

New Type of Piezoelectric Transformer With Very High Power Density

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ABSTRACT

A new innovative multilayer PT design for operation with high power density and frequencies up to several MHz is presented. The design is based on a ring-shaped element operating in thickness vibrational mode, where the primary and secondary sides are separated by an isolation layer. Prototypes with intricate geometry, a result of FEM simulations for maximising the effective coupling factor of the working mode and suppressing spurious modes, are presented. Initial results show power densities above 40 W/cm³ at efficiencies above 98%. This is a clear improvement over present state-of-the-art transformers.

The flexibility of the general design with respect to changing power levels and transformation ratios opens a variety of new enormous markets in the electronic industry.

INTRODUCTION

A piezoelectric transformer (PT) can in general be seen as two coupled ultrasonic transducers, one transmitting (primary side) and the other receiving (secondary side), whereby differences in capacitance between the two sides will accommodate a transformation of voltage. The first devices utilising this principle was described by C. A. Rosen in 1956 [1], and commercial PT's have essentially only been changed by the adaptation of multilayer technology for higher transformation ratios in the early 1990's [2].

Piezoelectric transformers, based on the original Rosen Type, or in the various multilayer configurations, are generally known to be an excellent way to obtain a high voltage transformation with high power density, low profile and no electromagnetic noise. These characteristics have thus made PT's suitable for e.g. applications in LCD backlighting and high voltage generators for TV sets. The output power levels in these transformers are typically in the range of 0,5 – 5 W, with power densities of 5-10 W/cm³. In many modern consumer electronic applications, for example power supplies for portable equipment, there are however a strong need for low-voltage transformers with power levels above 10 W, and there is thus an extremely large potential use of PT's, if the power densities can be increased significantly. Power densities of 26-30 W/cm³ have recently been reported for various high-voltage PT's [3-4], but these designs cannot be directly converted to

low-voltage mode because of demands to a galvanic separation between the two sides. When an isolation layer is incorporated in these structures, the power density decreases, and values of only 15-20 W/cm³ have been reported [5-8].

The objective of this work has therefore been to increase the possible maximum power density, which can be obtained from a PT. As a demonstration of this technology the miniaturisation of an AC/DC converter for charging mobile phone batteries was selected. This objective is shown schematically in Fig 1, and the general specifications are summarised in Table 1.

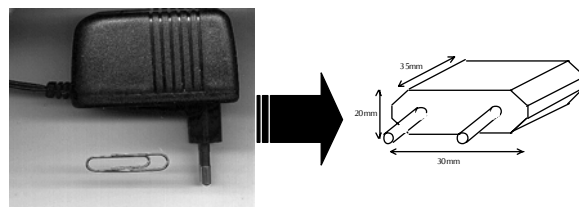


Fig. 1. Illustration of the objective of the work. Miniaturisation of a conventional 10 W AC/DC converter through implementation of a new piezoelectric transformer.

Table 1 General specifications to the selected application and their implications on the specification for the separate piezoelectric transformer.

Parameter	Requirement
Application	AC-DC Converter. Mobile phone battery charging.
Input	Universal, 84-264 V (50-60 Hz)
Output	12 V DC
Output Power	10 W
Optimum Load	23 Ω
Converter size	≈20 cm ³
PT output power	>10 W
PT footprint	≈ OD 12-15 mm
PT Isolation	Galvanic, EN 60950, 3,3 kV _{rms}
PT power density	40-50 W/cm ³

NEW CONCEPT FOR PT'S

With a required power density (PD) of 40-50 W/cm³ and demands for galvanic separation, it is clear, that the Rosen-Type and its various derivatives most likely do not posses the potential to fulfil the objective of this work. By working systematically with eq.1 it was therefore concluded that a new concept should be developed.

$$PD \propto K_{33}^T \cdot f_{res}^2 \cdot k_{eff}^2 \quad (1)$$

where K_{33}^T is the relative dielectric constant, f_{res} the resonance frequency for the working mode and k_{eff} the effective piezoelectric coupling constant for the working mode.

It was concluded that it would be necessary to use a Navy Type1 material, which is known to have high permittivity and low losses; a thickness extensional resonance working mode, which will give the highest possible frequency; and with a geometry which would give a high effective piezoelectric coupling coefficient (k_{eff}).

