DESIGN OF A CLASS-E INVERTER FOR PIEZOELECTRIC ULTRASOUND GENERATION AGAINST LOAD VARIATION

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Piezoelectric transducers are used for generating ultrasound around their resonant frequencies. Single-ended class-E resonant inverter has a simple configuration and high conversion efficiency; therefore, was investigated for driving piezoelectric transducer for ultrasound generation. However, both piezoelectric transducer and class-E circuit are sensitive to load variation. This paper studies the susceptibility of output power and conversion efficiency of a class-E based piezoelectric ultrasound generator under different load conditions. By using the iteration-free extended impedance method, the integration of class-E inverter and piezoelectric transducer can be efficiently analyzed; parameters can be properly designed and optimized. An in-situ adapting approach, which tunes the duty ratio and dc supply voltage for maximizing the conversion efficiency at constant output power against load variation, is investigated. Simulation results show that, by taking this parameter tuning, the susceptibility of output power and conversion efficiency can be alleviated within a wide range of load.

Keywords: Piezoelectric transducer; Ultrasonic generation; Class-E power amplifier; Extended impedance method

1. INTRODUCTION

Piezoelectric ceramic transducers (PCT) are widely used in ultrasonic machining, such as ultrasonic cleaning, grinding, and welding. For efficient generation of ultrasound, a PCT is usually driven at one of its mechanical resonant frequencies [1-2]. Single-ended class-E resonant inverter, which is also known as class-E power amplifier (PA), has a simple configuration and high efficiency for converting dc power into ac for high frequency applications [1-3]. These remarkable features make it attractive towards low-cost and light-weight ultrasonic solutions [4]. However, the operation of class-E inverter is sensitive to load variation. Working slightly away from the optimal class-E condition, i.e., zero-voltage switching (ZVS) and zero-derivative switching (ZDS), might cause a large drop in its conversion efficiency [3, 5-6]. Yet, because of the differences and changes of density, geometry, position, temperature, etc., of the workpieces [6], it was shown that load variation might happen from time to time in ultrasonic machining. The load variation problem should be better evaluated and diminished before the class-E inverter can be substantially used for high efficient piezoelectric ultrasound generation (PUG).

This paper studies the susceptibility of output power and conversion efficiency under different load conditions in a piezoelectric ultrasound generator, which is driven by a class-E inverter circuit. Simulation and optimization are carried out based on the iteration-free *extended impedance method* [7]. When the device is subjected to load variation, possible in-situ tuning mechanism is studied towards a robust and efficient piezoelectric ultrasound generation.

2. MODEL

A PCT can be modeled as an impedance network which consists of two parallel branches: one is a series-connected RLC and the other is a capacitor [4-6]. The equivalent circuit can be integrated into the classical class-E inverter for comprehensive investigation.

As shown in Figure 1, the topology of a single ended class-E inverter for PUG consists of six components: two capacitors C_S and C_1; two inductors L_0 and L_1; a PCT loading and an active switch *sw*. When PCT works as an ultrasound generator, it operates at one of its resonant frequencies, and thus its equivalent circuits can be simplified as shown in Figure 2. Assuming the capacitors and inductors are ideal, only the switch *sw* and the load R_m consume real power. Since the power converting efficiency η of a class-E inverter is the ratio of the average power consumed by R_m over that supplied by the dc source, η can be increased by minimizing the power consumption of *sw*. The class-E condition, i.e. zero-voltage switching (ZVS) and zero-derivative switching (ZDS), can make sure that high voltage and high current do not appear at the same time. Thus, the single ended class-E inverter can achieve high

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converting efficiency.

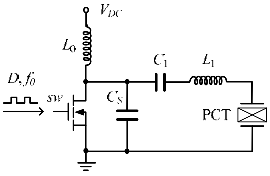


Figure 1. A single-ended class-E inverter for PUG.

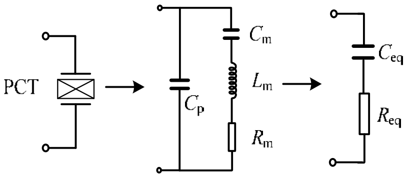


Figure 2. Equivalent circuit of a PCT under resonance.

By modeling the time-dependent component *sw* into a special impedance, the *extended impedance method* can perform efficient steady-state analysis in the frequency domain for a class-E circuit [7]. Figure 3 shows the extended impedance network of a class-E based PUG. In this model, the switch *sw* is described by the matrix as follows:

$$\mathbf{Z_{SW}} = \begin{bmatrix} R_{sw,0} & \cdots & R_{sw,-K} & \cdots & R_{sw,-2K} \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ R_{sw,K} & \ddots & R_{sw,0} & \ddots & R_{sw,K} \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ R_{sw,2K} & \cdots & R_{sw,K} & \cdots & R_{sw,0} \end{bmatrix}, \tag{9}$$

where

$$R_{sw,k} = \begin{cases} R_{\text{on}} D + R_{\text{off}}\left(1-D\right), & k=0, \\ \left(R_{\text{on}} - R_{\text{off}}\right)\dfrac{\sin\left(k\pi D\right)}{k\pi} e^{-jk\pi D}, & k=-2K,\cdots,-1,1,\cdots,2K \end{cases} . \tag{10}$$

