

# Generic Operational Characteristics of Piezoelectric Transformers

Gregory Ivensky, Isaac Zafrany and Sam Ben-Yaakov\*

Tel: +972-7-6461561; Fax: +972-7-6472949; Email: sby@bgu.ac.il

Power Electronics Laboratory  
Department of Electrical and Computer Engineering  
Ben-Gurion University of the Negev  
P. O. Box 653, Beer-Sheva 84105, ISRAEL

**Abstract** - The universal attributes of piezoelectric transformers (PT) were derived by an approximate analysis that yielded closed form equations relating the normalized load resistance to the voltage gain, output power per unit drive and efficiency. It is suggested that the closed form formulas developed in this study could be invaluable when studying, specifying and designing practical PTs applications.

## I. INTRODUCTION

Piezoelectric Transformers (PT) have some advantages over electromagnetic transformers in specific applications [1-5]. Notwithstanding the fact that practical applications of PTs have been described in the literature, clear delineation of the engineering characterization of these devices is still missing. For example, the questions of trade-offs between voltage gain and efficiency, maximum per unit output power and the effect of the quality factor of the PT on its performance - have not been thorough analyzed as yet (at least in the open literature). These issues were probed in this study and the theoretical results, verified by measurements and simulations, provide tools for evaluating the expected performance of a PT in a given application. Although this paper is concerned with PTs in inverter (AC-AC) applications, the study can be used to assess the PT performance in converter applications (AC-DC) by applying the equivalent AC resistance approach ( $R_{ac}$ ) [6] or the RC model for a converter with a capacitive filter [7, 8].

## II. AN INTUITIVE ANALYSIS

The general equivalent circuit of a PT when operating around one of its mechanical resonant frequencies is depicted in Fig. 1a. In this figure we replaced the output transformer shown in earlier papers, by two dependent sources:

$\frac{v_{Co}}{n}$  and  $\frac{i_{Lr}}{n}$ . This presentation is valid even when the output is exposed to a DC voltage. The electromagnetic transformer presentation (used by other authors) would be undesirable in such a case, especially when the equivalent circuit is studied by circuit simulation. This is due to the fact that the windings of an electromagnetic transformer represent a short circuit to DC voltage.

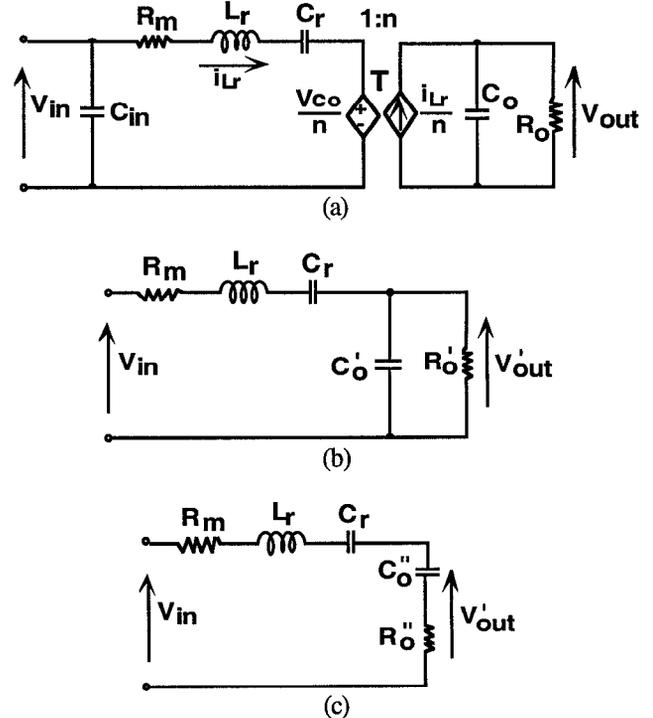


Fig. 1. Equivalent circuits of a piezoelectric transformer (PT): (a) general model; (b) after reflecting the output capacitance and load resistance to the primary; (c) after parallel to series transformation.

From the power transfer point of view the basic equivalent circuit can be simplified to that of Fig. 1b in which the network at the secondary is reflected to the primary. Note that the input capacitance ( $C_{in}$  of Fig. 1a) is eliminated in Fig. 1b since it does not affect the power transfer of the PT. The values of the reflected resistance ( $R_o'$ ), reflected capacitance ( $C_o'$ ) and reflected output voltage ( $V_{out}'$ ) will be :

$$R_o' = \frac{R_o}{n^2} \quad (1)$$

$$C_o' = n^2 C_o \quad (2)$$

$$V_{out}' = \frac{V_{out}}{n} \quad (3)$$

where  $R_o$  is the load resistance,  $C_o$  is the output capacitance,  $V_{out}$  is the output voltage and  $n$  is the mechanical output transfer ratio.

