A Buck-Boost bidirectional converter to drive piezoelectric actuators

Oriol Gomis-Bellmunt, Daniel Montesinos-Miracle, Samuel Galceran-Arellano and Antoni Sudrià-Andreu

Centre d’Innovació Tecnològica en Convertidors Estàtics i Accionaments (CITCEA-UPC), Departament d’Enginyeria Elèctrica, Universitat Politècnica de Catalunya.

ETS d’Enginyeria Industrial de Barcelona, Av. Diagonal, 647, Pl. 2. 08028 Barcelona, Spain

Tel.: +34 / 93 4016727
Fax: +34 / 93 4017433
E-Mail: oriol.gomis@upc.edu
URL: www.citcea.upc.edu

Acknowledgements

Supported by CICYT through grant DPI2005-08668-C03-03.

Keywords

«Piezoelectric devices», «Intelligent actuators», «Variable structure systems».

Abstract

The present work deals with the development and control of a converter to drive piezoelectric actuators. In order to maximize the field in the piezoelectric ceramic important voltages are needed. To fulfill such requirements with a limited input voltage a bidirectional buck-boost converter is proposed. The converter is controlled by means of a sliding mode control strategy. The converter is validated by means of simulations.

Introduction

The increasing number of applications where the piezoelectric actuators are used is motivating the development of specific converters to drive such actuators. Different switching converter topologies have been employed to drive such elements, including flyback [13], buck-boost [8], push-pull [12] and converters based on piezoelectric transformers [10]. The most common strategy to control the position and force of a piezoelectric actuator is the direct regulation of the voltage applied [12]. The non-linear relationship between displacement and voltage can be improved working with the electric charge instead of the voltage. This strategy has been used successfully by many authors [1-3,5-7,9,18]. The main drawback of the charge control is the necessity of sensing and integrating the current supplied to the load, with the corresponding problems involved. Piezoelectric loads differ from the conventional loads assumed in the conventional converters. They behave as voltage sources and there is only current when the voltage is changing or when they are producing mechanical work. If the voltage is unchanged and the actuator is unloaded there is no current. Hence the converter can operate in either continuous or discontinuous conduction mode depending on the converter and load state. Furthermore, the voltage in the output capacitance (or load) cannot be considered constant and therefore the currents cannot be assumed linear. Such a complexity increase is to be introduced in the converter design in order to optimize the actuator drive performance.

This work introduces a bidirectional buck-boost converter and a sliding mode control strategy. The necessity for such a control strategy arises from the fact that a PI controller cannot deal properly with small capacitance ranges. The converter works with a supply voltage of 325 V and has been designed for load voltages between 0 and 1000 V, changing at frequencies up to 2 kHz. This topology has been chosen against the push-pull configuration [12] because of its voltage elevation capability. It is important to remark that the employed model for the piezoelectric actuator is valid for frequencies far
away from the resonance (aprox. 40 kHz), where another branch would have to be included to describe the behavior of the actuator.

**Converter**

The converter analyzed is shown in Fig. 1. It consists in a bidirectional buck-boost converter. The main advantage of such a converter is its capability of both elevating and reducing the voltage. This is of particular interest dealing with piezoelectric actuators due to the need of voltage elevation to maximize the field in the piezoelectric element. The main drawbacks are the high voltage of the switches (the output is negative and thus, the voltage supported is the input plus the output) along with the non-linear transference function \(-D/(1-D)\) where D is the duty factor. The converter can operate with positive and negative iL current but always with negative uC voltage. It is important to note that no output capacitor is used, only the equivalent capacitance of the piezoelectric load is considered. It improves the efficiency of the converter, since no power is needed to charge and discharge the output capacitor, but it complicates the control, not allowing normal PID control. The converter show two clear operating modes: charging and discharging. It can be noted that the circuit under study can be either an inductance connected directly to a voltage source or a LC circuit connected to a voltage source. Depending on the case different equations and results will be considered.

