

Non-linear predictive control of a DC-to-DC converter¹

M. Lazar* - R. De Keyser**

** Department of Electrical Engineering, Control Systems Group
Eindhoven University of Technology*

*P.O. Box 513, 5600 MB Eindhoven, The Netherlands
Tel: 31-40-2473795 - Fax: 31-40-2434582 - E-mail: m.lazar@tue.nl*

***EeSA - Department of Electrical energy, Systems & Automation
Ghent University, Technologiepark 913, B-9052 GENT, Belgium
Tel: 32-9-2645585 - Fax: 32-9-2645603 - E-mail: rdk@autoctrl.UGent.be*

Abstract

In this paper we develop a non-linear predictive controller for regulating DC-DC power converters. The proposed control strategy is implemented and tested using two models: an averaged non-linear model for control purposes and a switched Buck-Boost circuit model as the controlled plant. A comparison with classical PID control in terms of start-up behavior and robustness to disturbances is given in order to outline the performance of the predictive controller.

1. - INTRODUCTION

Some of the most important circuits within the family of power circuits are the DC-DC converters. They are extensively used in power supplies for electronic equipment to control the energy flow between two DC systems (e.g. well-regulated DC-to-DC power converters are critical for mission success on space platforms). Control of a DC-DC converter power circuit is based, explicitly or implicitly, on a model that describes how control actions and disturbances are expected to affect the future behavior of the plant. Usually, the control problem consists in defining the desired nominal operating condition, and then regulating the circuit so that it stays close to the nominal, when the plant is subject to disturbances and modelling errors that cause

its operation to deviate from the nominal. Typical control system configurations for power circuits include open-loop as well as closed-loop control strategies.

In both cases, PID controllers are utilized, which can be designed using classical methodologies based on the Nyquist stability criterion and Bode plots or tuned with Ziegler-Nichols techniques. The controller must keep the DC-DC converter within a certain percentage of the specified nominal operating point in the presence of disturbances and modelling errors. Unfortunately, PID control does not always fulfil the above mentioned control specifications, especially when disturbance rejection and transient response time requirements are concerned, due to the highly non-linear characteristics of the DC-DC converters. As a result of this fact, there is much interest in developing more intelligent and robust

¹*This work has been partially financially sponsored by the Dutch Science Foundation (STW), Grant "Model Predictive Control for Hybrid Systems" (DMR.5675).*

control structures. Either microcontroller-based or DSP-based approaches have been used to implement advanced/improved control algorithms such as nonlinear PID [7], Fuzzy Logic [4], Feedforward Control [2].

This paper proposes a new control strategy for DC-DC converters, in which the non-linear EPSAC predictive control approach [3] is used to calculate the control input. The Non-linear Model based Predictive Control (NMPC) methodology [1], already very successful in industry [6], uses a process model to forecast the future behaviour of the plant over a finite horizon in time. As a result, the non-linear characteristics of the controlled plant are explicitly taken into account when the control input is calculated and thus, better performance and robustness can be achieved.

A Buck-Boost DC-DC converter has been designed considering all the details of a real power circuit (including parasite components) and implemented in the Matlab Simulink environment. The EPSAC predictive control algorithm uses an *averaged* non-linear model to predict the future behaviour of the *switched* Simulink Buck-Boost converter, which is the plant to be controlled. The results obtained are compared with the ones achieved with *classical* PID control in terms of start-up behaviour and robustness to disturbances.

2. - PLANT AND NON-LINEAR MODEL

2.1 - Plant model for the predictive controller

The Buck-Boost converter has a highly non-linear characteristic, due to the incorporated switch. This converter is capable of producing a DC output voltage at a level either higher or lower than the input voltage, depending on the application. In order to achieve this, the switch (represented by an electronic switch – a transistor) is controlled to produce a voltage that contains a non-zero DC component. This component is extracted by the low-pass LC filter to obtain the output voltage. The main parameters of the power circuit are the load resistor R , the capacitor C and the inductor L . The goal is to keep the average output voltage v_0 within 3% of the desired nominal or reference value V_{ref} , despite changes in the input DC supply voltage v_{in} (nominal value V_{in}) and despite variations of the load R . The following switching function, $q(t)$, represents the switch

status, with $q(t) = 1$ when the transistor is On and $q(t) = 0$ when it is Off; let $q'(t)$ denote $1 - q(t)$. In order to obtain the state-space model of the circuit, the state variables have been naturally chosen as i_L (inductor current) and v_C (capacitor voltage). The inputs are the input DC supply voltage v_{in} and the control input q .

Introducing the notations $x_1 = i_L$, $x_2 = v_C$, the simplified switched model [5] is obtained:

$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix} = \begin{bmatrix} 0 & q'(t)/L \\ -q'(t)/C & -1/RC \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} q(t)/L \\ 0 \end{bmatrix} v_{in}(t) \quad (1)$$

or in a matrix notation:

$$\dot{x}(t) = A_{q(t)}x(t) + B_{q(t)}v_{in}(t) \quad (2)$$

The discrete-time model required for the implementation of the predictive control algorithm is developed assuming that the switching period T is much smaller than the time constants associated with the circuit. As a result, the inductor current and the capacitor voltage wave forms, in each switch configuration, are essentially straight-line segments. Under this assumption, the following discrete-time model is obtained using the forward Euler approximation, from the continuous time version (2):

$$x(k+1) = (I + TA_{d(k)})x(k) + TB_{d(k)}v_{in}(k) \quad (3)$$

with $A_{d(k)} = d(k)A_1 + d'(k)A_0$, $B_{d(k)} = d(k)B_1 + d'(k)B_0$.

This model is *nonlinear*, time-invariant, discrete in time and in a state-space form with inputs $d(k)$ (the duty cycle - control input, present in matrices $A_{d(k)}$ and $B_{d(k)}$) and $v_{in}(k)$ (acts as a disturbance), and $x_2(k) = v_0(k)$ (the controlled variable) as output.

2.2 - Matlab Simulink Buck-Boost circuit

In order to test the nonlinear EPSAC algorithm, a more complex model of a Buck-Boost DC-DC converter is needed. Note that the model used for control purposes is the averaged model (3), which *includes* the PWM and has as control input the duty ratio $d(k)$ (continuous signal between 0% and 100%) instead of the transistor status $q(t)$ (discrete signal of value 0 or 1 – the control input of model (2)), which makes it more suitable for the predictive control algorithm. Contrary to this, in practice, the control signal is applied to the converter via a PWM, which generates the switching function $q(t)$. Thus, in

order to obtain a control structure more close to the real case, a *true* switched Buck-Boost converter, also including parasite components such as diode parasite resistance R_d , shunt resistance R_s , inductor parasite resistance R_{ind} and capacitor parasite resistance (ESR) R_C , has been implemented in the Matlab Simulink environment together with a PWM. The resulting Simulink model, validated by comparison with a PSpice Buck-Boost circuit for the same values of the components, has been utilized as the controlled plant.

3. - MODEL PREDICTIVE CONTROL

Model Predictive Control (MPC) is a relatively recent control methodology, which is very successful in industry [6], mainly based on the fact that it is capable to cope with hard constraints. The distinguishing features of MPC are the following: the use of a process model to predict the future behavior of the plant, solving on-line an optimization problem to calculate future optimal control actions and the use of the receding horizon strategy [1]. These principles remain the same with respect to the model, but the computational complexity of the control algorithm strongly depends on the type of process model used. Initial MPC algorithms were exclusively designed for linear systems and many ideas were soon suitably generalized to nonlinear systems [1]. One of the first MPC algorithms is the (linear) EPSAC algorithm [3], which has been chosen due to its reduced on-line computational complexity. This aspect is crucial for the plant considered in this paper, because the sampling period T needed to obtain an accurate model (3) of the power converter is very small (i.e. of the order of milliseconds). The extension of the EPSAC algorithm to non-linear models uses a recurrent procedure (which is based on an analytic solution of the corresponding optimization problem) to calculate the control input. Thus, in general, the non-linear EPSAC algorithm requires less computational time than other non-linear MPC algorithms [1]. The fact that the EPSAC approach is also capable to take into account the effect of noise and disturbances makes this MPC controller the most appropriate one for real-time implementation in the case of DC-to-DC converters.

The control problem is to calculate a sequence of inputs that will take the process from its current state to a

desired state, and which is obtained in MPC by solving a local optimization problem based on a cost function. The optimal control sequence must be recalculated at each sampling instant because disturbances affecting the plant may change the location of the optimal operating point. The controller output is then the result of minimizing the cost function:

$$V(\mathbf{U}) = \sum_{k=N_1}^{N_2} [r(t+k/t) - y(t+k/t)]^2 \quad (4)$$

with $r(t+k/t)$ the desired 'reference trajectory' and the 'horizons' N_1 , N_2 being design parameters. The output $y(t+k/t)$ is obtained at each sampling instant k (using the non-linear model (3) and the measured states as initial conditions) as the sum of two components, $y_{base}(t+k/t)$ and $y_{optimized}(t+k/t)$, respectively (see [3] for details). Only the first element of the optimal sequence of inputs \mathbf{U} is then employed to obtain the control input that is applied to the plant. The whole procedure is repeated at the next sampling instant.

