BIDIRECTIONAL BUCK-BOOST CONVERTER WITH VARIABLE OUTPUT VOLTAGE

Bhaskar Krishnamachari

Department of Electrical Engineering
The Cooper Union
New York, NY 10003
krishn2@cooper.edu

Dariusz Czarkowski

Department of Electrical Engineering
Polytechnic University
Brooklyn, NY 11201
dcz@pl.poly.edu

ABSTRACT

An increasing number of manufacturing processes rely on ultra-high speed and accuracy machines. Piezoceramic actuators are being utilized as parts of such machines. So far, only linear and switched-capacitor power supplies have been used for driving piezoceramic actuators in such applications. This paper proposes a switch-mode power supply to reduce cost and increase system efficiency. In the proposed design, the traditional PWM buck-boost topology is modified to accommodate bidirectional operation, and dynamic compensation is applied between the reference and the output to ensure good frequency response and low steady-state error of the variable output voltage. The converter operation is verified by Saber simulations.

1. INTRODUCTION

Piezoceramic actuators are used in ultra-high speed and accuracy machinery. A power supply with a variable output voltage capability is required for driving these actuators. Although switch-mode power supplies (SMPS) are lightweight and efficient, due to design difficulties, they have not been used for such applications so far.

An equivalent model of a piezoelectric actuator can be represented at low frequencies (below 1 kHz) as a capacitance of the dielectric [1]. The value of this capacitance for actuators investigated in this study is in the order of $C = 10\ \mu$F.

The power supply system should be able to convert a 120 V_{rms} ac line voltage to a stabilized and regulated dc output voltage V_{out}. The dc range of V_{out} is 0–250 V. In a stand-by mode, the voltage across the actuator is kept in the middle of the voltage range, that is, at about 125 V. For an actuator maximum operating frequency $f = 500$ Hz, the maximum output current of the power supply can be calculated as

$$I_{Omax} = \pi f C V_{out,max} = 3.93 \text{ A}. \tag{1}$$

The ac line voltage is rectified in a peak rectifier consisting of a diode bridge and a large capacitor. The peak rectifier provides an unstabilized dc voltage of about $V_{in} = 170$ V to the input of a dc-dc converter. The task of the dc-dc converter is to supply a stabilized dc voltage to the actuator and to regulate the output voltage according to a motion-control goal. The required magnitude of the output voltage is indicated by a reference voltage input to the power supply. Most SMPSs are built to provide a stabilized dc output voltage of a constant value. There are no reports on SMPSs with output voltage tracking capabilities over the large range required for such capacitive loads as piezoelectric actuators. For this application, it is also desirable to have high speed operation so that the output voltage follows the reference even at frequencies up to 500 Hz. Large changes in the output voltage and fast dynamic response make topology selection and the design of the converter very challenging.

2. TOPOLOGY SELECTION

There are several methods of controlling SMPSs, e.g., pulse-width modulation (PWM), frequency control, phase control, and cycle-by-cycle control. A PWM dc-dc converter is proposed for the investigated application because of its simple structure, well-known dynamic behavior, and possibility of a pulse-by-pulse current limiting and instantaneous shutdown. The output voltage in PWM converters is controlled against line and load variations by adjusting the duty ratio D of the switches

$$D = \frac{t_{on}}{t_{on} + t_{off}} = \frac{t_{on}}{T}. \tag{2}$$

The buck-boost topology is selected as a basic power-conversion cell. This topology has the ability to provide an output voltage higher or lower than the input voltage, can be easily implemented using a few circuit elements, and is well-researched and established in its conventional unidirectional form. The simplified transfer function for the buck-boost converter is given by

$$\frac{V_{out}}{V_{in}} = \frac{-D}{1-D}. \tag{3}$$

0-7803-4455-3/98/$10.00

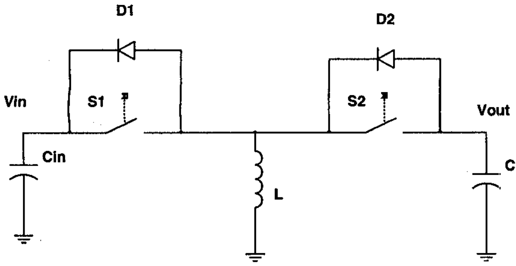

Figure 1: Bidirectional buck-boost topology.

Usually, it is considered a drawback of the buck-boost topology that it provides a negative output voltage. In this application, however, the actuator can be appropriately biased by simply reversing the terminals because it does not require referencing to ground.

