*Miniaturised Battery Charger using Piezoelectric Transformers**

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Abstract- **Piezoelectric materials is a technology that in recent years has raised enormous interest for its possible use as power transformers. Its main features are high power densities, absence of electromagnetic noise and high voltage isolation capability. This paper presents the results obtained* in a prototype of a miniaturized battery charger for mobile phones. Due to the reduced size of the piezoelectric transformers, the charger has been introduced in a plug type case, smaller than a matchbox.**

I. INTROCUCTION

Piezoelectric materials have been used for many years in applications such as actuators, resonators, transducers, etc. Its use as power transformer though known since the 60's is still mostly under research phase. Nevertheless, their promising benefits (such as power densities much higher than conventional magnetic transformers, absence of electromagnetic noise, high voltage isolation between primary and secondary, high frequency operation leading to reduction in the filter capacitors) has generated much interest, and in recent years there is increasing activity in this field.

Bearing in mind all these features, a battery charger was one of the best applications in which piezoelectric transformers (P.T.'s) could mean a large break-through when compared to current state-of-the-art solutions. Mobile phones chargers, are generally bulky, heavy and specially annoying when travelling. Therefore, the main goal of this work has been to develop a miniaturized travel charger, which could easily be carried in a pocket. The main specifications of the charger are: universal input voltage, 8.5W (12V@0.8A), size lower than 20cm^3, and weight lower than 50gr.

This paper addresses the design, modeling and construction of a piezoelectric transformer to be used in a battery charger for mobile phones. It also describes the operation of the power topology and its adaptation to best suit the features of the piezoelectric transformer, and finally presents the most relevant results obtained in the battery charger.

II. PIEZOELECTRIC TRANSFORMER DESIGN

The operating principle of a piezoelectric transformer is rather simple. The transformer is made out of 3 main parts: an ultrasonic transmitter, a coupling piece and a receiver. Electrical energy is applied into the transformer through the transmitter, and is transformed into a mechanical vibration (piezoelectric effect). This vibration is transmitted through the coupling part, over to the receiver. At the receiver, the mechanical energy is again transformed into electrical energy (inverse piezoelectric effect).

The first design goal of the piezoelectric transformer was to obtain a high power density. For a given geometry it is proportional to resonance frequency, permittivity and the coupling coefficient squared:

$$\frac{Power}{Volume} \propto f_{resonance} \cdot \varepsilon \cdot k_{eff}^{2}$$

To limit the switching losses in the power stage, the resonance frequency needs to be limited to f_{res}<500 kHz.

Permittivity is a material parameter, so only parameter left to optimize is k_{eff}.

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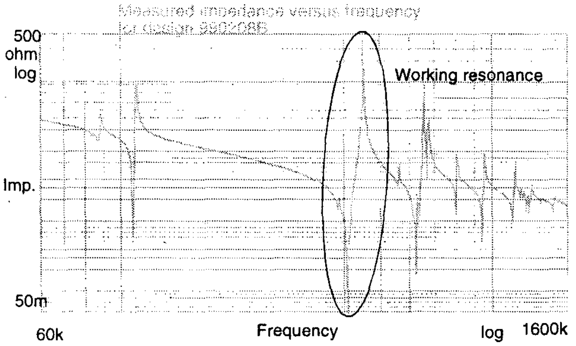

Fig. 1 Impedance measurement. Notice the clean working resonance due to the absence of overtones from the fundamental radial mode. $k_{eff} = 0.42$.

Second goal was removing of spurious modes from the working frequency to make it easier for the control circuit to track the working resonance. This can be obtained by using anisotropic materials [1] but the choice fell on high power PZT materials [2], which can stand higher power levels in high Q devices. Both targets were met by the same means – selecting a proper geometry. Using a ring shaped transformer made it possible to cancel out spurious modes and obtain a high coupling.