\* Corresponding author.

Further simplification can be achieved by converting the parallel network  $R_O', C_O'$  to a series network (Fig. 1c) in which the series resistance  $R_O''$  and series capacitance  $C_O''$  are defined as :

$$R_O'' = \frac{R_O'}{1+(\omega C_O' R_O')^2} \quad (4)$$

$$C_O'' = C_O' \frac{1+(\omega C_O' R_O')^2}{(\omega C_O' R_O')^2} \quad (5)$$

where  $\omega$  is the operating frequency.

Examination of the dependence of  $R_O''$  and  $C_O''$  on  $R_O'$  reveals some interesting and important features. As  $R_O'$  varies from 0 to  $\infty$ ,  $R_O''$  varies from zero back to zero with a maximum  $R_{Om}''$  at :

$$R_{Om}'' = \frac{1}{\omega C_O'} \quad (6)$$

On the other hand, over the entire range of  $R_O'$ , series capacitance  $C_O''$  varies from infinity back to the value of  $C_O'$ .

Based on this simple observation some general conclusions can already be drawn:

1. For a given reflected load  $R_O'$ , maximum output voltage will be obtained at the resonant frequency  $\omega_m$  (Fig. 1):

$$\omega_m = \frac{1}{\sqrt{L_r C_{eq}}} \quad (7)$$

where  $C_{eq}$  is the series value of  $C_r$  and  $C_O''$ :

$$C_{eq} = \frac{C_r C_O''}{C_r + C_O''} \quad (8)$$

2. The range of the series resonant frequency is dictated by the range of  $C_O''$ :

$$\omega_{rs} < \omega_m < \omega_{ro} \quad (9)$$

where  $\omega_{rs}$  is the resonant frequency at short circuit ( $R_O=0$ ):

$$\omega_{rs} = \frac{1}{\sqrt{L_r C_r}} \quad (10)$$

and  $\omega_{ro}$  is the series resonant frequency at open circuit

( $R_O=\infty$ ):

$$\omega_{ro} = \frac{1}{\sqrt{L_r \frac{C_r C_O'}{C_r + C_O'}}} \quad (11)$$

3. For any given load  $R_O$ , output voltage can be controlled by shifting the frequency above or below  $\omega_m$ . This is, in fact, the method used in inverters and converters operating in frequency-shift control mode.
4. For any given load ( $R_O$ ) the fraction of power transferred to the load at the resonant frequency will depend on the ratio of  $R_O''$  to  $R_m$  (Fig. 1c).
5. Maximum power will be delivered to the load when  $R_O''=R_m$ . Since  $R_O''$  is convex, two  $R_O'$  (and hence two  $R_O$ ) satisfy the maximum power condition.
6. At maximum output power ( $R_O''=R_m$ ) the PT efficiency will be 0.5.
7. Maximum efficiency is obtained at the peak of  $R_O''$ .
8. Since maximum efficiency point corresponds to the maximum  $R_O''$ , it also corresponds to a local minimum of output power (per a given input voltage).

### III. DETAILED ANALYSIS

#### A. Operating Frequency and Output to Input Voltage Ratio

The output to input voltage ratio  $k_{21}$  (Fig. 1) was found to be:

$$k_{21} = \frac{V_{out}'}{V_{in}} = \frac{1}{\sqrt{Y}} \quad (12)$$

where

$$Y = \{1 - c \left[ \left( \frac{\omega}{\omega_{rs}} \right)^2 - 1 \right] + \frac{R_m}{R_O'}\}^2 + \left\{ \frac{\omega_{rs} c}{\omega Q} \left[ \left( \frac{\omega}{\omega_{rs}} \right)^2 - 1 \right] + \frac{\omega}{\omega_{rs} Q_m} \right\}^2 \quad (13)$$

$$c = \frac{C_O'}{C_r} \quad (14)$$

$$Q = \omega_{rs} C_O R_O \quad (15)$$

$$Q_m = \frac{1}{\omega_{rs} C_r R_m} \quad (16)$$

$Q$  is the electrical quality factor and  $Q_m$  is the mechanical quality factor.

Equation (12) implies that  $k_{21}$  has a maximum value ( $k_{21m}$ ) when  $Y$  has a minimum value. Therefore, the

frequency ratio  $\frac{\omega_m}{\omega_{rs}}$  corresponding to  $k_{21m}$  can be found by

setting derivative of the function (13) to zero. This was carried out two ways: by an exact and by an approximate analysis.

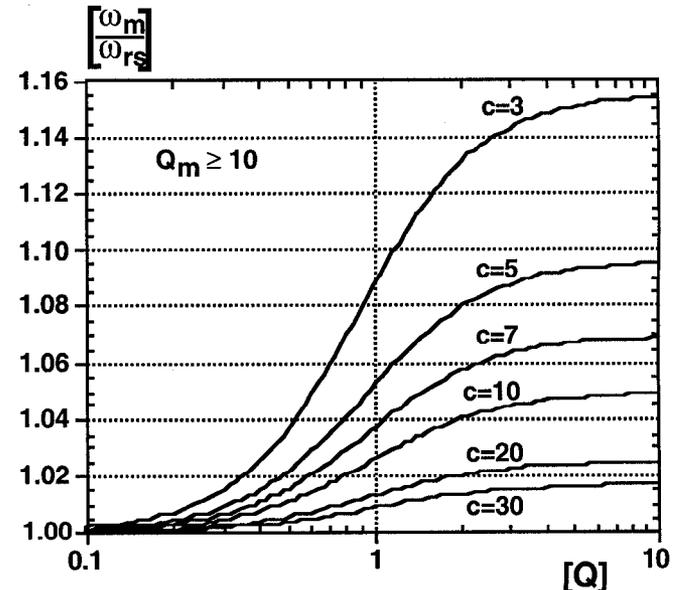


Fig. 2. Normalized operating frequency  $\omega_m$  corresponding to the maximum output to input voltage ratio as a function of the electrical quality factor  $Q$  and capacitances ratio  $c$  for mechanical quality factor  $Q_m \geq 10$  ( $\omega_{rs}$  is the resonant frequency in short circuit mode).

Exact analysis was based on the solution of the derivative of the third order equation (13) which can be presented by the canonical form:

$$x^3 + \left[ \frac{1}{2Q^2} + \frac{1}{2Q_m^2} - 1 - \frac{1}{c} \right] x^2 - \frac{1}{2Q^2} = 0 \quad (17)$$

where

$$x = \left( \frac{\omega_m}{\omega_{rs}} \right)^2 \quad (18)$$

The frequency ratio  $\frac{\omega_m}{\omega_{rs}}$  corresponding to the maximum value of  $k_{21}$  ( $k_{21m}$ ), as a function of  $Q$ ,  $Q_m$  and  $c$  was found from (17) and (18) applying the "Mathematica" software package [9]. This dependence is plotted in Fig. 2. It shows that an increase of  $Q$  from zero to infinity shifts  $\omega_m$  from  $\omega_{rs}$  to  $\omega_{ro}$  as expected. The curves are valid for a large range of  $Q_m$  (10 to 1000) in which range the discrepancy is less than 0.22%.

By inserting the values of  $\frac{\omega_m}{\omega_{rs}}$  into (13) and applying (12) we found the relationships between  $k_{21m}$  and circuit parameters  $Q$ ,  $Q_m$  and  $c$  (Fig. 3).

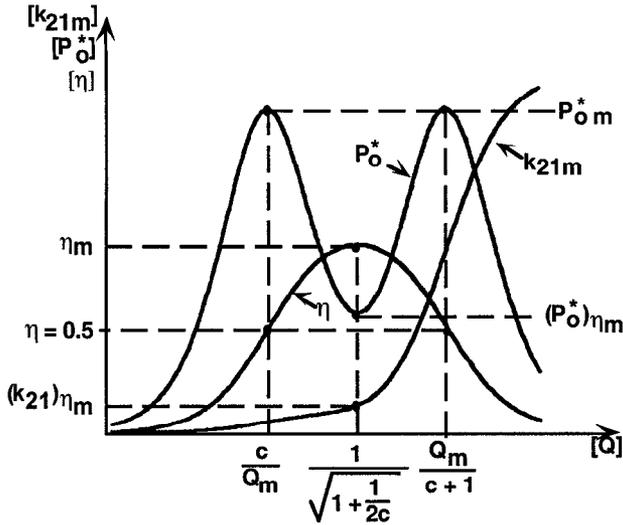


Fig. 3. Maximum value of the output to input voltage ratio  $k_{21m}$ , output power in per unit system  $P_o^*$  and efficiency  $\eta$  as a function of the electrical quality factor  $Q$  for  $c=\text{const}$  and  $Q_m=\text{const}$ .