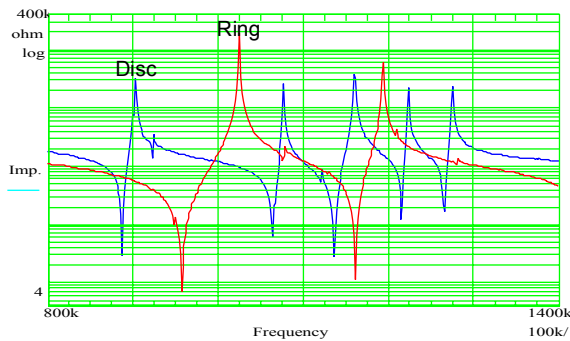


Fig. 2. Impedance plot for PZT Type I disk and ring of comparable size. The ring has very clear resonances without spurious modes.

Fig 2 shows a comparative impedance plot between a disk- and ring-shaped element of comparable size. It can be seen, that the ring-element, given the right relation between OD vs ID vs TH, will give a very clear resonance without interference of higher order modes, and it will thus be easier to obtain the required high k_{eff} .

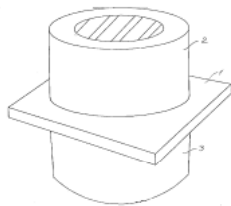


Fig. 3. Schematic presentation of the new design for piezoelectric transformers

A new basic design, Fig 3, is thus proposed [9], where the above features are incorporated. This design is in contrast to the Rosen type based on two ring-shaped elements separated by an isolation layer operating in thickness extensional mode. One ring can be composed of

several layers to accommodate a large transformation ratio.

MANUFACTURING OF PT'S

Transformers were manufactured using Ferroperm Pz26 material (Navy Type 1), which was tape-cast, printed with Pt electrodes, stacked, and laminated. Separate elements were diced and machined to its external dimensions, and the elements were burned out, sintered, electroded and poled using conventional production techniques. The manufacturing process is illustrated in Fig 4.

The selected production method made it possible to produce fully co-fired transformers with intricate geometry and a very good acoustic coupling between the primary and secondary parts. Examples of different co-fired elements with intricate geometry are given in Fig. 5.

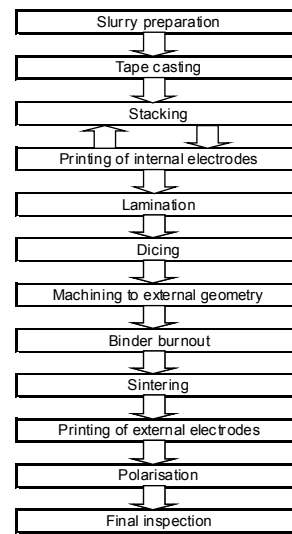


Fig. 4. Schematic presentation of the process used for production of Piezoelectric multilayer transformers

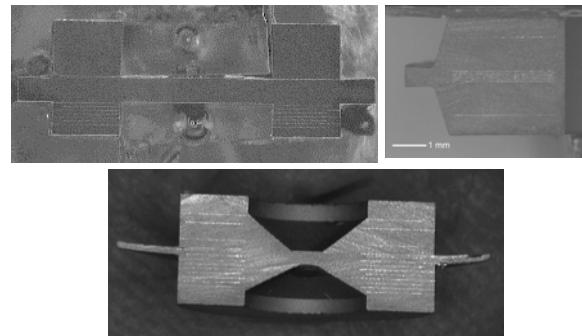


Fig. 5. Examples of cross-sectioned prototype co-fired piezoelectric transformers. The outer diameters are 10-15 mm.

FEM SIMULATION AND OPTIMISATION OF PT DESIGNS

RESULTS

The specific design of transformers was based on FEM simulations (ATILA[®], Cedrat Recherche), which could predict the mechanical and electrical behaviour of various geometries and electrode configurations. Initial comparison between simulations and actual measurements however showed a significant discrepancy, which primarily was caused by unsuitable input data to the model. Fig. 6 illustrates the difference, in predicted and measured resonance frequencies for various modes in a simple disk- and ring-geometry when a traditional input matrix based on IEEE 176 are used. An iterative method was therefore applied to improve the predictability of the model, and Fig 7 shows the same simulation as above, but with a new “optimised” input data matrix. It can clearly be seen that the predictability is strongly improved, and it can therefore generally be concluded that standard input data cannot be used, if higher order resonances in complicated geometries have to be simulated.

