Improving the Transient Responses of Piezoelectric Transformer with Loads Using a Parallel Resistor

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Abstract-- This paper investigates the characteristics of a voltage transient response existing at input terminals of a piezoelectric transformer (PT) under open-circuit operation. The characteristics, including peak voltages, time constants and response times, are affected by a parallel resistor connected to the input side of the PT and a load resistor connected to the output side of the PT. Also, the transient response is induced immediately after an AC voltage applied to the PT is switched off. In doing so, an equivalent circuit of a PT is first expressed. Then, the equivalent circuit with a sinusoidal voltage is used to derive steady-state responses of the PT. The equivalent circuit with the initial conditions is used to derive a voltage transient response, involving a DC component and an AC component, existing at input terminals of the PT. Moreover, an AC power supply is implemented using a resonant inverter circuit, and a relay circuit is used to control the connection or disconnection between the AC power supply and the PT, and govern the generation of the transient response. Furthermore, the effects of both a parallel resistor and a load resistor on the characteristics of the transient response are measured and discussed.

KEYWORDS: Piezoelectric transformer, transient response, maximum voltage, time constant, response time

I. Introduction

Piezoelectric transformers (PTs) have many advantages over conventional magnetic transformers in high power densities, large step-up voltage gains, and high efficiencies at high frequencies. Also, a liquid crystal display (LCD) market is rapidly growing in high power densities, high efficiencies at high frequencies. For this reason, a cathode cold fluorescent lamp (CCFL) has been used as a light source for lighting up a backlight system of a LCD device. [1], [2] This CCFL was driven by a driving resonant inverter with a PT. Also, a PT has been used as a key component of an AC adopter to minimize the size of the adopter. [3] Meanwhile, a PT has been used as a key component of a DC-DC converter with high conversion efficiency and low electromagnetic interference. [4] The DC-DC converter was employed to convert a low input DC voltage to a high output DC voltage. Additionally, a PT has been used as a key component of a high-frequency resonant inverter that is employed to convert a low DC voltage (DC 12V) to a high AC voltage (typically 1500 Vrms) applied to start the ionization of a Neon lamp. [5]

In operations of a PT with large step-up voltage gain, a high-voltage transient response is induced at the input side of the PT immediately after a sinusoidal voltage applied to the PT is switched off. When the PT is operated at output open, the maximum value of the transient response occurs. Also, the transient response and its maximum value are affected by a load resistor connected to the output side of the PT and a parallel resistor connected to the input side of the PT. So far, little literatures exist for elucidating the transient response of a PT under open-circuit operation.

II. Description of Equivalent Circuit

With reference to Fig. 1, a Rosen-type PT (ELECERAM, ELS-41) with 44 mm length, 6.5 mm width, 2.2 mm height and 5.6 g mass comprises a driver section connected to an AC voltage, \( V_s \), and a generator section connected to a load resistor, \( R_L \). An equation of the PT shown in Fig. 2 is expressed as follows: \( R \) represents an electrical component of the mechanical loss, \( C \) represents an electrical component of the stiffness, and \( L \) represents an electrical component of the mass. Then, \( C_{st1} \) and \( C_{st2} \) represent the input static capacitance and the output static capacitance, respectively; \( n \) represents the transformation ratio.

Next, a digital storage oscilloscope (YOKOGAWA, DL1520) and its associate probe are used to measure electrical responses of the PT, as shown in Fig. 3. Meanwhile, an equivalent circuit of the oscilloscope is formed of a resistance, \( R_{scope} \), and a capacitance, \( C_{scope} \), mutually connected in parallel, as depicted in Fig. 4. According to Figs. 2 and 4, the equivalent resistance, \( R_e \), and the equivalent capacitance, \( C_e \), are calculated as follows:

\[
R_e = R + \frac{R_o (ln^2)}{1 + (\omega C R_o)^2} \tag{1}
\]

\[
C_e = \frac{C (1 + (\omega C R_o)^2)}{1 + (\omega C R_o)^2 (1 + C (ln^2 R_o))} \tag{2}
\]

where \( \omega \) represents the angular frequency. Additionally, \( L_e = L \), where \( L_e \) represents the equivalent resistance. Using an impedance analyzer (HP4194A), one obtains

![Fig. 1 Structure of a Rosen-type PT.](image-url)
Fig. 2 Equivalent circuit of the PT.

