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Effect of Operating Frequency On Piezo-Based DC-DC Converter

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Abstract—This paper introduces an analysis of effect of frequency on dc-dc converter based on Piezoelectric Resonator. A single PR is used at low and high frequency by employing radial and thickness mode vibration for input-output voltage of 200-60 V. A current density of 1A/cm² is reached at 1 MHz for an output power of 100 W compared to 0.2 A/cm² and power of 22 W reached at 100 kHz. The first results show an improvement of current density and power density by increasing the operating frequency.

I. INTRODUCTION

Nowadays, high efficiency and high power density of power converters are in constant demand. The inductor based power converters are widely used. Downsizing of the inductor comes with increasing of the operating frequency; however, its performances decline for small-scale limiting the miniaturization and integration of power converters. Recently, piezo-based converters with a new conversion mechanism show good performances at low power and low operating frequency ($f < 100 \text{ kHz}$, $P < 100 \text{ W}$) in radial mode vibration [1]-[4]. Indeed, the operating principle was introduced and fully demonstrated in [1], and extended to a various topologies and conversion cycles in [2]-[3], by using Lead Zirconate Titanate (PZT) ceramic. The operating principle of such converter is based on energy and charge balance while ensuring zero voltage switch-on to reduce switching losses. The piezoelectric resonator operates in inductive region allowing power conversion free of inductor. In addition, the planar shape of PR makes it suitable for integrated power supply.

In this paper, we investigate on scaling up of the operating frequency by using the same PR. The operating principle is briefly described with a topology dedicated for high-to-low

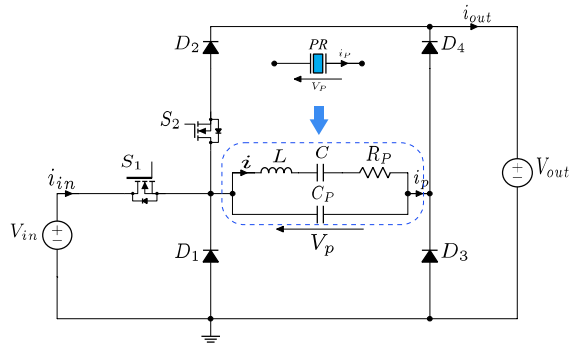


FIGURE 2. CONVERTER TOPOLOGY.

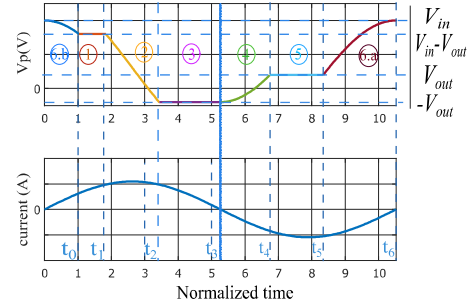


FIGURE 1. THEORETICAL WAVEFORMS OF THE CONVERSION CYCLE.

voltage conversion. In addition, we analyze the operating of PR at low and high frequency by using radial and thickness mode vibration. Experimental results are also presented to exhibit the performances at low and high frequency.

II. ANALYZE OF OPERATING PIEZO BASED STEP DOWN CONVERTER

A. Operating principle

The conversion principle is based on energy and electric charge balance during each period of conversion. In one period, the input source transfers electrical energy to PR, which stores it temporarily as mechanical energy (indirect effect of piezoelectricity). Then, PR transfers this energy as electrical form when it is connected to the output load (direct effect of piezoelectricity). Therefore, connected steps are performed to exchange energy with PR; in addition, open-circuit enables to charge and discharge C_P to changing voltage level between each connected step, which allows operating with zero voltage switch-on. Figure 1 shows a step-down dc-dc converter and the electric model of PR. Figure 2 illustrates the conversion cycle that ensures multiple connections PR with the output load leading to reduce the energy stored in PR and maximizing the energy transferred to load. The conversion cycle is composed of six steps, where PR is connected successively to $\{V_{in}-V_{out}, -V_{out}, V_{out}\}$, and opened-circuit between each constant voltage.

$$(V_{in} - V_{out})Q_1 - V_{out}Q_3 + V_{out}Q_5 = 0 \quad (1)$$

$$Q_1 + Q_3 + Q_5 = 0 \quad (2)$$

TABLE 1. PR'S ELECTRICAL MODEL FOR RADIAL AND THICKNESS MODE VIBRATION (THICKNESS=2MM, DIAMETER=25MM, PZT-C213 FROM FUJI)

Vibration mode	L	C	R_p	C_p	f_r	Q	k
Radial	2.7mH	1.19nF	1.087 Ω	3.3nF	88.8kHz	1387	0.51
Thickness	32 μ H	0.72nF	0.2049 Ω	3.3nF	1.051MHz	1026	0.42