- Design and modeling strategy

Finite element simulations were used for maximizing k_{eff}, removal of spurious modes, identifying vibration nodes for mounting of the transformer and investigating sensitivity to production tolerances. The only way to carry out this design stage is using simulation tools that take into consideration 2D/3D effects. FEA solvers are a good alternative to be used in this design stage.

Once the shape has been designed in order to eliminate undesirable spurious modes, the behavior of the PT can be assumed as 1D along the main vibration direction. Therefore, 1D analytical models can be used to design the PT. Since these models are based on analytical expressions, they are very useful to be implemented in any electrical simulator to design the PT. Using these models, it is possible to select the following important parameters in order to accomplish with the electrical specifications of the transformer: the area and length of the transformer, the number of layers, the thickness of the layers, the position of primary and secondary electrodes...

The design inputs that have been considered are: power to be transferred, load, input waveform, ZVS requirements, efficiency...

- 1D PT models

Although the behavior of the PTs is very dependent on the 2D effects, once the component has been geometrically designed in order to eliminate the vibrations in any direction different than the "main" one, their behavior can be assumed as 1D. 1D models are very useful in order to design the PT because they can be used to extract a lot of information about the influence of many constructive parameters (length, area, number of layers, etc). The simplest 1D model of PTs is the Mason model, that it is represented in figure 2. This model is valid to take into account the behavior of the PT around the frequency of resonance assuming that no spurious modes exists.

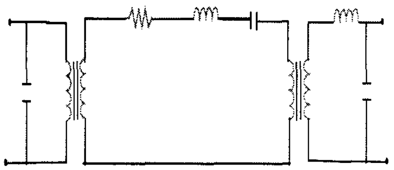

Fig 2. Mason model of a PT

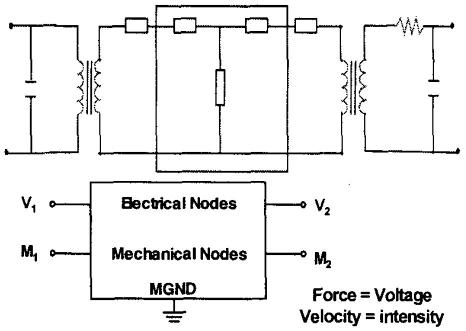

Fig 3. Transmission lines based model of a PT

However, it is possible to create models based on transmission lines that are able to represent the behavior of the PT around each vibration mode along the main direction. This model presents several frequencies of resonance, although the spurious modes are also neglected. Each piezoelectric material block is modeled by means of a four terminal box. Two terminals represent the electric behavior and the other two represent the mechanical behavior.

Therefore, using this structure, it is possible to model any electrode strategy of a multi-layer transformer, as it is shown in figure 4.

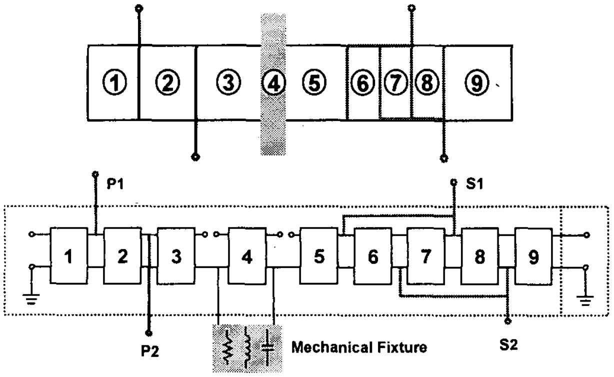

Fig 4. Model of a multi-layer PT

III. DEVELOPMENT OF THE P.T.

The final structure of the P.T. was defined based on FEM simulations with several iterations of the design. The final prototype transformers were manufactured using Ferroperm Pz26 material (Navy Type 1), which was tape-casted, electroded, stacked, and laminated. Separate elements were subsequently diced and machined to their external dimensions, and the elements were burned out, sintered, electroded and poled using conventional piezoceramic production techniques.