Fig. 3 Schematic diagram of test system.

Fig. 4 Equivalent circuits of the PT and the oscilloscope.

following parameters: $R_{\text{scope}} \approx 12.7 \, \text{M}\Omega$ and $C_{\text{scope}} \approx 3.8 \, \text{pF}$ for the oscilloscope; $R_m \approx 72.8 \, \Omega$, $C_m \approx 35.54 \, \text{pF}$, $L_m \approx 115.6 \, \text{mH}$, $C_{d1} \approx 744 \, \text{pF}$ and $C_{d2} \approx 8.5 \, \text{pF}$ for the PT.

III. Transient Response Analysis

From Fig. 5, a voltage transient response, $v_{oc}$, is induced by the initial conditions, such as $v_{oc}$, $v_{om}$ and $I_a$. In order to derive an equation for $v_{oc}$ in the time domain, a modified equivalent circuit in the s-domain depicted in Fig. 6 is first obtained by adopting the Laplace transform theorems. In Fig. 6, $V_{oc}(s)$ is the Laplace transform of $v_{oc}$. Using the Kirchhoff current law (KCL), one yields an equation of $V_{oc}(s)$:

$$V_{oc}(s) = \frac{A}{s + \alpha_{dc}} + \frac{C \cdot (s + \alpha_{ac})}{(s + \alpha_{ac}) + \beta} + \frac{D \cdot \beta}{(s + \alpha_{ac}) + \beta}$$  \hspace{1cm} (3)

where $\alpha_{dc} = 1/(R_C C)$;
$R_p = R_p // R_{\text{scope}} = R_p R_{\text{scope}}/(R_p + R_{\text{scope}})$;
$C_i = C_{\text{scope}} + C_{d1}$;
$\alpha_{ac} = R_p/(2L_m)$;
$A \approx V_{oc} + (C_i/C)(\alpha_{ac} L_m I_a + V_{om})$;

Then, using the inverse-Laplace transformation, one yields

$$v_{oc} = Ce^{-\alpha_{dc} t} + e^{-\alpha_{ac} t} \left( C \cos \beta t + D \sin \beta t \right)$$ \hspace{1cm} (4)

or

$$v_{oc} = A e^{-\alpha_{dc} t} + B e^{-\alpha_{ac} t} \cos(\beta t - \delta)$$ \hspace{1cm} (5)

where $\tau_{dc} = 1/\alpha_{dc} = R_C C$;
$\tau_{ac} = 1/\alpha_{ac} = 2L_m R_p$;
$B = \sqrt{C^2 + D^2}$;
$\delta = \arctan(D/C)$.

Here, $\tau_{dc}$ and $\tau_{ac}$ represent the DC time constant and the AC time constant, respectively. The transient response, $v_{oc}$, given by Eq. (5) is plotted in Fig. 7. From Eq. (5), amplitude of the DC term, $Ae^{-\alpha_{dc} t}$, is about 0.368A at $t = \tau_{dc}$, and amplitude of the AC term, $Be^{-\alpha_{ac} t} \cos(\cdot)$, is about 0.368B at $t = \tau_{ac}$, as depicted in Fig. 7. Also, the DC term approaches zero at $t = \tau_{dc} =$
DC power
supply
(LPS-305)
DC-to-AC
chopper
Resonant
tank
Driven and
isolated circuit
Function generator
(FG506)
Oscilloscope
(DL1520)
Fig. 8 Block diagram of AC power supply.

Fig. 9 Resonant inverter circuit.

\( 5\pi / \omega \), and the AC approach zero at \( t = t_{ac} = 5\pi / \omega \). Here, \( t_{ac} \) and \( t_{dc} \) represent the AC response time and the DC response time, respectively.