Although the topology of the conventional buck-boost converter is successfully used for constant-output-voltage power supplies, it is not suitable for use with piezoelectric actuators. In the conventional circuit, the inductor current can only charge the output capacitor C_{out}. The discharge of the capacitor is due to the load current. Such a slow and uncontrollable discharge dynamics is not acceptable for an actuator. Moreover, the actuator may be charged from the load side during mechanical oscillations. Hence, a controllable, bidirectional power flow to and from the output capacitor is needed.

3. DESIGN FOR BIDIRECTIONAL OPERATION

To achieve bidirectional operation [2], the conventional buck-boost topology needs to be augmented by addition of an anti-parallel diode to the input switch and a controllable switch to the output diode as seen in Fig. 1. The two switches, which can be implemented using MOSFETs, are operated in a complementary fashion, i.e., when switch S1 is on, S2 is off and vice-versa. With this modification, a negative current through the inductor L is now possible which enables the recovery of mechanical energy from the load, its conversion to electrical energy and subsequent storage in the input filter capacitor C_{in}. The bidirectional arrangement of switches results in a synchronous rectifier topology which also increases the efficiency of the converter, especially for low output voltages. It requires, however, a more complicated control circuit.

Challenging design issues arise in compensating the closed loop for control of the device. The k-factor method described by Venable [3] is applied to obtain the resistance and capacitance values in the compensating error amplifier used in voltage control mode. Computational software tools, such as Saber and Matlab, are used at each stage for design, testing, and analysis. The design process is carried out in incremental stages. The initial circuit designs utilize averaged models of PWM switches [4] that allow for fast simulations; the next step involves using ideal switches with a separate PWM controller; in the final simulations, these ideal switches are replaced with models of MOSFETs.

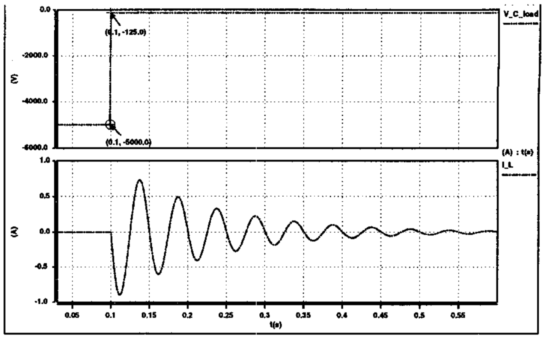

Figure 2: Bidirectional current flow in inductor L due to load disturbance (averaged model).

A damped-resonant R_m-L_m-C_m circuit with a resonant frequency of 20 Hz and 0.03% damping represents the mechanical load. The values of the load model components are $R_m = 2.5\ \Omega$, $L_m = 63.3$ H, $C_m = 1.0\ \mu$F.

Fig. 2 demonstrates the bidirectional operation of this power supply. To simulate external disturbance, the capacitor C_m is charged to an initial voltage of -5000 V. At this moment, C_m is isolated from the output capacitor C_{out} which represents the piezoelectric actuator. Then, the load is connected to the output at the time instant $t = 0.1$ s. After the disturbance, the output current shows an exponentially decaying sinusoidal pattern with frequency equal to the characteristic frequency of the load, and amplitude and time constant of the decay determined by the settings of the converter control circuitry. The simulation results show that the inductor current reverses direction, transferring energy back and forth between the input and output of the converter.

The presented simulation example together with analytical considerations show that the designed converter is stable. However, the requirement of reference-to-output tracking at high speeds requires further attention.

4. REFERENCE-TO-OUTPUT COMPENSATION

Fig. 3 shows a block diagram of the closed-loop bidirectional buck-boost converter where T_1 is the control to output transfer function of the power stage, and Z_1 and Z_2 represent values of impedances chosen for the compensating Op-Amp. $T_c = -Z_2/Z_1$ represents the compensation obtained earlier for the closed loop under the assumption that the non-inverting terminal is held constant. The following simple manipulations yield a transfer function between the

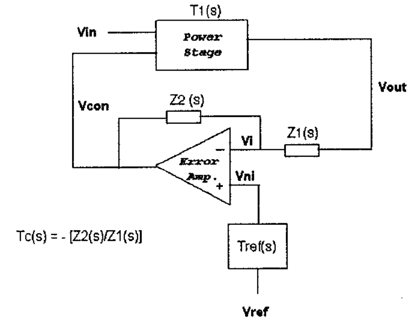

Figure 3: Block diagram of bidirectional power supply.

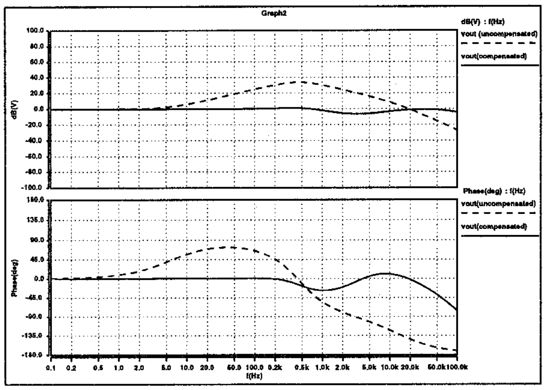

Figure 4: Reference-to-output frequency compensation.

non-inverting terminal and the output node:

$$V_{ni} \approx V_i$$

$$\frac{V_{out} - V_i}{Z_1} = \frac{V_i - V_{con}}{Z_2} \tag{4}$$

$$V_{con} = \frac{V_{out}}{T_1}.$$

Hence,

$$\frac{V_{out} - V_{ni}}{Z_1} = \frac{V_{ni} - V_{out}/T_1}{Z_2}$$

$$-T_c T_1 (V_{out} - V_{ni}) = T_1 V_{ni} - V_{out} \tag{5}$$

$$V_{out}(1 - T_c T_1) = V_{ni}(T_1 - T_c T_1)$$

and, finally,

$$T_{ni} \equiv \frac{V_{out}}{V_{ni}} = \frac{T_1 - T_c T_1}{1 - T_c T_1}. \tag{6}$$

The dashed lines in Fig. 4 present the amplitude (top) and the phase (bottom) characteristics of the transfer function T_{ni}. It can be seen that T_{ni} has a zero at about 5 Hz and ence signal components in the frequency range from 5 Hz to 20 kHz are amplified in comparison to the dc component.

The considered application demands a flat reference-to-output gain for frequencies up to 500 Hz. Hence, an additional compensation T_{ref} is required in the reference signal path as shown in Fig. 4. Solid lines in Fig. 4 present the amplitude and phase characteristics of the compensated transfer function $V_{out}/V_{ref} = T_{ref}T_{ni}$. It can be noticed that the desired flat amplitude response is achieved up to 50 kHz. T_{ref} has been implemented with two simple second-order compensators in series. The complete circuit diagram of the proposed bidirectional buck-boost converter is shown in Fig. 5.

5. DYNAMIC BEHAVIOR SIMULATION

To check the output tracking capabilities of the converter, a 500 Hz sinusoidal reference signal has been applied. The parameters of the reference signal have been selected in such a way that the desired output is a sinusoid with -125 V average value and amplitude of 100 V. Fig. 6 compares the desired (dashed) and actual (solid) output voltages. It can be observed that the amplitude tracking error is less than 5% with a phase shift of about 20°.

Fig. 7 shows the converter response to a step change in the reference voltage which decreases the desired (dashed line) output voltage level by 5 V. Solid lines in Fig. 7 represent the actual output voltage (top) and the inductor current (bottom).

The presented simulations have been obtained with Saber hybrid simulator version 4.2. The power circuit components used in the simulation were $V_{ac} = 170\sin(2\pi \times 60t)$ V, $C_{in} = 100\,\mu$F, $L = 100\,\mu$H, $C_{out} = 10\,\mu$F, and APT40M50JN MOSFET models. The switching frequency was selected to be 100 kHz.

6. CONCLUSION

The selection of an appropriate topology of a SMPS for a piezoelectric actuator application is a complicated process involving both rigorous and heuristic approaches. Often contradictory requirements for static and dynamic performance of the power supply as well as for the interaction with the electromechanical environment demand great skills from the designer.

A bidirectional PWM buck-boost converter is proposed to serve as a power supply for piezoelectric actuators. Design and simulation results in both frequency and time domain show that the proposed converter is able to provide the required dynamic performance. Experimental verification of the concepts presented here is planned as a next step of this research. For practical reasons, it may be easier to implement the proposed bidirectional converter using a trans-