The electrode material in the PT's is platinum, though a more cost-effective silver/palladium paste was tested with promising results.

The selected production method made it possible to produce fully co-fired transformers with the following features:

- Bevels on inside to suppress unwanted spurious modes.
- Dead-areas to eliminate 3rd order harmonics.
- 4 layers on primary, two being floating in order to provide isolation distance.
- 14 layers on secondary side.

An illustration of the final design is given in Fig 5.

Tests performed on the obtained samples showed efficiencies ranging from 96% to 98% depending on the power level extracted (maximum achieved was 12W) and the input voltage conditions.

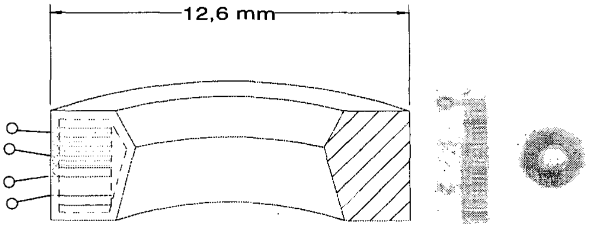

Fig 5. Cross-section and overview picture of the developed P.T.

IV. TOPOLOGY SELECTION

The choice of the topology to be used with the piezoelectric transformer was based on simplicity. Thus, a class-D topology was chosen, for it would take advantage of its resemblance to the PT equivalent circuit. It must be mentioned, though, that it has the disadvantage of including a floating control terminal and being very dependent on the performance of the piezoelectric transformer.

Despite this being a simple solution to drive a piezoelectric transformer, it must be taken into account that the PT parameters are not always convenient to give place to the desired resonant transitions. Moreover, it might be possible that load and line ranges are not covered. Thus, the basic topology was slightly modified by including a series input filter and an output stage comprising a full rectifier with a capacitive filter as shown in Figure 6. The series input filter.

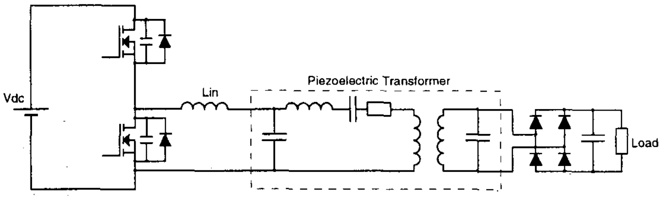

Figure 6. Final topology to be used.

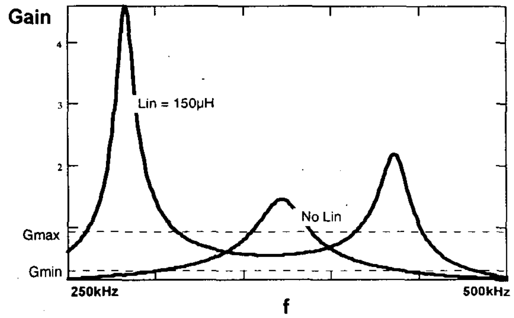

Figure 7. Gain plots with and without input filter.

would be nothing but an inductor. It must be mentioned that this filter might also be added even though the PT parameters were suitable to obtain ZVS, for it would also contribute to reducing common-mode noise by making the PT input voltage sinusoidal instead of quasi-square (see reference [III]). The advantages of including such a filter could be summarized as follows: a) constitutes a low-pass filter together with the equivalent input impedance of the piezoelectric transformer, thus making its input voltage be close to a sinusoidal one; b) eliminates the circulating current present in other kind of input filters that would increase converter losses; c) facilitates the achievement of zero-voltage switching (ZVS) operation in the power MOSFETs; d) reduces common-mode noise, thus reducing conducted EMI; e) might allow obtaining an auxiliary voltage to supply the control circuitry by adding a secondary winding to this input filter inductor. It must be taken into account, though, that the inclusion of this inductor modifies the gain vs. frequency plot as shown in Figure 7. The choice of the filter inductor must then be carefully made.