In (10), R_{on} and R_{off} are the resistance of the switch *sw* at *on* and *off* states, respectively; D is the duty cycle of the square wave driving signal; K is the order of the Fourier series. According to *extended impedance method*, the total impedance of the class-E driving circuit is given by

$$\mathbf{Z_{Class\text{-}E}} = \mathbf{Z_{L0}} + \left[\mathbf{Z_{SW}} \| \mathbf{Z_{Cs}} \| \left(\mathbf{Z_{L1}} + \mathbf{Z_{C1}} + \mathbf{Z_{Req}} + \mathbf{Z_{Ceq}}\right)\right] . \tag{11}$$

Writing other parameters in $2K$+1 order vectors, the vector expression of the class-E characteristic voltage $\mathbf{V_{SW}}$ in frequency domain is given by

$$\mathbf{V_{SW}} = \left[\mathbf{Z_{SW}} \| \mathbf{Z_{Cs}} \| \left(\mathbf{Z_{L1}} + \mathbf{Z_{C1}} + \mathbf{Z_{Req}} + \mathbf{Z_{Ceq}}\right)\right] \mathbf{Z^{-1}_{Class\text{-}E}} \mathbf{V_{DC}} . \tag{12}$$

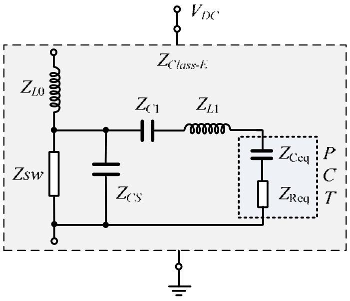


Figure 3. The extended impedance network of a class-E based PUG.

The time-domain expression of $\mathbf{V_{SW}}$ can be obtained by:

$$v_{\text{SW}}(t) \approx \left[e^{-jK\omega_0 t} \quad \cdots \quad e^{-j\omega_0 t} \quad 1 \quad e^{j\omega_0 t} \quad \cdots \quad e^{jK\omega_0 t} \right] \mathbf{V_{SW}} . \tag{13}$$

Based on the *extended impedance method*, the input power, output power, and energy conversion efficiency can also be derived by using conventional circuit laws [7].

3. DESIGN

The circuit parameters of C_S, C_1, L_0, L_1, R_{on} and R_{off} are passive. Their values cannot be changed once the circuit is fabricated. While the others, such as D, V_{DC}, and f_0 are *in-situ* tunable. For the parameters of a piezoelectric transducer, i.e. R_m, C_m, and L_m, they may vary at different working conditions. In this situation, the tunable parameters of the class-E inverter can be used to deliver a self-adjustment, in order to maintain an optimal performance against the parameter variation, which is caused by the condition change of a workpiece.

Taking a 42-W ultrasound cleaner [4] as a design case, the design procedures for the class-E driving circuit include four steps:

a) Select the switch and PCT. The same PCT characteristics mentioned in [4], whose equivalent parameters are listed in Table 1, are used in this study. According to (3) and (6) in [2], the rated voltage of the switch can be determined. Then a proper type of electronic switch can be selected according to this rating. The parameters of R_{on} and R_{off} can be obtained according to the component datasheet, as listed in Table 2.

Table 1. Equivalent parameters of a piezoelectric transducer.

C_p (nF)	R_m (Ω)	L_m (mH)	C_m (pF)
10.6	310	213	71

Table 2. Parameters of class-E power amplifier for driving PCT.

Parameter (unit)	*Initial*	*Passively optimized*	*Actively tuned I*	*Actively tuned II*
V_{DC} (V)	119	119	184.6	88.4
f_0 (kHz)	41	41	41	41
D (%)	50	50	53.7	54.2
R_{on} (Ω)	4	4	4	4
R_{off} (kΩ)	100	100	100	100
L_0 (mH)	10	10	10	10
C_S (nF)	4.37	5.47	5.47	5.47
L_1 (mH)	4.9	4.9	4.9	4.9
C_1 (nF)	4.37	4.31	4.31	4.31
R_m (Ω)	310	310	124	620

Other parameters including C_p, L_m, and C_m maintain the same values as those given in Table I throughout the design procedures.

b) Calculate the tunable parameters. V_{DC} can be calculate from (3) and (6) in [2]; D can be 50% to leave enough tuning margin; f_0 can be set to the resonant frequency of the PCT.

c) Determine the passive parameters. C_1, C_s, and L_0 can be determined according to (8)-(10) in [2]. L_1 can be determined by

$$L_1 = QR_{eq}/2\pi f_0, \tag{14}$$

where Q is the quality factor of the load network. In this study, Q is selected to be 7. Since L_0 is used as a choke inductor, a smaller value, say 10 mH, is preferred for further reducing its geometric size. All initial parameters are obtained and listed in Table 2. The initial parameter set is simulated using the *extended impedance method*. The results show that the conversion efficiency reaches up to 95.6%; while the output power is 45.6-W, which is a little bit higher than the targeted power.

d) Optimize the passive parameters. Here, C_1 and C_S are selected as the free variables for optimization. In real application, the output power is usually required to be a constant value P_0. Thus, the optimization problem is expressed as follows

$$\max_{C_S, C_1} \eta, \quad \text{s.t. } \overline{P}_{out} = P_0, \tag{15}$$

where $\overline{P}_{out}$ is the average power consumed by R_m. The optimized parameters are listed in the third column of Table 2. Compared to the results obtained with the initial parameters, the efficiency increases a little bit to 96.2%; while the output power attains the targeted 42-W. The waveforms before and after the passive optimization are shown in Figure 4. The class-E circuit approaches the nominal condition after the passive optimization.

