Electrical Modeling of Piezoelectric Elements and Efficient Driving Method

Dongjin.Park, Jintae.Kim, Youngsik.Lee, Gwanbon.Koo, Youngbae.Park
System&Application Gr. Analog Power Group in Fairchildsemiconductor

ABSTRACT

Piezoelectric elements are one of good candidates able to replace motors in various electronics devices. It is slim and compact and low power consumption compare to motors. Linear regulator or class-D amplifier are generally used for piezoelectric element driver, however, suffers from severe power consumption.

In this paper, electrical modeling of piezoelectric element will be presented and switching losses on the driver due to the parasitic capacitance will be analyzed. And new ZVS full bridge converter with an inductor will be proposed so as to reduce the power losses.

Introduction

In portable applications, piezoelectric elements recently take attentions in various areas because it could be manufactured with simplicity, compact and provide low power consumption. As for a piezoelectric element driver, conventional PFM(pulse frequency modulation) full-bridge converters (or called as class-D amplifier) are widely used. However, severe switching loss at switching transition could happen due to parasitic capacitance in piezoelectric elements[1].

This paper will not only introduce easier method to develop an electrical modeling of a piezoelectric element, but also analyze switching losses of the conventional driver. Furthermore, new ZVS full bridge converter with an external inductor will be proposed which is able to reduce the power losses compared to the conventional full bridge converters.

Electrical Modeling of Piezoelectric

Figure1 shows (a) electrical impedance curves of piezoelectric element, and (b) equivalent circuit of a piezoelectric element derived from (a). As can be seen in Figure 1, there are two resonance points of series-resonance and parallel-resonance. Thus it

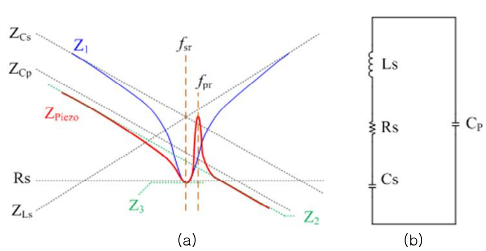


Figure 1. Electrical characteristics of a piezoelectric element

can be assumed that an electrical equivalent circuit of the piezoelectric element is composed by a series resonant circuit (Z_1) composed of R_S-L_S-C_S in parallel with capacitor (C_P), This is called as VanDyke Model well known[2].

Based on the electrical impedance curve, each parameter can be easily obtained as the following equations;

$$Z_2 = \left| \frac{1}{j\omega(C_S + C_P)} \right| \quad (1) \qquad Z_3 = \left| R_S \parallel \frac{1}{j\omega C_P} \right| \quad (2)$$

$$f_{sr} = \frac{1}{\omega \cdot \sqrt{L_S \cdot C_S}} \quad (3) \qquad f_{pr} = \frac{1}{\omega \cdot \sqrt{L_S \cdot ((C_S \cdot C_P)/(C_S + C_P))}} \quad (4)$$

,where ω is the angle frequency, $2\pi \cdot f_s$ depending on an applied switching frequency, f_s.

Conventional Full-bridge vs. ZVS Full-bridge Converter

Figure 2 shows conventional PFM switching[3]. When the switch M1 and M3 are turned on, the input voltage is applied to the piezoelectric element and C_P is rapidly charged to +Vin. After M1 and M3 are turned off, M2 and M4 are turned on after some dead time. Accordingly the input source starts to reversely charge C_P to –Vin from +Vin. At the switching transition, severe spike current periodically happens, which make large power consumption. The power consumption can be calculated as the following

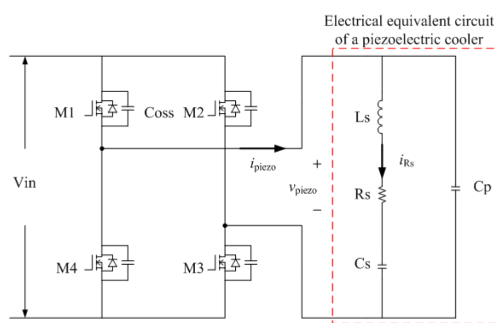


Figure 2. Full-bridge converter & electrical equivalent circuit of a piezoelectric element

$$P_{CP} = C_P \cdot ((V_{in} - (-V_{in}))^2 \cdot f_s \quad (5).$$

Figure 3 shows the proposed ZVS full-bridge converter using an external inductor. The switching scheme is same as the conventional full−bridge converter.

While M1 and M3 turn on, +vin is charged at C_P. Once M1 and M3 turn off, i_{piezo} starts to discharge C_P until C_P voltage becomes −Vin. After that, ZVS condition can be achieved for switches, M2 and M4.

