MODEL-FREE CONTROL OF NONLINEAR POWER CONVERTERS

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ABSTRACT

A new "model-free" control methodology is applied to a boost power converter. The properties of the boost converter allow to evaluate the performances of the model-free strategy in the case of switching nonlinear transfer functions, regarding load variations. Our approach, which utilizes "intelligent" PI controllers, does not require any converter model identification while ensuring the stability and the robustness of the controlled system. Simulation results show that, with a simple control structure, the proposed control method is almost insensitive to fluctuations and large load variations.

Index Terms— Power engineering computing, Automatic control, DC-DC power converters, Computer simulation, State-space methods

1. INTRODUCTION

The model-free control methodology, originally proposed by [1], has been widely successfully applied to many mechanical and electrical processes. The model-free control provides good performances in disturbances rejection and an efficient robustness to the process internal changes. A preliminary work on power electronics [2] presents the successful application of the model-free control method to the control of dc/dc converters. The control of nonlinear power converters has been deeply studied and some advanced methods have been successfully developed and tested (e.g. [3] [4] [5] [6] [7]). This paper extends the previous results to the control of the boost converter working in different conduction modes. In particular, we will show that the proposed control method is robust to strong load changes that may involve switching working modes.

The paper is structured as follows. Section II presents an overview of the model-free control methodology including its advantages in comparison with classical methodologies. Section III presents the basic theory of the boost converter. Section IV discusses the application of the model-free control to the boost converter. Some concluding remarks may be found in Section V.

2. MODEL-FREE CONTROL: A BRIEF OVERVIEW

2.1. General principles

We only assume that the plant behavior is well approximated in its operational range by a system of ordinary differential equations, which might be highly nonlinear and time-varying. The system, which is SISO, may be therefore described by the input-output equation:

\[ E(t, y, y^{(\epsilon)}, u, u^{(\kappa)}) = 0 \]  

- \( u \) and \( y \) are the input and output variables,
- \( E \), which might be unknown, is assumed to be a sufficiently smooth function of its arguments.

From (1), we define an ultra-local model, which represents (1) over a small time period.

Definition 2.1 If \( u \) and \( y \) are respectively the variables of input and output of a system to be controlled, then this system can be described as the ultra-local model defined by:

\[ y^{(\alpha)} = F + \alpha u \]  

where \( \alpha \in \mathbb{R} \) is a non-physical constant parameter, such that \( F \) and \( \alpha u \) are of the same magnitude, and \( F \) contains all structural information of the process.

In all the numerous known examples, it was possible to set \( n = 1 \) or 2 [8]. Let us emphasize that one only needs to give an approximate numerical value to \( \alpha \). The gained experience shows that taking \( n = 2 \) allows to stabilize switching systems.
2.2. Intelligent PI controllers

Definition 2.2 [7] We close the loop via the intelligent PI controller, or i-PI controller,

\[ u = \frac{[F]}{\alpha} + \frac{y^{(n)}}{\alpha} + C(\varepsilon) \]  

where

- \([F]\) is an estimate of \(F\) in (2), computed on-line as \([y^{(n)}] - \alpha u\), where \([y^{(n)}]\) is an approximation of the output derivative;
- \(y\) is the measured output to control and \(y^*\) is the output reference trajectory;
- \(\varepsilon = y^* - y\) is the tracking error;
- \(C(\varepsilon)\) is of the form \(K_p\varepsilon + K_i \int \varepsilon\). \(K_p\) and \(K_i\) are the usual tuning gains.

Equation (3) is called the model-free control law or model-free law.

The i-PI controller (3) is compensating the poorly known term \(F\) and controlling the system therefore boils down to the control of an integrator. The tuning of the gain \(K_p\) and \(K_i\) becomes therefore straightforward.

Our implementation of (3) assumes a sampled-data control context, where the control input is kept constant over the inter-sampling interval and the output derivatives are approximated by finite-differences of the outputs. At the \(k\)th sampling instants, we have [9]:

\[ u_k = u_{k-1} - \frac{1}{\alpha T_c} \{(y_{k-1} - 2y_{k-2} + y_{k-3}) - (y'_{k-1} - 2y'_{k-2} + y'_{k-3})\} + C(y'_{k-1} - y_{k-1}) \]  

where \(u_k\) refers to the averaged duty-cycle at the \(k\)th sampling instant and \(T_c = 0.1\) ms is the switching period. The main advantage of the proposed control approach is that sudden changes in the model, e.g., due to load changes, and model uncertainty can be overcome as \(F\) in (2) is re-estimated at every sampling instant from the output and inputs derivatives. We note that the potential amplification of noise by differentiation of the output can be countered by using moving average filters, see [9].

3. THE BOOST CONVERTER

The boost converter is a well-known power converter that produces a dc output voltage greater in magnitude than the dc input voltage [10]. It has two working modes, the continuous mode and the discontinuous mode, that involve two different nonlinear transfer functions according to the output current.

Consider the boost converter depicted in Fig. 1 whose parameters are given in the Tab. 1. The parameter \(f_c\) is the switching frequency.

A full state-space averaged model, derived by [11], allows to describe the working modes of the boost converter. The model-free control implementation is based on this formulation and aims to control the output voltage \(V\) according to a reference output \(V^*\).