The results of the exact analysis, given above, are presented by tables and graphs. The results of the approximate analysis given below, are presented in closed form which is more convenient for design procedures. The approximation is based on the fact that the derivatives some terms in (17) with respect to  $x$  are smaller than others and hence could be considered constant.

Taking into account the fact that near resonance  $\left\{ \left( \frac{\omega}{\omega_{rs}} \right)^2 - 1 \right\}$  is changing much more rapidly as a function of  $\left( \frac{\omega}{\omega_{rs}} \right)$  than

does  $\left( \frac{\omega}{\omega_{rs}} \right)$ , we replace here the first order multipliers  $\left( \frac{\omega}{\omega_{rs}} \right)$  and  $\left( \frac{\omega_{rs}}{\omega} \right)$  in (13) by as yet unknown constants:

$$g = \frac{\omega}{\omega_{rs}} \quad \text{and} \quad \frac{1}{g} = \frac{\omega_{rs}}{\omega} \quad (19)$$

Hence, (13) can be transformed into a following form:

$$Y = \left\{ 1 - c \left[ \left( \frac{\omega}{\omega_{rs}} \right)^2 - 1 \right] + \frac{R_m}{R_o'} \right\}^2 + \left\{ \frac{c}{gQ} \left[ \left( \frac{\omega}{\omega_{rs}} \right)^2 - 1 \right] + \frac{gc}{Q_m} \right\}^2 \quad (20)$$

Taking the derivative of (20) and equating it to zero, we solved the equation for the frequency ratio  $\frac{\omega_m}{\omega_{rs}}$  corresponding to the maximum value of output to input voltage ratio  $k_{21m}$ :

$$\frac{\omega_m}{\omega_{rs}} = \sqrt{1 + \frac{C_r}{C_o'} \frac{\left( \frac{\omega_m}{\omega_{rs}} \right)^2 Q^2}{1 + \left( \frac{\omega_m}{\omega_{rs}} \right)^2 Q^2}} \quad (21)$$

or

$$\frac{\omega_m}{\omega_{rs}} = \sqrt{1 + \frac{C_r}{C_o'} \sin^2 \varphi_m} \quad (22)$$

where  $\varphi_m$  is the phase angle of the parallel circuit  $R_o' C_o'$  (Fig. 1b) at the frequency  $\omega_m$  corresponding to the maximum value of the output to input voltage ratio  $k_{21m}$ :

$$\varphi_m = \tan^{-1} \left( Q \frac{\omega_m}{\omega_{rs}} \right) = \tan^{-1} (\omega_m C_o' R_o') \quad (23)$$

Applying (14) we define from (21) the expression of  $\frac{\omega_m}{\omega_{rs}}$  in a convenient form for calculation:

$$\frac{\omega_m}{\omega_{rs}} = \sqrt{0.5 \left( 1 + \frac{1}{c} \frac{1}{Q^2} \right)} + \sqrt{0.25 \left( 1 + \frac{1}{c} \frac{1}{Q^2} \right)^2 + \frac{1}{Q^2}} \quad (24)$$

Note that the values of  $\frac{\omega_m}{\omega_{rs}}$  obtained by the approximate analysis are independent of  $\frac{R_m}{R_o'}$  (the terms including  $\frac{R_m}{R_o'}$  in (20) were reduced during the mathematical transformation).

Inserting (22) into (13) and applying (12), (14)-(16) and (23), we define now expressions, that are convenient for calculation, for the maximum value of the output to input voltage transfer ratio  $k_{21m}$ :

$$k_{21m} = \frac{1}{\cos \varphi_m + \frac{R_m}{R_o' \cos \varphi_m}} = \frac{1}{\cos \varphi_m + \frac{c}{Q_m Q \cos \varphi_m}} \quad (25)$$

Detailed comparison between simulation, exact analysis and approximate formulas for  $Q$  in the range of 0.01-100,  $Q_m$  in the range of 10-1000 and  $c$  in the range 0.5-50 reveal that the maximum discrepancy is smaller than 4.5%. In most operational regions, however, the agreement was found to be better than 0.1%. We believe therefore that the approximate (closed form) equations derived in this study are more than sufficient from the engineering point of view.

## B. Output Power and Efficiency

The output power  $P_O$  can be calculated from the following expression:

$$P_O = \frac{(k21mV_{in})^2}{R_{O'}} \quad (26)$$

or in per unit system (taking into account (14) and (15)):

$$P_{O}^* = \frac{P_O}{P_{bas}} = \frac{ck21m^2}{Q} \quad (27)$$

where  $P_{bas}$  is the base power unit:

$$P_{bas} = V_{in}^2 \sqrt{C_r/L_r} \quad (28)$$

Efficiency can be found from [5]:

$$\eta = \frac{R_{O}''}{R_{O}'' + R_m} \quad (29)$$

where  $R_{O}''$  is the reflected load resistance in the equivalent series circuit  $R_{O}''C_{O}''$  (Fig. 1c).

Applying (4) and (14)-(16) we transform (29) to obtain the expression for  $\eta$  in a form that is convenient for calculation:

$$\eta = \frac{1}{1 + \frac{c}{Q_m} \left[ \frac{1}{Q} + \left( \frac{\omega}{\omega_{rs}} \right)^2 \right]} \quad (30)$$

The values of  $P_{O}^*$  and  $\eta$ , calculated from (27), (25) and (30) as a function of the electrical quality factor  $Q$  for  $c=\text{const}$  and  $Q_m=\text{const}$ , are plotted in Fig. 3. These graphs reveal three extremes. Two of them correspond to the equal-height peaks of the output power  $P_{O}^* = P_{Om}^*$ . The third extreme point corresponds to the maximum efficiency  $\eta_m$  and a local minimum per unit output power  $(P_{O}^*)_{\eta_m}$ .

To derive the location of these extreme points we find first the relationship between the output power  $P_{O}^*$  and efficiency  $\eta$ . Applying equations (27) and (29) of  $P_{O}^*$  and  $\eta$  and taking into account (23) and (25) we obtain:

$$P_{O}^* = \frac{c}{Q} \frac{1 + Q^2 \left( \frac{\omega_m}{\omega_{rs}} \right)^2}{1 + \frac{2R_m}{R_{O}''} + \left( \frac{R_m}{R_{O}''} \right)^2} \quad (31)$$

$$\frac{R_m}{R_{O}''} = \frac{1}{\eta} - 1 \quad (32)$$

from where

$$\frac{P_{O}^*}{\eta^2} = c \left[ \frac{1}{Q} + Q \left( \frac{\omega_m}{\omega_{rs}} \right)^2 \right] \quad (33)$$

Inserting (33) into (30) we find:

$$\frac{P_{O}^*}{Q_m} = \eta(1-\eta) \quad (34)$$

This relationship is plotted on Fig. 4. It is clear that maximum output power  $P_{Om}^*$  corresponds to the efficiency  $\eta=0.5$  and hence:

$$P_{Om}^* \approx 0.25 Q_m \quad (35)$$

Inserting  $\eta=0.5$  into (30) we find the following equation for the power peak points:

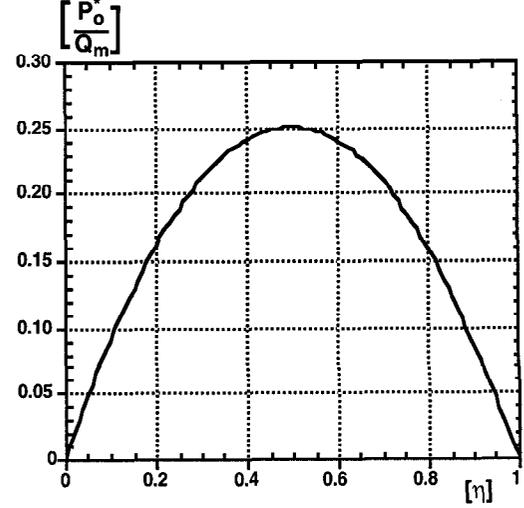


Fig. 4. Output power in per unit system  $P_{O}^*$  as a function of the efficiency  $\eta$  ( $Q_m$  is the mechanical quality factor).

$$Q^2 - \frac{Q_m}{c \left( \frac{\omega_m}{\omega_{rs}} \right)} Q + \frac{1}{\left( \frac{\omega_m}{\omega_{rs}} \right)^2} = 0 \quad (36)$$