![Converter diagram](Image)

(a) Charging operation. S1 ON.  
(b) Charging operation. S1 OFF.  
(c) Discharging operation. S2 ON.  
(d) Discharging operation. S2 OFF.

Fig. 1: Converter under study with the considered states

**Control**

The non-linearity of the converter along with the problems encountered when working with classical PI controllers for low equivalent capacitance values have motivated the election of a non-linear control strategy. Among them the sliding mode control has been chosen due to the appropriate physical interpretation of the sliding surface as an energy surface, its ease of implementation and the suitability to drive power converters as shown in [16,11]. Two energy based sliding surfaces have been introduced to allow the controller disconnect the switches when the needed energy is in the inductance, before the voltage raise in the equivalent capacitance occurs.
Taking $x_1 = i_L$ and $x_2 = u_C$, the control law is based on the sliding surfaces:

\[
    S_1(e, t) = E_1^* - E_1 = \frac{1}{2} C_P x_2^2 - \frac{1}{2} L_M x_1^2
\]

\[
    S_2(e, t) = E_2^* - E_2 = \frac{1}{2} C_P x_2^2 - \frac{1}{2} C_P x_2^2
\]

The control law yields:

\[
    U_1(t) = \begin{cases} 
        0 & S_1(e, t) < -\varepsilon \\
        1 & S_1(e, t) > \varepsilon 
    \end{cases}
\]

\[
    U_2(t) = \begin{cases} 
        1 & S_2(e, t) < -\varepsilon \\
        0 & S_2(e, t) > \varepsilon 
    \end{cases}
\]

### Results

The converter has been simulated using Matlab Simulink © (see Figs. 2 and 3) for different equivalent capacitance values and different voltage reference signals with sampling and calculation frequency of 500 kHz. For all the simulations the time and state plane response is shown.

It can be noted in the simulation results that the more the voltage increases the more current the converter needs. It is a consequence of the fact that the energy increment is not linear against the voltage. The power exchanged between the source and the converter can be equaled to the energy variation in the capacitance as:

\[
    \bar{V}_S \bar{i}_L \frac{\bar{u}_C}{\bar{u}_C} \bar{V}_S = \dot{E} = C_P \bar{u}_C \bar{i}_C \Rightarrow \bar{i}_L = C_P \left( \frac{\bar{u}_C}{\bar{V}_S} + 1 \right) \bar{u}_C
\]

The latter expression can be analyzed in order to obtain the maximum frequency available for a given maximum current and certain voltage and capacitance value. The value of $\bar{u}_C$ for a triangular reference voltage yields $2 f \Delta u_{ref}$ $\psi$. For a sinusoidal reference the maximum value $\bar{u}_C_{max} = f \pi \Delta u_{ref}$ $\psi$.

Hence it can be written as $\bar{u}_C_{max} = f k \Delta u_{ref}$ $\psi$ where $k$ depends on the reference signal type. The frequency is then limited by:

\[
    f_{max} = \frac{\bar{i}_L}{k \Delta u_{ref} f C_P \left( \frac{\bar{u}_C}{\bar{V}_S} + 1 \right)}
\]
that also the filtered data is plotted.

Fig. 2: Simulation results for a sinusoidal reference signal
Fig. 3: Simulation results for a rectangular reference signal

(a) Time response $C = 0.1\mu F$

(b) State plane response $C = 0.1\mu F$

(c) Time response $C = 0.25\mu F$

(d) State plane response $C = 0.25\mu F$
Conclusions

A bidirectional buck-boost converter with its control strategy has been presented. This converter has been designed to deal with the drive of piezoelectric actuators and considers their particular requirements (capacitive load behavior). The control strategy is based on sliding mode control. Two different sliding surfaces based on the energy are introduced to optimize the performance of the controller. The designed converter is simulated and the results obtained have shown to be reliable. The state-space evolution of the voltages and currents has been analyzed and the limitations of the converters have been discussed. Further work will be done to test experimentally the described converter.

References