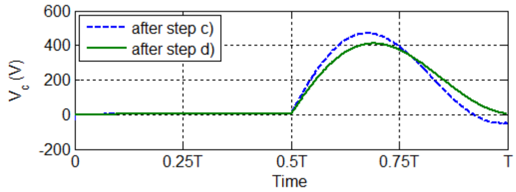


Figure 4. Characteristic waveform of class-E based PUG before and after passive optimization.

4. TUNING AGAINST LOAD VARIATION

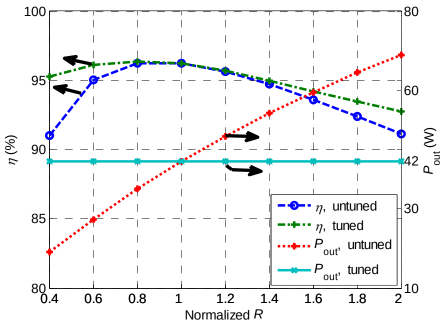
In practical applications, the load resistance R_m may vary within a certain range [6]. We can provide an *in-situ* tuning for the active parameters, in order to track the maximum efficiency point. The active tuning problem can be expressed as follows

$$\max_{D, V_{DC}} \eta, \quad \text{s.t. } \overline{P}_{out} = P_0,\ f_0 = f_r \tag{16}$$

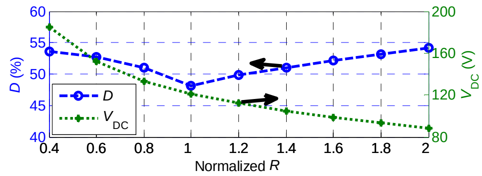
In (16), the driving frequency f_0 is used to trace the operating frequency of the PCT f_r. In practice, f_r might only shift slightly [6], therefore, the variation of R_m is taken as the major variation in our study. Table 2 lists two sets of actively tuned parameters under two different changes of normalized R_m, i.e., 0.4 and 2.

Figure 5 shows the susceptibility of the class-E inverter when it is subjected to the variation of R_m. As illustrated by the dash line in Figure 5(a), the efficiency decreases when the normalized R_m deviates from unity. The working efficiency is lowered because of the violation of ZVS condition for the class-E inverter, as shown by the dash line and the dash-dot line in Figure 5(c). On the other hand, the output power increases monotonically as the normalized R_m increases. The output power will shift from the targeted power when R_m varies. Some intervene must takes place for maintaining the output power level, and at the same time, counteracting the drop of conversion efficiency.

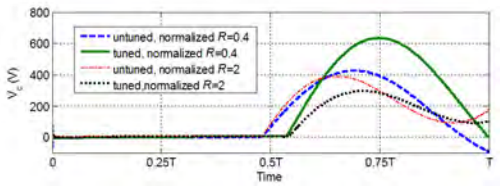
According to the objective set by (16), the active parameters, i.e., duty ratio D and supply voltage V_{DC}, are tuned for maintaining the highest efficiency at constant



(a)



(b)



(c)

Figure 5. In-situ tuning of class-E based PUG under different load conditions. (a) Efficiency and output power; (b) The tuned values of duty ratio and supply voltage under different loads (c) Characteristic voltage waveforms.

output power. The dash-dot line and the solid line in Figure 5(a) show the efficiency and the output power of the class-E inverter, respectively, after the active parameters are tuned. It is shown that the power converting efficiency of the class-E inverter can significantly enhanced when the normalized R_m is smaller than unity. As we can observe from the solid line in Figure 5 (c), the characteristic waveforms resume its ZVS condition after the tuning. When the normalized *R* is greater than 1, the class-E nominal conditions cannot be achieved by tuning these two active parameters. As shown by the dot line in Figure 5(c), only ZDS condition can be achieved. Thus the efficiency can only be improved by a small amount. Figure 5 (b) shows the tuned values of *D* and V_{DC} versus the load conditions.

5. CONCLUSION

Based on the efficient iteration-free *extended impedance method*, this paper has investigated the power and conversion efficiency of a class-E based piezoelectric ultrasound generator (PUG), when it is subjected to load variation. Simulation results show that the conversion efficiency decreases when the load resistance deviates from its initial design value; on the other hand, the output power increases along with this load resistance. Given the importance of power control and efficiency optimization in PUG, an active tuning method has been proposed and studied by adjusting two in-situ tunable parameters, i.e., the duty ratio and supply voltage, in order to counteract the load variation in PUG.

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