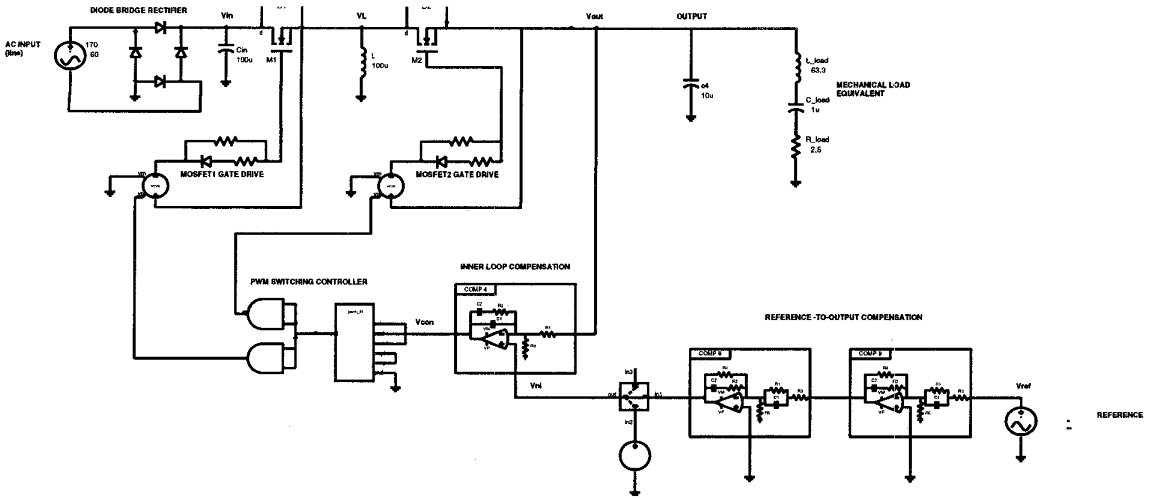

Figure 5: Circuit diagram of the bidirectional buck-boost converter with compensation in the reference signal path.

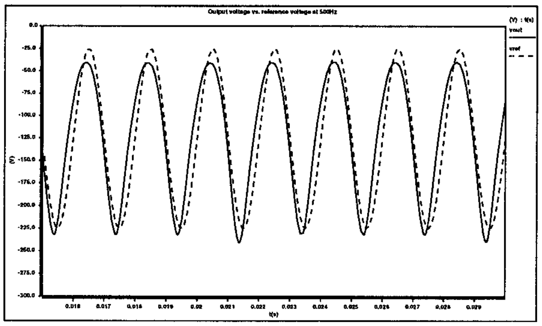

Figure 6: Desired (dashed) and actual (solid) output voltage for a 500 Hz reference signal (averaged model).

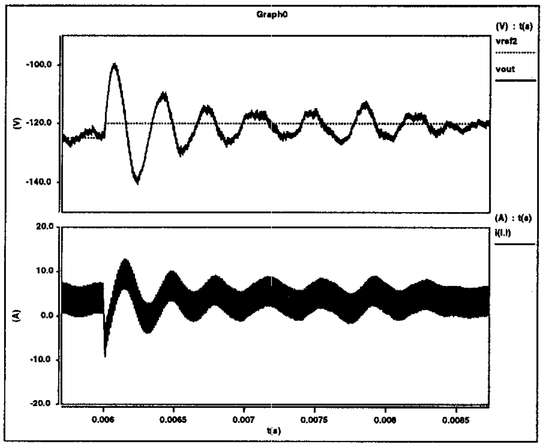

Figure 7: Effect of step change in reference voltage (model with MOSFETs).

former version of the buck-boost topology, namely, the flyback converter.

7. ACKNOWLEDGMENTS

Bhaskar Krishnamachari's work was supported by the National Science Foundation under the Research Experience for Undergraduates Grant EEC-9619749.

8. REFERENCES

[1] C. Kasuga, T. Nishimura, F. Harashima, and H. Ezuhara, "Characteristics analysis method of multilayer piezoelectric actuator," *Proc. of the IEEE International Conf. in Industrial Electronics, Control, Instrumentation, and Automation (IECON'92)*, San Diego, CA, November 9-13, 1992, vol. I, pp. 336-339.

[2] D. Czarkowski and M. K. Kazimierczuk, "Application of state feedback with integral control to pulse-width modulated push-pull DC-DC convertor," *IEE Proc., Pt. C, Control Theory Appl.*, vol. 141, No. 2, pp. 99-103, March 1994.

[3] Venable, D. H., "The k-factor: a new mathematical tool for stability analysis and synthesis,"*Proceedings of Powercon 10*, San Diego, CA, March 22-24, 1983.

[4] Vorperian, V., "Simplified analysis of PWM converters using averaged model of PWM switch – part I: continuous conduction mode," *IEEE Trans. on Aerospace and Electronic Systems*, vol. 26, no. 3, pp. 490-496, May 1990.