This equation has two solutions:

$$Q_1 = \frac{1}{\frac{Q_m}{2c} + \sqrt{\left( \frac{Q_m}{2c} \right)^2 - \left( \frac{\omega_m}{\omega_{rs}} \right)^2}} \quad (37)$$

$$Q_2 = \left[ \frac{Q_m}{2c} + \sqrt{\left( \frac{Q_m}{2c} \right)^2 - \left( \frac{\omega_m}{\omega_{rs}} \right)^2} \right] \left( \frac{\omega_{rs}}{\omega_m} \right)^2 \quad (38)$$

We simplify these solutions taking into account the following conditions:

-  $\left( \frac{Q_m}{2c} \right)^2$  is usually much larger than  $\left( \frac{\omega_m}{\omega_{rs}} \right)^2$ ;

- the value of  $Q_2$  is practically very large and therefore

$$\left( \frac{\omega_m}{\omega_{rs}} \right)^2 \approx 1 + \frac{1}{c} \quad (\text{see (21) and Fig. 2}).$$

Under these conditions we obtain:

$$Q_1 \approx \frac{c}{Q_m} \quad (39)$$

$$Q_2 \approx \frac{Q_m}{c+1} \quad (40)$$

Now we consider the extreme point corresponding to the maximum value of the efficiency  $\eta_m$ . Analysis of (30) shows that  $\eta = \eta_m$  when

$$Q \frac{\omega_m}{\omega_{rs}} = 1 \quad (41)$$

i. e. when  $\varphi_m = \frac{\pi}{4}$  (see (23)). The values of  $\frac{\omega_m}{\omega_{rs}}$  and  $Q$  corresponding to  $\eta_m$  are defined from (22) and (41):

$$\frac{\omega_m}{\omega_{rs}} = \sqrt{1 + \frac{1}{2c}} \quad (42)$$

$$Q = \frac{1}{\sqrt{1 + \frac{1}{2c}}} \quad (43)$$

Inserting (42) and (43) into (30) we obtain the expression of the maximum efficiency:

$$\eta_m = \frac{1}{1 + \frac{2c}{Q_m} \sqrt{1 + \frac{1}{2c}}} \quad (44)$$

Inserting (44) into (34) we obtain the output power at the point corresponding to the maximum value of the efficiency  $\eta_m$ :

$$(P_o^*)_{\eta_m} = \frac{2c \sqrt{1 + \frac{1}{2c}}}{\left(1 + \frac{2c}{Q_m} \sqrt{1 + \frac{1}{2c}}\right)^2} \quad (45)$$

In the case that  $Q_m \gg 2c$  the equation can be simplified to:

$$(P_o^*)_{\eta_m} \approx 2c \sqrt{1 + \frac{1}{2c}} \quad (46)$$

### C. Output to Input Voltage Ratio and Efficiency

Dependence between the output to input voltage ratio  $k_{21m}$  and efficiency  $\eta$  is found in the same manner as above. From (23) and (25) we define:

$$k_{21m} = \frac{\sqrt{1 + \left(Q \frac{\omega_m}{\omega_{rs}}\right)^2}}{1 + \frac{c}{Q_m Q} \left[1 + \left(Q \frac{\omega_m}{\omega_{rs}}\right)^2\right]} \quad (47)$$

Inserting (47) into (30) we obtain:

$$\eta = \frac{k_{21m}}{\sqrt{1 + \left(Q \frac{\omega_m}{\omega_{rs}}\right)^2}} \quad (48)$$

The value of  $k_{21m}$  corresponding to the efficiency peak point ( $\eta = \eta_m$ ), defined as  $(k_{21m})_{\eta_m}$ , is found from (41) and (48):

$$(k_{21m})_{\eta_m} = \sqrt{2} \eta_m \quad (49)$$

or taking into account (44)

$$(k_{21m})_{\eta_m} \approx \frac{\sqrt{2}}{1 + \frac{2c}{Q_m} \sqrt{1 + \frac{1}{2c}}} \quad (50)$$

## IV. PT WITH A MATCHING INDUCTOR CONNECTED IN PARALLEL TO THE OUTPUT TERMINALS

The current of the output capacitance  $C_o$  (Fig. 1a), is lowering the efficiency since it passes through  $R_m$ . Hence,

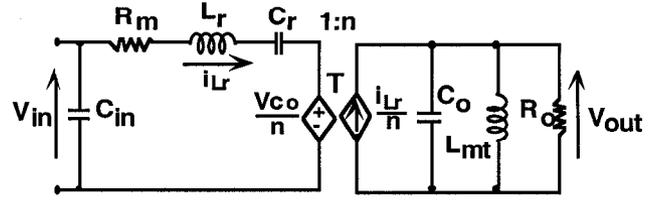


Fig. 5. Connection of a matching inductor  $L_{mt}$  in parallel to the output terminals of PT.

the overall efficiency of a PT can be improved by compensating the reactive current of  $C_o$  by an inductor  $L_{mt}$  connected in parallel to the output terminals of PT (Fig. 5).