B. Piezo electrical model

PR can be modeled by a L - C - R series branch equivalent to the mechanical behavior in parallel with intrinsic capacitance C_p . PR is selected to obtain a resonant frequency around 90 kHz in radial and 1 MHz in thickness mode. TABLE 1 shows the electrical model of PR in radial and thickness mode vibration extracted from an impedance measurement by using an Impedance Analyzer. Figure 3 shows the electrical connections used to measure the PR's impedance. Indeed, for radial displacement it is recommended to ensure electrical contacts at the center of disc (neutral axis) otherwise the quality factor decreases due to mechanical constraints. For thickness mode, we can use multiple electric contacts to reduce the contact resistance, which is significant compared to R_p . In addition, the current amplitude is higher at higher operating frequency, which induces significant losses $\frac{1}{2}R_{contact}I^2$.

C. Current estimation

Assuming the energy balance given by Eq.1 in steady state, the amplitude of the resonant current i is constant, inducing sustainable-oscillation. By using Eq.1 and Eq.2 and considering sinusoidal waveform of i , the amplitude I can be estimated by Eq.3 [3]. Therefore, I is separated into two parts; the first part αI_{out} (where $\alpha = \pi/2$) only depends on the output current and the conversion cycle. The second part corresponds to the current required to charge/discharge the capacitance C_p that is depending on $\{C_p, (V_{in}+V_{out}), f\}$ (named I_0).

$$I = \frac{\pi}{2} I_{out} + \frac{(V_{in}+V_{out})}{2} 2\pi f C_p \quad (3)$$

At low operating frequency, I_0 is low as $C_p \cdot f$ is low, so αI_{out} is preponderant at full output power (near the resonant frequency L - C), as consequence, the time duration of connected steps is preponderant. However, by increasing the operating frequency, I_0 increases and becomes significant which limits the output power by reducing the proportion part of I that contribute to the output current.

III. RESULTS AND DISCUSSION

Figure 4 illustrates the conversion cycle at radial and thickness modes. For radial mode at $f = 91$ kHz, we have

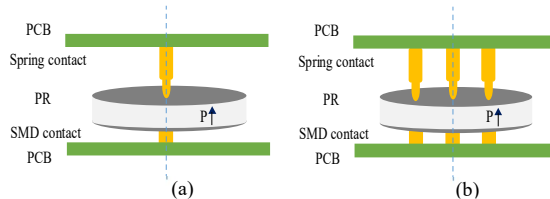
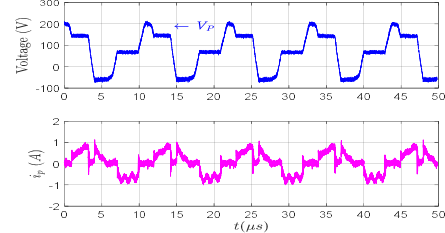


FIGURE 3. ELECTRICAL CONNECTIONS FOR: (A) RADIALE MODE AND (B) THICKNESS MODE VIBRATION.

(a): $V_{in} = 200$ V, $V_{out} = 60$ V, $f = 91$ kHz, $P_{out} = 22$ W, $\eta = 90\%$



(b): $V_{in} = 200$ V, $V_{out} = 60$ V, $f = 1.08$ MHz, $P_{out} = 100$ W, $\eta = 90\%$

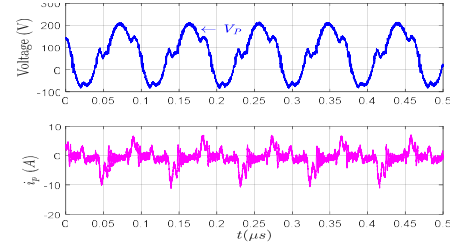


FIGURE 4. WAVEFORM OF VOLTAGE AND CURRENT OF PR NEAR RESONANT FREQUENCY FOR: (A) RADIAL MODE, (B) THICKNESS MODE.

measured an output power of 22 W inducing a current density of 0.2 A/cm² ($I/\pi r^2$) in the PR. For thickness mode that operates at 1 MHz, the output power measured is 100 W inducing a current density of 1 A/cm². Therefore, by increasing the frequency by a factor 10, the power and current density increased by factor 5. However, I_0 becomes significant ($I_0 = 2.7$ A, half of current I) which is the limiting factor for increasing the operating frequency. To overcome that limitation, material having low permittivity ϵ are promising (reducing capacitor C_p for high frequency and high power density applications [5]).

IV. CONCLUSION

This paper illustrates the scaling of the frequency for piezo-based DC-DC converter. The first results show high power and high power density for high-to-low voltage conversion by using PZT ceramic. A current density of 1A/cm² is reached at 1 MHz that is five times higher than reached at 100 kHz. A Peak output power of 100W is reached at 1 MHz.

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