V. DEMONSTRATOR RESULTS

The obtained results show that piezoelectric transformers can successfully replace magnetic ones, reducing to a great extent size. The main results obtained in the battery charger are summarized as follows:

- The developed piezoelectric transformer has a power density around 25W/cm^3 (410W/in^3) which is around 5 times higher than what could be achieved in a high frequency magnetic transformer.

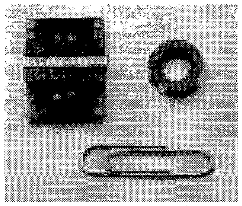
Fig.8 Comparison of the P.T. vs. a magnetic transformer

- The size of the battery charger is 3,3cm x 4,4cm x 1,4cm WxLxH (20cm^3) in a plug-type case similar in size to a matchbox. The following figure shows the final appearance of the battery charger and its main components.
- The weight of the battery charger is lower than 20gr. which is 10 times lower than a conventional linear charger, and even half of a state-of-the-art travel charger.

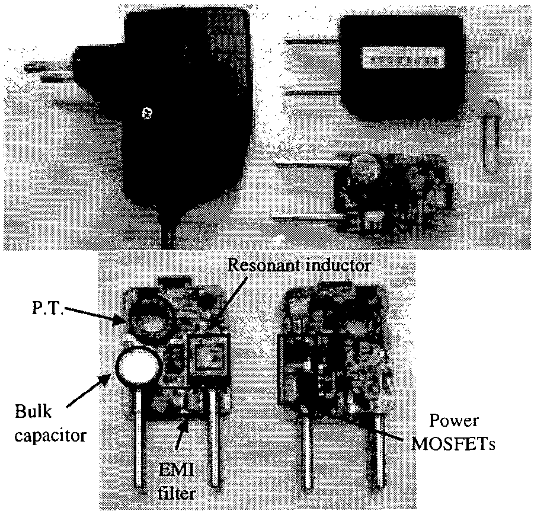

Fig 9. Final appearance of the battery charger and comparison vs.a linear one.

- Electromagnetic radiated noise is also a key factor in favor of piezoelectric transformers. As explained previously, due to the fact that the energy transfer is done via mechanical vibration, electromagnetic interference is almost absent. The following figures show the comparison between a P.T. and a magnetic transformer with a similar power level.

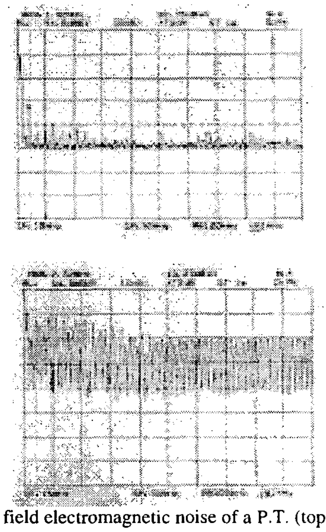
Figure 10. Near field electromagnetic noise of a P.T. (top) and a magnetic transformer (bottom).

- Finally, the characteristics obtained in the novel battery charger are superior to those of a linear charger, as can be seen in the following table:

	Linear charger	Novel charger
Efficiency	64%	75%
Size	9cmx5cmx7cm (315cm^3)	3,3cmx4,4cmx1,4cm (20cm^3)
Weight	260gr.	18.7gr
Static regulation	±4.5%	±1.36%
Output voltage ripple	1.85V	0.06V
Safety	EN60950	EN60950
EMC	EN55022 class B	EN55022 class B

VI. CONCLUSIONS

This paper presents the results obtained in the development of a miniaturized travel charger for mobile phones, based on piezoelectric transformers. These transformers can prove to be a suitable substitute for magnetic transformers in a near future, if proper investments in development are made. The main results obtained in this work are a battery charger smaller than a matchbox.

VI. REFERENCES

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