For a perfect compensation :

$$L_{mt} = \frac{1}{\omega^2 C_o} \quad (51)$$

where  $\omega = \omega_{rs}$  is the operating frequency. The losses in the resistor  $R_m$  are lower in this case and therefore the efficiency of PT will be higher. In such a case, the equivalent resistances  $R_o''$  and  $R_o'$  (Figs. 1c and 1b) have identical values and hence equation (29) of the PT efficiency is reduced to a following form:

$$\eta_L = \frac{1}{1 + \frac{R_m}{R_o'}} \quad (52)$$

The ratio between the efficiency values in the two cases: without and with the matching inductor  $L_{mt}$  ( $\eta$ , and  $\eta_L$ ) is found from (52), (29) and (4):

$$\frac{\eta}{\eta_L} = \frac{1 + \frac{R_m}{R_o'}}{1 + \frac{R_m}{R_o'} [1 + (\omega C_o R_o')^2]} = \frac{1}{1 + \frac{(\omega C_o R_o')^2}{1 + \frac{R_o'}{R_m}}} \quad (53)$$

This relationship is shown in Fig. 6. We see that in general  $\eta < \eta_L$ , but for small  $R_m/R_o'$  and  $\omega C_o R_o'$  values we find  $\eta \approx \eta_L$ .

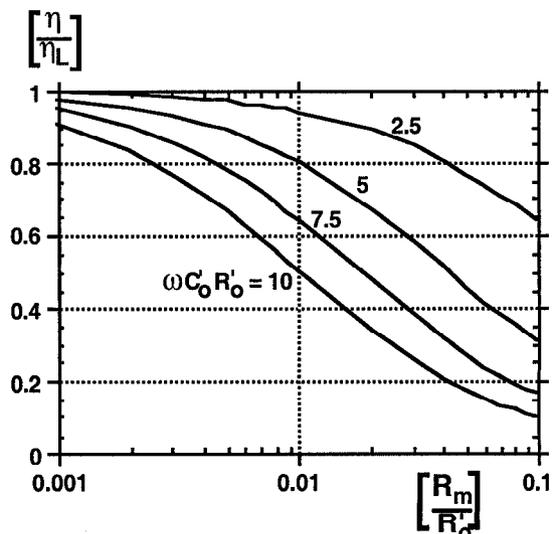


Fig. 6. Ratio between efficiency values when the matching inductor  $L_{mt}$  is missing ( $\eta$ ) and when this inductor is present ( $\eta_L$ ) as a function of  $R_m/R_o'$  and  $\omega C_o R_o'$ .

Note that the matching inductor  $L_{mt}$ , operating in the resonant mode with  $C_0$ , decreases the output to input voltage transfer ratio  $k_{21m}$ :

$$(k_{21m})L \approx \eta L \quad (54)$$

To conserve the same output voltage  $V_{out}$ , input voltage  $V_{in}$  of PT must be increased.

## V. EXPERIMENTAL

Philips piezoelectric transformer (RT 35x8x2 PXE43-S) with thickness polarization [5] was investigated experimentally. Its main parameters were measured to be (Fig. 1a):  $L_r=170\text{mH}$ ,  $C_r=14.7\text{pF}$ ,  $R_m=100.5\Omega$ ,  $C_0=500\text{pF}$ ,  $n=0.988$ ,  $f_{rs}=\omega_{rs}/2\pi=100.68\text{kHz}$ ,  $f_{ro}=\omega_{ro}/2\pi=102.18\text{kHz}$ . The experiments were carried out for a load resistance  $R_0$  range of  $10\Omega$  to  $540\text{k}\Omega$ . The input voltage  $V_{in}$  was a sine wave of  $1\text{Vrms}$ . It was found that the performance of this PT is practically independent of the magnitude of input voltage. For each measurement point, the frequency was adjusted to obtain the maximum output voltage  $V_{out,m}$ . Excellent agreement was found between the experimental results and the corresponding values predicted by the equations derived in this study for the voltage gain and output power (Fig. 7).

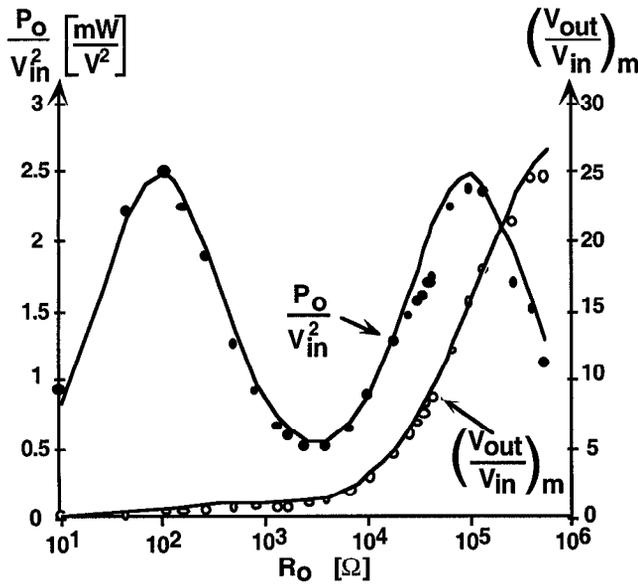


Fig. 7. Maximum value of the output voltage  $V_{out,m}$  and the output power  $P_0$  as a function of load resistance  $R_0$ : circles - experimental results; lines - theoretical prediction.

## VI. DISCUSSION AND CONCLUSIONS

The generic equations developed in this study reveal some universal relationships between key parameters of a PT. These physical trade-off can be used two ways: to optimize the design of a PT for a given application and/or specifying the desired PT to fill given tasks. From the engineering point of view it is clear that the range for high efficiency operation for a PT is:

$$\frac{c}{Q_m} < Q < \frac{Q_m}{c+1} \quad (55)$$

Over this range the voltage transfer ratio is bound as follows:

$$0.5 < k_{21m} < \frac{0.5Q_m}{\sqrt{c(c+1)}} \quad (56)$$

Connection of a matching inductor  $L_{mt}$  in parallel to the output terminals of PT will increase the efficiency, but will decrease the output to input voltage ratio. The results displayed in Fig. 6 can be used to estimate the improvement in efficiency that can be gained by incorporating the compensating inductor. Trade-off between cost and performance can be examined.

The main conclusion of the paper is that the characteristics of a PT are described to a very good approximation by the equations developed in this study. These closed form formulas could be invaluable when studying, specifying and designing practical PTs applications.

## REFERENCES

- [1] C. Y. Lin and F. C. Lee, "Design of a piezoelectric transformer converter and its matching networks", *IEEE PESC'94 Record*, pp. 607-612.
- [2] M. Imori, T. Taniguchi, H. Matsumoto, T. Sakai, "A photomultiplier high voltage power supply incorporating a piezoelectric ceramic transformer", *IEEE Trans. Nuclear Science*, vol. 43, no. 3, pt. 2, pp. 1427-1431, June 1996.
- [3] P. J. M. Smidt and J. L. Duarte, "Powering neon lamps through piezoelectric transformers", *IEEE PESC'96 Record*, pp. 310-315.
- [4] Y. Fuda, K. Kumasaka, M. Katsuno, H. Sato, Y. Ino, "Piezoelectric transformer for cold cathode fluorescent lamp inverter", *Jpn. J. Appl. Phys.*, vol. 36, pt. 1, no. 5B, pp. 3050-3052, May 1997.
- [5] Philips, "Piezoelectric transformers", *Application note Philips Magnetic Products*. Date of release: 2/97.
- [6] R. L. Steigerwald, "A comparison of half-bridge resonant converter topologies", *IEEE Trans. Power Electron.*, vol. 3, pp. 174-182, Apr. 1988.
- [7] G. Ivensky, A. Kats, S. Ben-Yaakov, "A RC-model of parallel and series-parallel resonant dc-dc converters with capacitive output filter", *IEEE Trans. Power Electron.*, vol. 14, pp. 515-521, May 1999.
- [8] G. Ivensky, M. Shvartsas, S. Ben-Yaakov, "Analysis and modeling of a piezoelectric transformer in high output voltage applications", *IEEE APEC'00 Record*, pp. 1081-1087.
- [9] S. Wolfram, "Mathematica. A system for doing mathematics by computer", *Addison-Wesley Publishing Company, Inc.*, 1988.