3.1. Nonlinear average modeling

There exist three possible states according to the value of the duty-cycle. Denote \(u\) the instantaneous control variable of the boost converter, \(d_1\) defines the on-state duration (i.e. \(u = 1\)), \(d_2\), the off-state duration in the continuous mode (i.e. \(u = 0\) and \(i_L \neq 0\) and \(d_3\), the off-state duration in the discontinuous mode (i.e. \(u = 0\) and \(i_L = 0\)). The equations take the form:

\[ \dot{x} = A_1 x + b_1 E \text{ for } t \in [0, d_1 T_s] \]
\[ \dot{x} = A_2 x + b_2 E \text{ for } t \in [d_1 T_s, (d_1 + d_2) T_s] \]
\[ \dot{x} = A_3 x + b_3 E \text{ for } t \in [(d_1 + d_2) T_s, T_s] \]  

where \((A_1, b_1), (A_2, b_2)\) et \((A_3, b_3)\) represent respectively the state-spaces of conduction, non-conduction and discontinuous conduction.

with:

\[ A_1 = \begin{pmatrix} 0 & 0 \\ 0 & -1/RC \end{pmatrix} \quad A_2 = \begin{pmatrix} 0 & 1/RC \\ 1 & -1/RC \end{pmatrix} \quad A_3 = \begin{pmatrix} 0 & 0 \\ 0 & -1/RC \end{pmatrix} \]

\[ b_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad b_2 = \begin{pmatrix} 1/RC \\ 0 \end{pmatrix} \quad b_3 = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \]

Table 1. Parameters of the boost converter.

| Componant | Value       |
|-----------|-------------|
| \(L\)     | 10 mH       |
| \(C\)     | 47 \(\mu\)F|
| \(R\)     | 50 - 200 \(\Omega\) |
| \(f_c\)   | 10 kHz      |
Ref. [11] presents a derivation of (5) in order to obtain a single state-space averaged representation that models the three working modes depending on the value of \( d_1 \). Assuming that the state vector of the boost converter (Fig. 1) is written \( x = (i_L, v_C)^T \), the state-space representation of the boost converter reads:

\[
\begin{pmatrix}
\langle \dot{i}_L \rangle \\
\langle \dot{v}_C \rangle 
\end{pmatrix} = \begin{pmatrix}
0 & -d_2/\tau \\
d_1 + d_2 & 0 
\end{pmatrix} \begin{pmatrix}
\langle i_L \rangle \\
\langle v_C \rangle 
\end{pmatrix} + \begin{pmatrix}
1/\tau \\
d_1/\tau 
\end{pmatrix} E
\]

(9)

where \( M \) is a matrix that corrects the resulting state-space according to the number of reactive elements in the circuit [12].

\[
M = \begin{pmatrix}
\frac{1}{d_1 + d_2} & 0 \\
0 & 1 
\end{pmatrix}
\]

(10)

The input of this state-space model \( d_1 \) is defined by \( d_1 \equiv \langle u \rangle \).

The averaged output voltage \( \langle v_C \rangle \) from (9) is directly used as the feedback measurement to compute the model-free control.

### 3.2. Conduction modes

We define two conduction modes of the boost converter according to the \( i_L \) current. In particular,

- **The continuous mode (CCM)** is defined by a \( i_L \) current which does not vanish during a switching period. The static transfer relation between the input \( u \) and the output \( V \) verifies:

\[
\frac{V}{E} = \frac{1}{1 - \langle u \rangle}
\]

(11)

The relation between the on-state \( d_1 \) and the off-state \( d_2 \) verifies:

\[
d_2 = f(d_1) = 1 - d_1
\]

(12)

- **The discontinuous mode (DCM)** is defined by a \( i_L \) current which vanishes during a switching period. The static transfer relation between the input \( u \) and the output \( V \) verifies:

\[
\langle v_C \rangle = E \left[ 1 + \langle u^2 \rangle \right] \frac{E}{2L \langle i_s \rangle}
\]

(13)

The relation between the on-state \( d_1 \) and the off-state \( d_2 \) verifies:

\[
d_2 = f(d_1, \langle v_C \rangle, E) = \frac{E}{\langle v_C \rangle} - E d_1
\]

(14)

According to the value of the duty-cycle \( \alpha \) and the maximum magnitude of the current going through the diode \(|I_D|\), the passage from the CCM and DCM modes can be described by a nonlinear relation such as:

\[
\frac{1}{2|I_D|} d_1(1 - d_1) = 1
\]

(15)

Note that in the DCM, \( d_2 \) depends not only of \( d_1 \) but also on \( \langle v_C \rangle \), which results finally in a nonlinear transfer function [10].

### 4. SIMULATION RESULTS

We adjust the parameters of the model-free control [4], which are not correlated to the model, such as the boost converter is stabilized at the beginning of the simulation, whatever the initial conduction mode. In particular, we take \( K_p = 2, K_i = 10 \) and \( \alpha = 30 \). Figure 2 presents the stabilization of the output voltage \( V \) following a constant output reference \( V^* \).

Fig. 2. Tracking and stabilization with a constant output reference.

Figures 3 and 4 present the tracking of an exponential output reference \( V^* \) in presence of a load change at \( t = 0.06 \) s that induces a switch of the working mode, according to (15). Figure 5 focuses on the initial resonant transient in the CCM in presence of a load change that does not involve a switch of the working mode.

Fig. 3. Tracking of an exponential output reference - at \( t = 0.06 \) s, the load switches from \( R = 100 \Omega \) to \( R = 50 \Omega \), inducing a switch from DCM to CCM.

We observe that the model-free control is able to stabilize the output voltage even if the change of the load induces a switch.
between the two conduction modes. To damp the oscillations that occur during each switching transient, an advanced model-free controller can be used [13].

5. CONCLUDING REMARKS

The simulations on the boost power converter aims to generalize the use of the model-free control to nonlinear power systems. Simulations show that the model-free control methodology yields robust performances with respect to disturbance rejection as well as the stabilization of the switching modes. This methodology moreover does not need any well-defined mathematical model, that would require some complex identification procedure. A single parameter only, $\alpha$, needs to be tuned properly in order to ensure a large variety of working points.

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