4. - NON-LINEAR PREDICTIVE CONTROL OF A BUCK-BOOST DC-DC CONVERTER

The Simulink implementation of the control structure is depicted in Fig. 1. An *S-function* Simulink block has been used to implement the predictive controller based on the non-linear EPSAC algorithm [3]. The controller block *measures* at each discrete-time instant k the inductor current and the output voltage, and makes use of the process model (3) to calculate the control signal, which is then applied to the PWM. The output of the PWM activates a flip-flop actuator that directly controls the electronic switch (a transistor) of the Buck-Boost DC-DC converter, also implemented with an *S-function* Simulink block. Note that the control structure shown in Fig.1 allows the simulation of input DC supply voltage and load resistor disturbances. The closed-loop control structure has been used to analyze the start-up behaviour and the robustness to disturbances of the non-linear EPSAC control algorithm.

For illustration purposes, several experiments have been carried out for different reference voltages (both the buck and the boost behaviour have been tested) and control parameters (prediction horizons). The performance obtained with the non-linear EPSAC based predictive controller is outlined in Fig. 2.

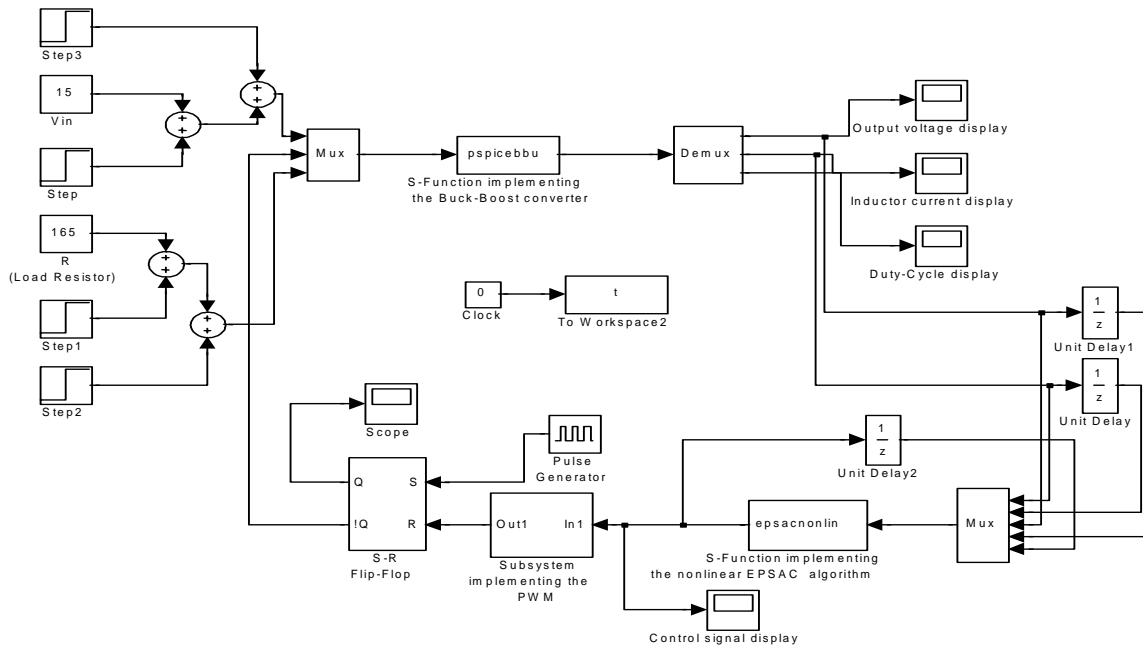


Fig. 1 Simulink diagram of the closed-loop control structure.