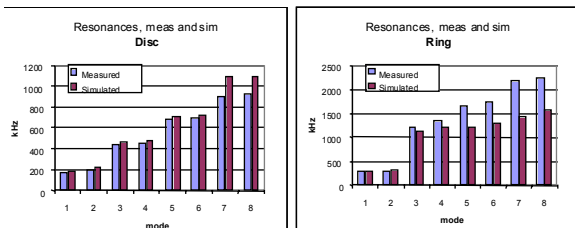


Fig. 6. Comparison of measured resonance frequencies for different vibration modes with simulated values obtained from the ATILA code using a “standard” input data matrix. Prediction of frequency is very poor at higher modes.

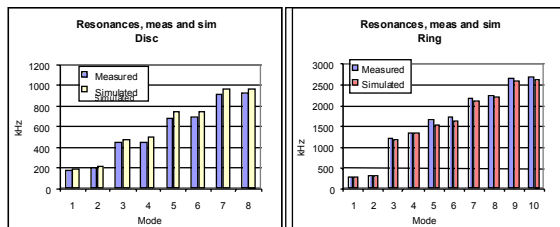


Fig. 7. Comparison of measured resonance frequencies for different vibration modes with simulated values performed with a new “optimised” matrix. A clear improvement in reliability can be observed.

Further work with improvements of the models was found necessary, as the predictability of the models with the new input data matrix did not show the required improvement. Comparisons between the behaviour of initial prototypes and the simulated values clearly indicated the importance of applying more detailed non rotation-symmetrical models, due to the inhomogeneous polarisation field around external electrodes and unelectroded volume inside the structure. It was thus concluded, that 3D simulation was necessary for sufficient accuracy of the modelling, but due to time-constraints this was only applied for limited cases.

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Two designs were developed to demonstrate the new PT concept. These designs were developed on the basis of extensive 2D and 3D simulation work on internal and external features, which served to maximise the k_{eff} and eliminate spurious modes close to the working resonance of approximately 400 kHz. Both designs had 14 internal electrode layer in the secondary sides, and were only processed to different external geometries. The difference in external designs was made in order to evaluate two different mounting strategies: mounting on a centre-pin and mounting in a hole in the converter PCB. The two different designs are shown in Fig.8.

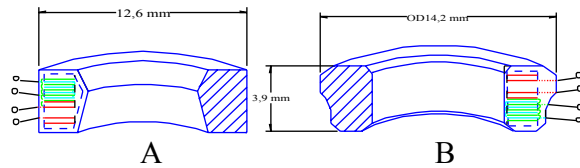


Fig. 8. Schematic presentation of the two final prototype designs. Type A is designed for mounting on centre pin, while Type B can be mounted into a hole in a PCB.

Fig 9 shows an impedance plot of the secondary side of a transformer with Type A design, and the general characteristics are summarised in Table 2. It can clearly be seen from these that a very clear resonance without disturbance from spurious modes and with a high k_{eff} has been obtained. The maximum power level, which can be extracted from these PT’s are 15 W. This gives an effective power density above 40 W/cm³ at efficiencies above 98%, and is thus a significant improvement over previously reported values. The breakdown isolation voltage is furthermore above 5 kV DC, and is therefore well above the required level of 3,3 kV_{RMS} required by safety regulations.

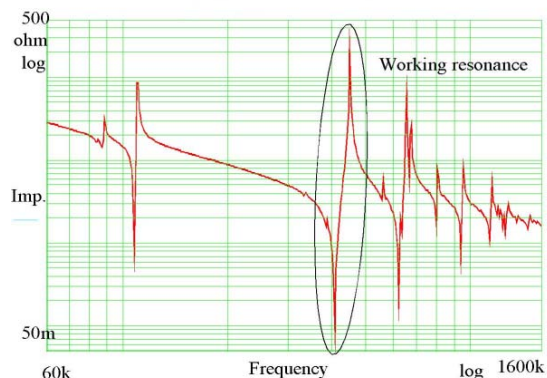


Fig 9. Impedance plot of PT. A clear working resonance without disturbance from spurious modes can be seen.