It results in that no spike current and switching losses occur, but conduction loss can be somewhat increases. During the operation, conduction loss can be obtained as follow;

$$P_{cond} = i^2{}_{piezo,rms} \cdot 2R_{ds(on)} \tag{6}$$

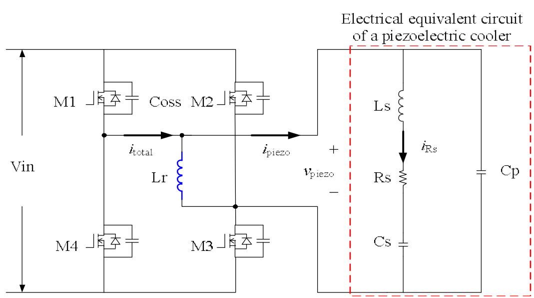
, where rms current flowing the piezo electric element, $i_{piezo,rms}$ can be easily calculated as the following based on the fundamental approximation and assumption of that the operation frequency is in the resonant frequency of the piezoelectric element;

$$i_{piezo,rms} \approx \sqrt{\left(\frac{V_{in} \cdot 4}{\sqrt{2} \cdot \pi \sqrt{R_S{}^2 + \left(\omega L_S - \dfrac{1}{\omega C_S}\right)^2}}\right)^2 + \left(\frac{V_{in}}{\sqrt{3} \cdot 4 \cdot L_r \cdot f_s}\right)^2} \tag{7}$$

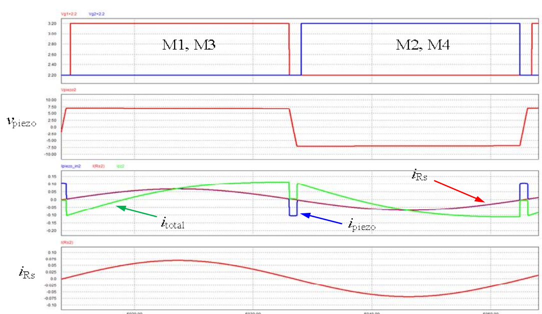
To obtain ZVS condition, L_r should be chosen as follow;

$$L_r < \frac{t_{dead}}{\left[8 \cdot \left(C_p + 2C_{oss}\right) \cdot f_s\right]} \tag{8}$$

,where t_{dead} is interval between signals of M1 and M2.



(a) ZVS Full-bridge converter using additional inductor



(b) Operating waveforms in conventional PFM

Figure 3. ZVS full−bridge converter

Experimental results

In experiments, RLC equivalent circuit was used as a load of the proposed converter, instead of real piezoelectric element. The each values of RLC were selected using a result of impedance curve measured by impedance analyzer and equations (1)−(4) as shown in Table 1.

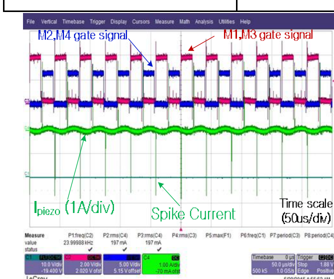
Table 1. Estimated values of a piezoelectric element

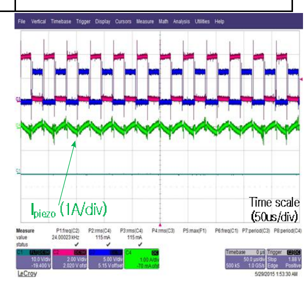
Parameter	R_S	C_S	L_S	C_P
Value	300 Ω	820 pF	45 mH	5.6 nF

The Piezoelectric driving amplitude was set as 100 V and its operating frequency was 24 kHz corresponding to the resonant frequency of RLC. Table 2 shows input power comparison results of the conventional and the proposed converter at the same conditions. Figure 4 shows that the proposed converter improved power consumption dramatically and eliminate spike current as well.

Table 2. Experimental Test Results.

	Pin	Power consumption
Full−bridge	3.50 W	100%
ZVS Full−bridge	2.25 W	64%





(a) Full−bridge (b) ZVS Full−bridge

Figure 4. Operating waveform

Conclusion

When the piezoelectric element is operated with full−bridge circuit, power consumption by C_P occurs pretty large. In this paper, new ZVS full bridge converter using an external inductor is proposed. This could be one of effective solution method able to reduce power consumption and eliminate spike current at the switching transition as well.

Reference

[1] Luca Battaglin, "High−efficiency driver circuit for capacitive loads", U.S.Patent 6828712, 2002, may

[2] T.L.jordan and Z.Ounaies, "Piezoelectric Ceramics Characterization" NASA/CR−2001−211225 and ICASE Report No. 2001−28.

[3] R.W.Erickson and D.Maksimovic, "Fundamentals of Power Electronics (2^{nd} edition)".