IV. Experimental Setup

From Fig. 8, a resonant inverter circuit, including a DC-to-AC chopper, a resonant tank, and the modified equivalent circuit, is used to generate a sinusoidal voltage across the input terminals of the PT. According to Fig. 9, \( v_{ap} = V_{dc} \), if \( S_1 \) and \( S_4 \) are ON, and \( S_2 \) and \( S_3 \) are OFF; \( V_{ap} = -V_{dc} \), if \( S_1 \) and \( S_4 \) are OFF, and \( S_2 \) and \( S_3 \) are ON. The switches, \( S_1 \) through \( S_4 \), are implemented using MOSFET devices (IRF840), and driven by rectangular voltages, \( v_{ap} \), through \( v_{g1}, \ldots, v_{g4} \), with an on-duty cycle of 50%, respectively. The tank includes an inductance, \( L_f = 47 \mu H \), and a capacitance, \( C_f = 0.1 \mu F \).

Next, amplitudes of both \( v_{ap} \) and \( v_s \) are determined by a DC power supply (AMERICAN RELIANCE, LPS-305), and frequencies of them are controlled using a function generator (AMERICAN RELIANCE, FG-506). Finally, a relay circuit depicted in Fig. 9 is used to control the connection or disconnection between the inverter and the PT, and cause the generation of the transient response. The relay circuit comprises a DC relay (DC12V, JCC-6F, 4098) and a MOSFET device (IRF840), \( v_{ap} \), driven by a rectangular voltage, \( v_{as} \). Also, the voltage, \( v_{ap} \), is obtained from a function generator (TOPWARD, 8112). Hence, both \( SW \) and \( S_0 \) are ON if \( v_{as} = 12V \), and both \( SW \) and \( S_0 \) are OFF if \( v_{as} = 0V \).

5.12 ms, is unaffected by a parallel resistor, and the DC response time is greatly decreased from 40 ms to 0.5 ms by adopting a 100-kΩ parallel resistor when the PT is operated at output open. Both the maximum voltage of \( v_{oc} \) and the maximum value of \( v_{oc}'s \) DC component decrease as the parallel resistance decreases. Also, the maximum voltage of \( v_{oc} \) is about 302V (o-p), or 30.2 times the driving voltage, 10V (o-p), without a parallel resistor. Even thought the high enough resistance (≥100 kΩ) reduces the DC response time, the steady-state responses of the PT are almost unaffected. Finally, when the PT is operated at various load resistors with a parallel resistor, all of the maximum voltage of \( v_{oc} \), the maximum value of \( v_{oc}'s \) DC component and the AC response time decrease as the load resistance decreases, as shown in Fig. 11.

V. Experimental Results

When the voltage, \( v_s \), with \( V_s = 10V \) and \( f_s = 79.50kHz \) is applied to the PT, the transient responses shown in Figs. 10 and 11 are induced immediately after the voltage, \( v_s \), is switched off. These transient responses are measured using the oscilloscope (YOKOGAWA, DL1520), and their approximate DC components are obtained by the smoothing-and-filtering function of the oscilloscope. From Fig. 10, the AC response time, about 12.5 ms, is unaffected by a parallel resistor, and the DC response time is greatly decreased from 40 ms to 0.5 ms by adopting a 100-kΩ parallel resistor when the PT is operated at output open. Both the maximum voltage of \( v_{oc} \) and the maximum value of \( v_{oc}'s \) DC component decrease as the parallel resistance decreases. Also, the maximum voltage of \( v_{oc} \) is about 302V (o-p) or 30.2 times the driving voltage, 10V (o-p), without a parallel resistor. Even thought the high enough resistance (≥100 kΩ) reduces the DC response time, the steady-state responses of the PT are almost unaffected. Finally, when the PT is operated at various load resistors with a parallel resistor, all of the maximum voltage of \( v_{oc} \), the maximum value of \( v_{oc}'s \) DC component and the AC response time decrease as the load resistance decreases, as shown in Fig. 11.
VI. Conclusions

A transient response is induced at input terminals of the PT immediately after an AC voltage applied to the PT is switched off. For a given load resistance, the DC response time of the transient response greatly decreases as the parallel resistance (≥ 100 kΩ) decreases. And, the AC response time of the transient response is almost unaffected by the parallel resistance. Even thought the parallel resistance reduces the DC response time, the steady-state responses of the PT are almost unaffected. For a given parallel resistance, both the maximum voltage and the AC response time greatly decreases as the load resistance (≥ 1 MΩ) decreases.

References: