Proceedings of the 36th
Conference on Decision & Control
San Diego, California USA • December 1997

An experimental comparison of several non linear controllers for power converters[1]

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Abstract

In this paper we present an experimental comparative study of five controllers for boost dc-to-dc converters recently reported in the control literature. For all these algorithms local asymptotic stability of the desired equilibrium is insured. To carry out the experiments we constructed a low cost electronic card, which captures the essential features of a commercial product. The algorithms are compared with respect to ease of implementation, in particular their sensitivity to the tuning parameters, and closed-loop performance. The latter is evaluated with the standard criteria of steady-state and transient behaviour to steps and sinusoidal references, and attenuation of disturbances in the power supply and sensitivity to unknown loads. Motivated by the experimental evidence we propose several modifications to the basic schemes, for some of them we establish some new theoretical results.

1 SWITCH-REGULATED BOOST CONVERTER

The boost DC-DC converter is a typical example of switched power converter described by a bilinear second order model with a binary input. The control task is further complicated by the fact that, with respect to the output to be regulated, the model is nonminimum phase.

1.1 Exact and averaged model

Throughout the paper we consider the switch-regulated "boost" converter circuit of figure 1.

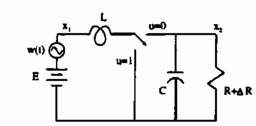

Figure 1: Switch-regulated Boost circuit

The "exact" model of the circuit is given by

$$\begin{aligned} \dot{x}_1 &= -(1-u)\frac{1}{L}x_2 + \frac{E+\omega}{L} \\ \dot{x}_2 &= (1-u)\frac{1}{C}x_1 - \frac{1}{(R+\Delta R)C}x_2 \end{aligned} \tag{1}$$

where x_1 is the inductor current and x_2 the capacitor voltage; $E > 0$ is the nominal constant value of the external voltage source and ω is an unknown (time-varying) disturbance ($|\omega| < E$); R is the nominal constant value of the output resistance and ΔR reflects the parametric uncertainty; $u \in \{0, 1\}$ is the control input (switch position). The regulated output is x_2 which should be driven to some constant desired value $V_d > E$.

Provided the switching is sufficiently fast and the capacitor voltage is bounded away from zero, the behaviour of the converter can be accurately described by the following approximate (continuous-time) averaged model[2] [5],

$$\begin{aligned} \dot{z}_1 &= -(1-\mu)\frac{1}{L}z_2 + \frac{E+\omega}{L} \\ \dot{z}_2 &= (1-\mu)\frac{1}{C}z_1 - \frac{1}{(R+\Delta R)C}z_2 \end{aligned} \tag{2}$$

with z_1, z_2 the corresponding averaged variables.

2 CONTROL LAWS

The control laws that we consider are divided in *continuous* and *switched laws* depending on whether they use or not an auxiliary PWM circuit to generate the control signal. This means also that for the control design, they use the continuous (averaged) or the switched (exact) model. In the absence of external disturbances and parameter uncertainty, i.e., when $\omega \equiv 0, \Delta R \equiv 0$, they all achieve (local) asymptotic stabilization.

2.1 Continuous control laws

- *Linear Averaged Controller (LAC)*: Linearization of the averaged model (2) around an equilibrium point[3] yields the linearized model $\dot{\tilde{z}} = A\tilde{z} + B\tilde{\mu}$, with (A, B) controllable. Hence, the poles of $(A-BK)$ can be located arbitrarily with a suitable choice of the state feedback gains $K = [k_1 \ \ k_2]$.

- *Feedback Linearizing Controller (FLC)*: In [3] is proposed a nonlinear (static state feedback) controller that linearizes the IO behaviour of the system, with output the circuit total energy, $H = \frac{1}{2}z^T Dz$.

- *Passivity-Based Controller (PBC)*: In [5] is proposed a nonlinear dynamic controller that preserves passivity of the closed loop system.

[1] This work was supported in part by the Consejo Nacional de Ciencia y Tecnología of Mexico.

[2] The only difference between the two models is that now μ is a continuous, and not a binary signal.

[3] See [8] for more details

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2.2 Switched control laws

• *Sliding Mode Controller (SMC)*: In [4] an indirect sliding mode controller is proposed.