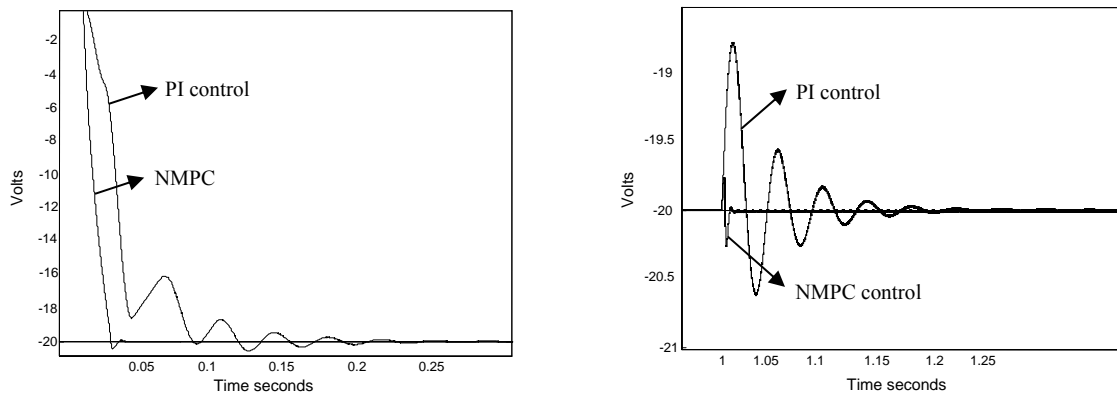


Fig. 2 Simulation results: Start-up behaviour and load disturbance rejection.

The predictive controller utilizes model (3) for control purposes and the Simulink switched Buck-Boost converter (which has been designed taking into account all the details of a real electric circuit, including parasite components) is the controlled plant, as depicted in Fig. 1. In order to make a comparison with the current practice of control for DC-DC converters [5], a PI controller was tuned using formulas based on optimization. The tuning parameters were determined from the step response of the Simulink plant model. The response was obtained with an input signal of 50% (duty ratio). Using formulas

based on optimization, the parameters of the PI controller were calculated, resulting in the proportional gain $K = 0.01$ and the reset time $T_r = 0.0096$. The nonlinear EPSAC predictive controller was compared with the tuned PI controller in terms of start-up behaviour and load disturbance rejection. The simulation results shown in Fig. 2 have been obtained for a Simulink Buck-Boost circuit with the following values for the components: equivalent voltage source $E_d = 1.2V$ and parasite resistance $R_d = 0.06\Omega$ for the Diode, shunt resistance $R_r = 0.5\Omega$ for the Transistor,

inductance $L = 2200\text{mH}$ and parasite resistance $R_{ind} = 0.42\Omega$ for the Inductor, capacitance $C = 2600\mu\text{F}$ and parasite resistance (ESR) $R_C = 0.05\Omega$ for the Capacitor, nominal load $R = 165\Omega$ and nominal input voltage $V_{in} = 15\text{V}$. Note that the *non-linear* model (3) used by the EPSAC NMPC controller to predict the behaviour of the Simulink *switched* circuit does not include the parasite elements of the circuit mentioned above.

The start-up behaviour is shown in Fig. 2 for the desired reference voltage $V_{ref} = -20\text{V}$ and the robustness to disturbances is illustrated in the case of a load disturbance (at the time instant equal to 1 second R drops to 20% of the nominal value). The results obtained show that the nonlinear predictive control algorithm ensures a much better performance than the one achieved with the tuned PI controller and that it guarantees a stable operation under ill conditions.

REFERENCES

- [1] Allgöwer, F.; Badgwell, T.A.; Qin, S.J.; Rawlings J.B.; Wright, S.J.: *Nonlinear predictive control and moving horizon estimation – An introducing overview*. In Advances in Control: Highlights of ECC'99 (P.M. Frank, Ed.), Springer, pp. 391-449, London, 1999.
- [2] Arbetter, B.; Maksimovic, D.: *Feedforward Pulse Width Modulator for Switching Power Converters*. IEEE Transactions on Power Electronics, Vol. 12, No. 2, March, 1997.
- [3] De Keyser, R.M.C: *A Gentle Introduction to Model Based Predictive Control*. European Union EC-ALFA-PADI 2 Int. Conference on “Control Engineering and Signal Processing”, Piura, 1998.
- [4] Gupta, T.; Boudreaux, R.R.; Nelms, R.M.; Hung, J. Y.: *Implementation of a Fuzzy Controller for DC-DC converters Using Inexpensive 8-bit Microcontroller*. IEEE Transactions on Industrial Electronics, January, 1997.
- [5] Kassakian, J.G.; Schlecht, M.F.; Verghese, G.C.: *Principles of Power Electronics*. Adisson-Wesley Publishing Company, Inc., 1992.
- [6] Qin, S.J.; Badgwell, T.A.: *An overview of industrial model predictive control technology*. In Chemical Process Control-AIChE Symposium Series (J. Kantor, C. Garcia and B. Carnahan, Eds.), AIChE, pp. 232-256, New York, 1997.
- [7] Zeller, J.; Zhu, M.; Stimac, T.; Gao, Z.: *Nonlinear Digital Control Implementation for a DC-to-DC Power Converter*. Proc. of 36th Intersociety Energy Conversion Engineering Conference IECEC'01, July 29 – August 2, Savannah, Georgia, 2001.