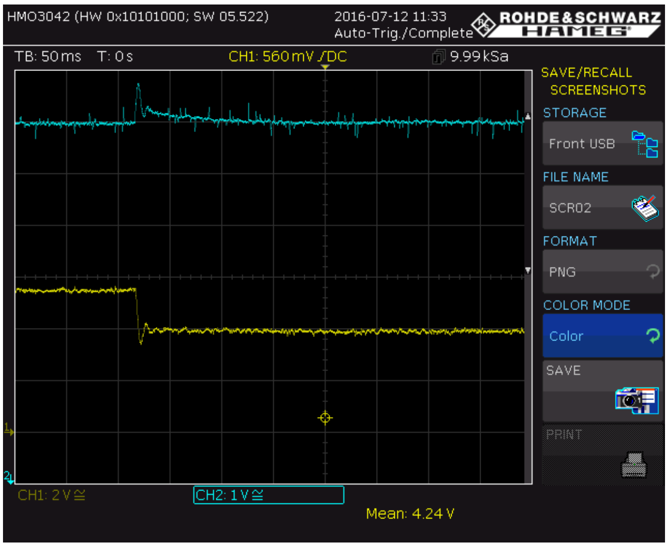

Fig.10 Zoom of output voltage Vc and inductor current i_L in presence of load step changes between 4A and 6A

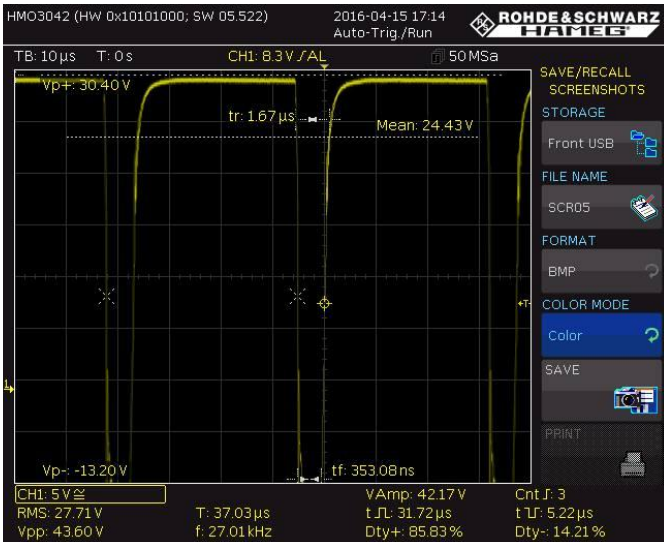

Fig.11 Binary control input signal u

V. CONCLUSION

The PI controller with anti-windup scheme has been designed to ensure large signal stability of the DC-DC buck converter and to improve its large signal dynamic response in presence of load variations. The PI controller with anti-windup technique has removed the limitation of the input signal and resolved the wind up effect caused by the integrator. It is formally shown, using experimental results that the proposed controller achieves a high level of performances in term of rapidity, stability and robustness against perturbations.

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