• *Sliding Mode plus Passivity Based Contr (SM+PBC)*: In [6] sliding modes with passivity are combined to try to reduce the energy consumption in **SMC**.

2.3 Adaptive schemes

• *Adaptive PBC*: In [7] is presented an *adaptive* version of the **PBC** where the parameter $\frac{1}{R}$ is estimated.

• *Adaptive SMC*: We propose the switching policy,

$$\begin{aligned} u &= 0.5\left[\,1 - sgn(x_1 - \hat{\theta}V_d^2/E)\right] && (3)\\ \dot{\hat{\theta}} &= -\gamma V_d\,(x_2 - V_d)\,, \quad \gamma < \frac{E^2}{V_d^4 L} && (4) \end{aligned}$$

where $\hat{\theta}$ is the estimated of $\frac{1}{R}$ and $\gamma > 0$ a design parameter.

• *Adaptive SM+PBC*: We propose to consider the same switching policy as above, but using the estimator

$$\dot{\hat{\theta}} = -\gamma x_{2d}\,(x_2 - x_{2d}) \qquad (5)$$

with the controller auxiliary dynamics

$$\begin{aligned} \dot{x}_{1d} &= -\frac{1}{L}(1-u)x_{2d} + \frac{R_1}{L}(x_1 - x_{1d}) + \frac{E}{L}\\ \dot{x}_{2d} &= \frac{1}{C}(1-u)x_{1d} - \frac{\hat{\theta}}{C}x_{2d} && (6) \end{aligned}$$

where $R_1 > 0$ and $\gamma > 0$ are design parameters.

2.4 Adding an integral term

In order to compensate the steady state error due to load resistance uncertainty we propose to add the integral term[4], $I(t) = -K_i \int_0^t [x_2(s) - V_d]ds$; $K_i > 0$.

3 EXPERIMENTAL RESULTS

In fig. 2 we show the card used to implement the five control laws. It is formed by a boost circuit, a PWM circuit , and some signal conditioners. In this card is possible to introduce disurbance signals to the source and output load. The boost circuit can be controlled by means of a PWM generated signal or by directly introducing a switching signal.

The behaviour of the five control laws is compared with the following basic criteria:

i) transient and steady state response to steps and sinusoidal output voltage references,

ii) attenuation of step and sinusoidal disturbances in the power supply,

ii) response to pulse changes in the output resistance.

4 CONCLUSIONS

• **FLC** performed very well in output regulation and tracking but exhibited a bigher sensitivity to voltage disturbances than the other schemes. Incorporating an integral action effectively compensated for a step change in load resistance, eventhough no theory is available to sustantiate this.

• The main drawback of **PBC**, which is shared also by **SMC** and **SM+PBC**, is the inability to shape the response of the output voltage, which evolves according to the open-loop dynamics. This, of course, stems from the fact that we cannot inject damping to the voltage subsystem without nonlinearity cancellation. On the other hand, **PBC** achieved a better disturbance attenuation, hence it may be a viable candidate for applications where rise time is not of prime concern.

• **SMC** and **SM+PBC**, these remarkably simple approaches proved very robust to source disturbances but highly sensitive to parameter uncertainty. The latter could be alleviated incorporating a novel adaptation mechanism. The lack of flexibility of **SMC** is somehow alleviated in **SM+PBC**, at least to shape the disturbance attenuation characteristic.

[4]Note that this term is continuous so we can add it only to the duty ratio $\mu(t)$ in the laws **LAC**, **FLC** and **PBC**.

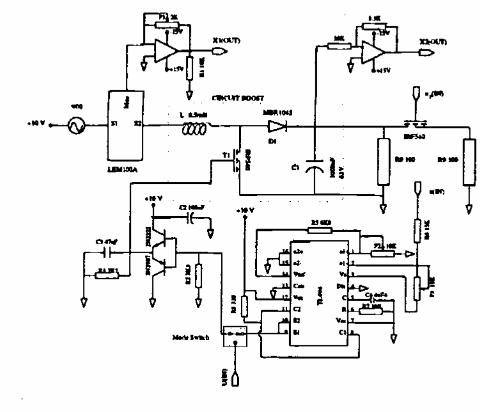

Figure 2: Boost circuit card

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