Fig 10 shows a comparison of measured k_{eff} values with a FEM simulation of this design. It can be noted that, even if the predictability of the model is acceptable, there is a difference in k_{eff} for the working mode of up to 12%. If the predicted value could indeed be obtained, it would mean a significant further increase in maximum power density, and it is therefore clear, that a further potential exist for this type of design, if improved 3D FEM modelling is applied to optimise future designs.

Table 2. Typical dielectric and piezoelectric properties of prototype transformers of Type A and Type B design.

	Cap	Res.	Imp.	k_{eff}
	nF	kHz	m Ω	%
Primary	2,4	430	2000	36
Secondary	95	425	120	38

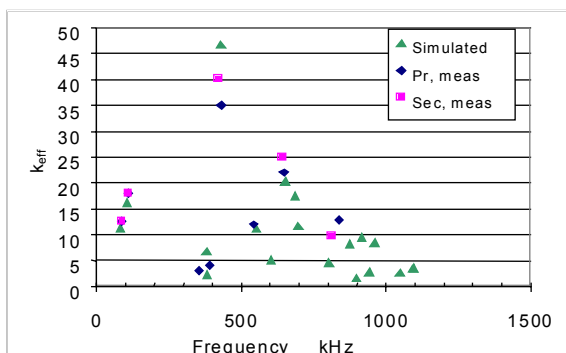


Fig 10. Comparison between k_{eff} for simulated and measured resonances. The working resonance is approximately 400 kHz.

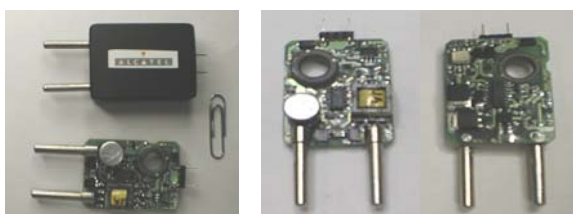


Fig 11. Overview pictures of the demonstration AC/DC converter based on the new Piezoelectric Transformer. *Courtesy of Alcatel España.*

The developed PT's were implemented in prototype AC/DC converters by Alcatel España, shown in Fig 11. Physical and electrical tests with these converters showed, that all specifications given in Table 1 could be fulfilled except the universal input voltage. The maximum input voltage with these two specific PT designs are limited to only approximately 130V AC, and can thus only comply with the American regulations. Increasing the maximum input voltage to the PT is however a minor problem of re-designing the internal electrode configuration, and new designs, which includes this feature has been proposed. 12th IEEE International Symposium on Applications of Ferroelectrics

Detailed characterisation of the prototype converter will be reported elsewhere.

CONCLUSIONS

This work has presented a new and innovative design for piezoelectric transformers. The primary application for the developed design is for use in AC-DC converters in mobile phone battery chargers, but can with a few minor changes in internal design be changed to a range of other applications as well. The design is based on a ring-shaped element operating in thickness vibrational mode, where the primary and secondary sides are separated by an isolation layer. This structure was selected because it, in contrast to all conventional PT designs, makes it possible to include an isolation layer without seriously decreasing the efficiency.

Technology has been developed for production of highly sophisticated multilayer elements by modifying a conventional multilayer production technology, and a very high degree of freedom in geometrical design was demonstrated. This process was used to produce PT's with intricate geometry, a result of FEM simulations for maximising the effective coupling factor of the working mode and suppressing spurious modes.

Initial results with the developed PT's show power levels up to 15W at efficiencies above 98%. This gives power densities above 40 W/cm³, which is a clear improvement over state-of-the-art magnetic and piezoelectric transformers.

The proposed specification for this type of piezoelectric transformer for use in battery-chargers in mobile phones, are therefore within reach. The flexibility of the general design in respect to changing power-levels and transformation ratios furthermore opens a variety of new enormous markets in the electronic industry.

ACKNOWLEDGEMENTS

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